

Modeling and Simulation of DC Motor Using Simelectronics and Simulink

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ÖZET

This paper describes the development of mathematical and physical Modeling based simulators in the Simulink © Simscape™ environment as interactive tools to demonstrate the DC motor responses in terms of current, speed and torque. This type of Modeling requires to join the physical components with physical connections to define the underlying dynamic equations of the DC motor. This approach is further compared with the analytical model in Simulink. To support our proposal, numerical simulations and mathematical Modeling of the DC motor are derived using the Lagrangian and Euler-Lagrange approach contrary to the existing Kirchhoff's and Newton laws. The state space model is formulated based on Hamilton's equation. The simulation models are developed as part of software laboratory support and to enhance undergraduate control systems and machinery courses at Olabisi Onabanjo University. A proportional Derivative (PD) controller is implemented for both the models to compensate for fast response in the armature current and electromagnetic torque. A comparative study of the model for the separately excited Dc motor has shown that the models have their own merits and demerits.

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1. INTRODUCTION (*Giriş*)

To stimulate students' interest in practical engineering based degree and also to bridge the gap between the practical and theoretical skills, the use of computer - based software tools has been integrated into the field of Engineering. Presently, educators and researchers developed a huge variety of resources to enhance the teaching of Engineering based Laboratory courses. In the Mechatronic and Control field, there are a considerable number of specialized and general purpose Virtual Laboratory tools available for experimental purpose. MATLAB® / Simulink© is introduced to the Engineering curriculum due to their extended use for both design and the simulation of the control system. Furthermore, the potential of Simulink© has been extended by adding a multitude of toolboxes, among which are interested in emphasizing Simscape™ for physical modeling. It is an object-oriented enriched environment which joins the physical components with physical connections to define the underlying dynamic equation of the system. Unlike other Simulink blocks, Simscape directly represents physical elements or

relation. Hence, a system model can be built in this environment in a similar way that a physical system is assembled. Therefore, Simscape as a Virtual Laboratory tool enhances students' motivation to learn and simulate dynamic of the complex system in an interactive mode. In recent times, DC motors have been proven as core ingredient in speed control and it is gaining a limelight with integration of renewable energy for most automobiles and mechatronics applications. It is widely used as energy conversion devices[1], serves as a speed drive control in electric cars and electric traction[2], [3], as an actuators in robotic manipulators [4], [5] and smart wheelchair[6], used in overhead cranes, medical treatment, power electronics dc drive applications [7]–[9]. Recently, the demand for DC motors in speed control for hybrid vehicles powered with internal combustion and electric engines is steadily increasing with the attention to reduce fossil-fuel based vehicles and to mitigate the global warming gas emissions. The existing works[10]–[12] have been limited to formulation of mathematical model using Kirchhoff's law and Newton's law of motion which is further

converted to frequency domain-Laplace transform to obtain the system transfer function. However, this paper proposed a novel Lagrangian and Euler-Lagrange coupled with Hamilton's approaches to formulate the mathematical models and developed two different simulation models to simulate the system dynamic of the DC motor accurately and emphasis the usefulness of such approaches in the field of electrical engineering to support teaching in automatic control. The general configuration, dynamic equation, analysis, characteristic and control of DC motor are presented in Nise[13]. Pal[14] proposed a generalized dynamic modeling of DC motor based on state space approach. In Khanna[15] presented a model predictive control model for a DC motor. Some models and simulation software based related to DC motor are presented in [16]–[18] and Gencer[19] further extended model to brushless DC motor in Simulink. Chen[11] further introduced a Simulink based model. Venu[20] proposed a PID controller algorithm for DC motor control in state space domain. A performance comparative analysis of PI controller and Artificial Intelligent control is investigated in Abdulrahman[21], [22]. Jafar et al [23] proposed an improve rotor speed of a brushless Dc motor using fuzzy controller. In [24] a proportional-integral (PI) controller is implemented to improve the battery performance of electric motor vehicle. A java web-application software is developed for a DC motor position control in[25]. Similarly, a virtual electrical machine laboratory tool for Dc the motor is developed to enhance practical electronic learning of DC moor dynamic and responses [26], [27]. The main objective of this paper is to show the advantages of using physical modeling to develop interactive resources to support teaching and learning in Automatic Control. Thus, the idea is to build a simulator for laboratory courses with which the students can validate their designed controller so as to provide an alternative to the use of real platform that needs a heavy budget in terms of resources.

2. MATERIAL AND METHODS (MALZEME VE YÖNTEMLER)

The electromechanical dynamic model of a separately excited DC motor is formulated based on Lagrange equations and Hamilton equation. The system structure of a DC motor is depicted in Fig.1, including the armature resistance R_a and the winding leakage inductance L_a . In most servo applications, dc motors are used in the neighbourhood of linear region of the magnetization curve, such that the airgap flux ϕ is proportional to the field current. For a separately excited dc motors, the field constant is held constant, so that the motor generates a torque T_m proportional to the armature current and the back emf V_b is proportional to angular velocity of the rotor in the motor. Obviously, the motor will encounter two external sources, the input voltage $V_s(t)$ to drive the motor and the torque $T_L(t)$ reacted from the load.

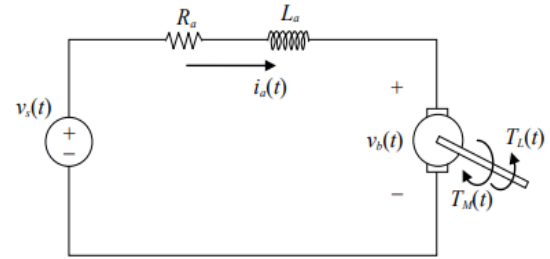


Figure 1. The System Structure of a DC Motor

2.1 Lagrange's equation (Lagrange denklemi)

The dynamic equation of the DC motor is determined using Lagrange's equation of the second kind. First, we calculate the kinetic energy T and potential energy, U , of the system and the Rayleigh's dissipative function is integrated into Lagrange's equation to account for the damping and resistive forces in the electromechanical system. In order to describe the physical motion of the electromechanical DC motor, we choose charge, q_1 and the angle of the rotor, q_2 as the generalized coordinates, such that $q_1 = q_1, q_2 = \theta$ and the first derivative as generalized current and speed as $\dot{q}_1 = i_a(t), \dot{q}_2 = \omega(t)$. Thus, the Lagrange function L is defined as the difference of the system's kinetic and potential energy.

$$L = T - U \quad (1)$$

Denoting by T_0, U_0 and T_1, U_1 , the kinetic and potential energy in the electrical part and mechanical part respectively. We obtain

$$L = (T_0 + T_1) - (U_0 + U_1) \quad (2)$$

According to conservation of energy, the kinetic and potential energy for the electromechanical DC motor are as follows:

$$T = \left(\frac{1}{2} L_a \dot{q}_1^2 \right) + \left(\frac{1}{2} J \dot{q}_2^2 \right) \quad (3)$$

$$U = -(V_s - V_b) q_1 \quad (4)$$

Rayleigh dissipative function in the electromechanical DC motor is:

$$R = \left(\frac{1}{2} R_a \dot{q}_1^2 \right) + \left(\frac{1}{2} B_m \dot{q}_2^2 \right) \quad (5)$$

Substituting equation (1–3) into the Lagrangian (2) gives:

$$L = \frac{1}{2}L_a \dot{q}_1^2 + \frac{1}{2}J_m \dot{q}_2^2 + (V_s - V_b)q_1 \quad (6)$$

Define the vector $q_i = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}$ as the generalized coordinate and the matrix $H = \begin{bmatrix} 0 \\ T_m + T_L \end{bmatrix}$ where T_m is the generalized coordinate torque exerted on q_2 and T_L as the load torque. Then, the generalized Euler-Lagrange equation can be written as

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \left(\frac{\partial L}{\partial q_i} \right) + \left(\frac{\partial R}{\partial \dot{q}_i} \right) = H \quad (7)$$

Lagrange's equations of the second kind for the electromechanical DC motor in terms of generalized coordinates are as:

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_1} \right) - \left(\frac{\partial L}{\partial q_1} \right) + \left(\frac{\partial R}{\partial \dot{q}_1} \right) = 0 \quad (8)$$

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_2} \right) - \left(\frac{\partial L}{\partial q_2} \right) + \left(\frac{\partial R}{\partial \dot{q}_2} \right) = T_m + T_L \quad (9)$$

After substitution of the partial derivatives, we obtain the set of the following second-order differential equations:

$$L_a \ddot{q}_1(t) = -R_a q_1(t) - V_b(t) + V_s(t) \quad (10)$$

$$J_m \ddot{q}_2(t) = -T_m(t) - B_m \dot{q}_2(t) + T_L \quad (11)$$

Thus, the back emf $E_b(t)$ and the torque $T_m(t)$ are expressed as:

$$E_b(t) = K_b \dot{q}_2(t) \quad (12)$$

$$T_m(t) = K_t \dot{q}_1 \quad (13)$$

Hence, the first and second derivatives of the generalized coordinates are:

$$\frac{d}{dt} (q_1(t)) = i_a(t)$$

$$\frac{d^2}{dt^2} (q_1(t)) = \frac{di_a(t)}{dt} \quad (14)$$

$$\frac{d}{dt} (q_2(t)) = \omega_m(t)$$

$$\frac{d^2}{dt^2} (q_2(t)) = \frac{d\omega_m(t)}{dt}$$

Substituting the derived derivatives in equation (14) into Eqs. (10) and (11) lead to:

$$\frac{di_a(t)}{dt} = \frac{-R_a}{L_a} i_a(t) - \frac{K_b}{L_a} \omega_m(t) + \frac{1}{L_a} V_s(t) \quad (15)$$

$$\frac{d\omega_m(t)}{dt} = \frac{K_t}{J_m} i_a(t) - \frac{B_m}{J_m} \omega_m(t) + \frac{1}{J_m} T_L \quad (16)$$

2.1.1. Hamilton's equation (*Hamilton'un denklemi*)

The Hamiltonian function $H = H(q, p, t)$, which is defined as the sum of the system's kinetic (inductive) energy and potential (capacitive) energy can be used to describe the dynamic equations of an electromechanical system such as a DC motor. Hence, Hamilton's function H is expressed as:

$$H = T + U \quad (17)$$

$$H = \frac{1}{2}L_a \dot{q}_1^2 + \frac{1}{2}J_m \dot{q}_2^2 - (V_s - V_b)q_1 \quad (18)$$

Then, Hamilton's equations:

$$\frac{\partial q_i}{\partial t} = \frac{\partial H}{\partial p_i} \quad (19)$$

$$\frac{\partial H}{\partial q_i} = -\dot{p}_i - \frac{\partial G}{\partial q_i} \quad (20)$$

State variables of the DC motor from Fig.1 are the charge flowing in the armature circuit and the angle of the rotor q_1, q_2 respectively and momentum p_1, p_2 . The kinetic (inductive) energy in terms of momentum is expressed as:

$$T = \frac{1}{2}L_a \left(\dot{q}_1 \right)^2 + \frac{1}{2}J_m \left(\dot{q}_2 \right)^2 = \frac{p_1^2}{2L_a} + \frac{p_2^2}{2J_m} \quad (21)$$

Potential (capacitive) energy

$$U = -(V_s - V_b)q_i \quad (22)$$

Rayleigh's dissipative function or content of the system

$$G = \frac{1}{2}R_a \dot{q}_i^2 + \frac{1}{2}B_{m_i} \dot{q}_i^2, i = 1, 2 \quad (23)$$

Generalized linear force for viscous (resistive) damping is expressed as the content of the system function as:

$$Q_i = \frac{-\partial G}{\partial \dot{q}_i}, i = 1, 2 \quad (24)$$

Generalized forces

$$Q_{e_1} = 0, Q_{e_2} = T_m(t) + T_L(t) \quad (25)$$

Dynamic equation of the electromechanical DC motor are obtain in the form:

$$\frac{\partial H}{\partial q_1} = \dot{q}_1 = \frac{dq_1(t)}{dt} \quad (26)$$

$$\frac{\partial H}{\partial q_2} = \dot{q}_2 = \frac{dq_2(t)}{dt} \quad (27)$$

$$\frac{dp_1(t)}{dt} = -\frac{\partial H}{\partial q_1} + Q_1 + Q_{e_1} \quad (28)$$

$$\frac{dp_2(t)}{dt} = -\frac{\partial H}{\partial q_2} + Q_2 + Q_{e_2} \quad (29)$$

So that,

$$\frac{dq_1(t)}{dt} = \frac{p_1(t)}{L_a} \quad (30)$$

$$\frac{dp_1(t)}{dt} = V_s - V_b - R_a \dot{q}_1 = V_s - V_b - \left(\frac{R_a}{L_a}\right)p_1 \quad (31)$$

$$\frac{dq_2(t)}{dt} = \frac{p_2(t)}{J} \quad (32)$$

$$\frac{dp_2(t)}{dt} = -B_m \dot{q}_2(t) + T_m(t) + T_L(t) \quad (32)$$

In matrix form:

$$\begin{bmatrix} \frac{dq_1(t)}{dt} \\ \frac{dp_1(t)}{dt} \\ \frac{dq_2(t)}{dt} \\ \frac{dp_2(t)}{dt} \end{bmatrix} = A \begin{bmatrix} q_1(t) \\ p_1(t) \\ q_2(t) \\ p_2(t) \end{bmatrix} + B \begin{bmatrix} V_s(t) \\ T_L(t) \end{bmatrix} \quad (33)$$

Based on (29), (30), (31), (32), (14) and choosing the state vector $x = [q_1(t), q_2(t), i_a(t), \omega(t)]^T$, the dynamic equation of the Dc motor can be expressed in state space description as:

State equation:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (34)$$

Output equation:

$$y(t) = Cx(t) \quad (34)$$

Where the state vector is

$$x(t) = \begin{bmatrix} q_1(t) \\ i_a(t) \\ q_2(t) \\ \omega_m(t) \end{bmatrix} \quad (35)$$

and the input vector is:

$$u(t) = \begin{bmatrix} V_s(t) \\ T_L(t) \end{bmatrix} \quad (36)$$

Figure 1Figure2. Control loop with PD Controller and the system matrices are:

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -\frac{R_a}{L_a} & -\frac{K_b}{L_a} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{K_t}{J_m} & -\frac{B_m}{J_m} \end{bmatrix} \quad (37)$$

$$B = \begin{bmatrix} 0 & 0 \\ \frac{1}{L_a} & 0 \\ 0 & 0 \\ 0 & \frac{-1}{J_m} \end{bmatrix} \quad (38)$$

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (39)$$

In most dynamic models of the DC motor the variables to control are predominantly the armature current (electrical variable), $i_a(t)$ and the angular velocity (mechanical variable), $\omega_m(t)$ of the motor; in such case, the system matrices A and B are in the form of [28].

$$A = \begin{bmatrix} -R_a & -K_b \\ L_a & L_a \\ K_t & -B_m \\ J_m & J_m \end{bmatrix}, B = \begin{bmatrix} 1 & 0 \\ L_a & 0 \\ 0 & -1 \\ J_m & J_m \end{bmatrix} \quad (40)$$

and the output is angular velocity $\omega_m(t)$.

2.1.2. PID Controller Implementation (Gecikmeli türev eşitliği tabanlı kaotik sistem modeli)

The control goal is to stabilize both the current and torque by minimizing the error and to achieve this stated objective a proportional-Derivative controller is implemented in such a way that the gain of the proportional controller, k_p , is high to produce a fast system and the derivative gain k_d , is select in a manner to decrease the oscillation. The PD controller algorithm combines the P-action and D-action to adjust the system. It is a two-term controller that is coined from the PID controller by setting the integral action to zero. The term domain expression for PD controller is given as:

$$u(t) = k_p e(t) + k_d \frac{de(t)}{dt} \quad (41)$$

Where $u(t)$ is the control signal, the error signal $e(t)$ is defined as $e(t) = r(t) - y(t)$, and $r(t)$ is the reference input signal. In the Simulink and Simelectronics models, a PD controller is implemented from the PD block in the Simulink toolbox library and converted to a physical system with Simulink-PS converter for the Simelectronics. The tuning of control parameters is done using PID tuner and the best performance of the controller parameter values are selected.

2.1.3. Results and Discussion (Sonuçlar ve tartışma)

This work presents a novel DC motor modeling based simulators to support teaching in automatic control. The simulation of the DC model was implemented directly using MATLAB/Simulink/Simelectronics.

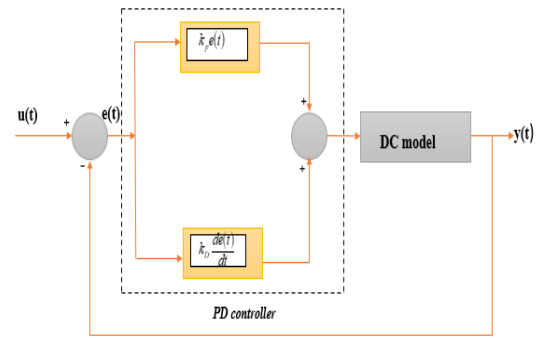


Figure2. Control loop with PD Controller

In this model, the full voltage is applied to the armature terminals with the varying load torques to investigate the speed, current and torque characteristic. Based on this, a Simulink model for the DC motor is established on the derived Euler-Lagrange and Hamilton's. Hence, a physical system is built in Simelectronics as illustrated in Figure.3 and Figure.4 respectively. The parameters of a separately excited Dc motor in Fig.1 are $R_a = 0.5 \Omega$, $L_a = 1.5 \text{ mH}$, $J_m = 0.00025 \text{ kgm}^2$, $K_t = 0.05 \text{ N-m/A}$, $K_b = 0.05 \text{ V/(rad/s)}$. Terminal voltage of the motor is $v_s(t) = 2 \text{ V}$. The parameter values are initialized and simulations are run for several values of load torque in the range of $(T_L = 0 - 0.5) \text{ N-m}$. Furthermore, the model is simulated related to the speed (ω_m) of DC motor without load ($T_L = 0$), with load 1 ($T_L = 0.3$) Nm and load 2 ($T_L = 0.5$) Nm. Figure 5a and figure 5b show the obtained simulation results of the current and speed respectively. From these figures, it can deduce that it is challenging to stabilize the responses with the proportional controller alone irrespective of the value of gain K chosen, hence, a combination of proportional and the derivative controller is implemented to compensate for fast response and steady error respectively. Figure.6 illustrates the electromagnetic torque and armature current response with PD controller. Again, from these figures we can observe the robustness of the proposed controller. A comparative study of the model for the separately excited DC motor has shown that the models have their own merits and demerits as illustrated in Table1. Furthermore, it can also be deduced from the table.1 that students do not need to master the mathematical equations before using the simulator. In much related research work [29], the dynamics are modeled with Kirchhoff's law and transformed into transfer function model using Laplace transformation to aids system analyze in the frequency domain. However, the novel Simelectronics approach allows for the description of physical structure of a system rather than the causal mathematics. The study conducted for the

undergraduate students on the use of Simulink and Simscape at Olabisi Onabanjo University revealed that Simscape simulation tool has more advantages than the

counterpart Simulink tool. Hence, the summary of the model evaluation is presented in Table1.

Table 1.Performance Comparison of the Models

Model	Controller	Model Formulation	Responses	Easy of Set-up	Performance	Model Accuracy	Students' Adaptability
Simulink	PD	Mathematical model is required	Excellent	complex	Good	Prone to model error	Yes, but require continuous practice
Simelectronics	PD	Required physical network connection	Excellent	easy	Excellent	Free from model error	Yes

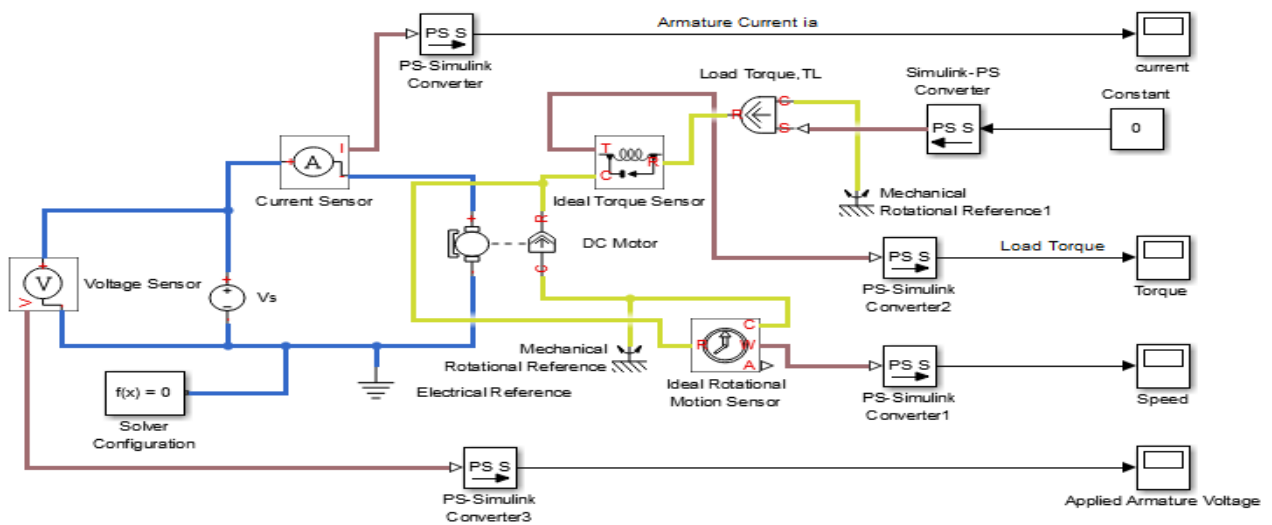


Figure 4.DC motor Simscape model

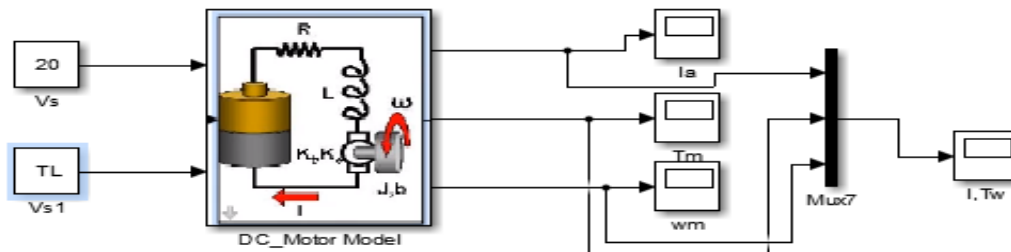


Figure 4. DC motor Simulink model

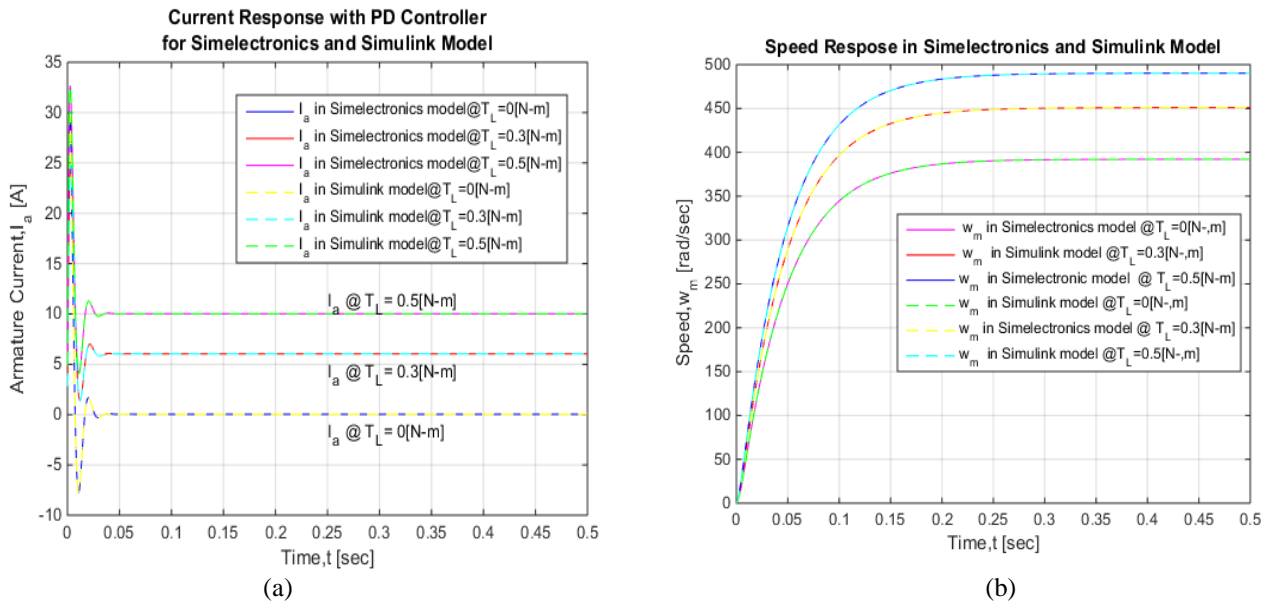


Figure.5 Simulation results in Simelectronics and Simulink for (a) current and (b) speed

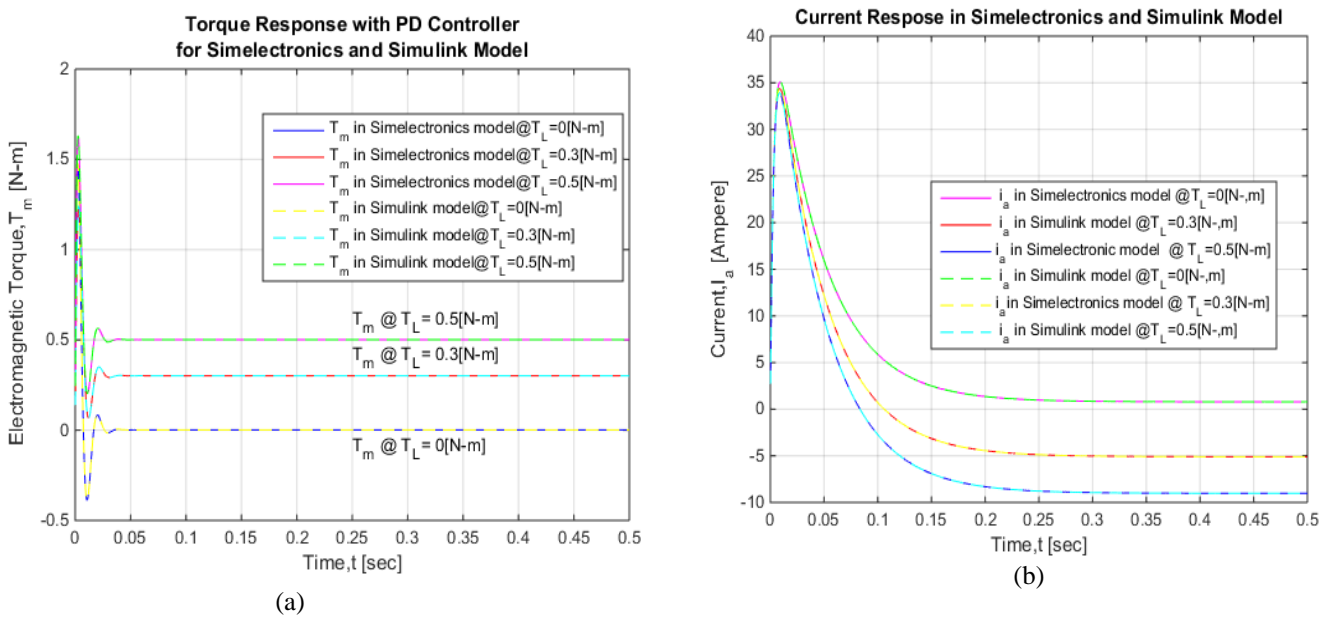


Figure.6. Simulation results in Simelectronics and Simulink with PD controller for (a) Electromagnetic Torque and (b) Armature current.

3. CONCLUSION (SONUÇ)

The paper presents modeling and simulation of the dynamic equations of electromechanical DC motor in Simelectronics and Simulink and to simulate the dynamic accurately Lagrange's and Hamilton's equations were adopted contrary to the conventional Kirchhoff's and Newton's laws methods. Results are shown graphically and the calculation is done for a model with speed, torque and load in MATLAB to illustrate the methodology. The validation of Simelectronics model are done with the state space model built in Simulink. This validation is done to ensure that Simelectronics model can be used to replicate the behaviour of a DC motor dynamic. In addition to modeling, a PD controller are implemented on the Simelectronics simulation model and the Simulink model. Results obtained are then compared and found to be in close agreement. The contribution of this work is significantly expedient in the field of automobile, mechatronics, and control systems and educative for hand-on laboratory. It also provides a novel approach to simulate the electromechanical system in a concise and precise method.

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Nomenclature

J_m	equivalent moment of inertial of motor and load referred to motor shaft
B_m	equivalent viscous friction coefficient of motor and load referred to motor shaft
L_a	inductance of armature winding
R_a	resistance of the armature winding
V_b	back emf (volts)
T_m	Torque developed by the motor
T_L	load Torque (Nm)
ω_m	angular velocity of motor shaft
K_t, K_b	motor torque constant and back emf constant
H	Hamilton's function
L	Lagrange's function
T	kinetic energy
U	potential energy
G, R	Rayleigh's dissipative function
p_i	momentum of the i-th numbe

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