International Journal of Applied Mathematics
Volume 38 No. 2s , 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

RESEARCH ON THE APPLICATION OF MATLAB/SIMULINK IN THE TEACHING OF ELECTRIC MOTOR SIMULATION AND CONTROL AT TECHNICAL TRAINING INSTITUTIONS

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Abstract

In the context of strong digital transformation in technical education, the use of simulation and digital tools in teaching is becoming an unavoidable trend. This study presents the process of setting up and evaluating an electric motor control system simulation model using MATLAB/Simulink software, and analyzes the pedagogical effectiveness of applying the model to training practice. The model is built on a DC electric motor with PID control, which allows visual observation of the relationship between electrical and mechanical quantities during operation. The simulation results showed that the error between the model and the experimental data was only about 2–5%, demonstrating high accuracy and applicability.

A survey of engineering students showed that the level of understanding and interest in learning increased by an average of 35% when using simulations instead of traditional methods. The MATLAB/Simulink model also helps instructors save time preparing lectures and reduce the cost of practical equipment. The study confirms the effectiveness, flexibility, and scalability of simulation in training modern engineers, especially in the modules of Electric Drive, Automatic Control, and Electric Vehicle Drive Systems.

Based on this, the research team proposes to standardize simulation textbooks, organize instructor training, and develop virtual laboratories combined with hardware to enhance teaching quality and scientific research. The future development will focus on advanced simulation for BLDC motors and PMSM, integrating intelligent control algorithms such as Fuzzy, MPC, and AI-based methods to meet the needs of engineer training in the Industry 4.0 era.

Keywords: Simulation; MATLAB/Simulink; Electric motors; Technical teaching; Virtual labs; Automatic control.

1. INTRODUCTION

In the context of the ongoing industrial revolution 4.0, the automotive industry is witnessing a rapid transition to electrification, automation, and artificial intelligence technologies [1], [2]. One of the prominent trends is the development of electric vehicles (EVs) and hybrid vehicles (HEVs) – where electric motors and control systems play a central role in drive, energy management and operational efficiency assurance [3], [4]. Therefore, training and teaching on

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ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

electric motor control in technical education institutions has become urgent, requiring new teaching methods associated with simulation technology and digital experiments [5]–[7].

In a traditional engineering training environment, students often approach the content of controlling electric motors through circuit theory, motor modeling, and basic experimental practice. However, the major limitation of this approach is the lack of the ability to visualize dynamic phenomena, especially in nonlinear, transient, or multivariate situations [8]. The use of modern simulation software such as MATLAB/Simulink has opened up the possibility of helping students gain a deeper understanding of the physical and control nature of the system [9], [10].

MATLAB/Simulink is a powerful simulation environment developed by MathWorks, which is widely used in research and training in control systems, power electronics, and electric motors [11], [12]. With the ability to model using block diagrams, real-time simulations, and link to hardware via Hardware-in-the-Loop (HIL) modeling, MATLAB/Simulink allows instructors to build interactive lectures and virtual experiments [13]–[15]. This is especially useful in modules related to DC motor control, asynchronous motors, permanent magnet synchronous motors (PMSM), and complex electric drive systems [16]–[19].

According to many studies, electric motor simulation using MATLAB/Simulink helps to shorten learning time, increase visualization and systems thinking for engineering students [20]–[23]. Simulation-based lectures also allow students to change parameters, test system responses, and compare between different control algorithms such as PID, Fuzzy Logic, Model Predictive Control (MPC), or Sliding Mode Control (SMC) [24]–[27]. Thereby, learners not only grasp the principle but also have the ability to evaluate the performance, stability and dynamic response of the control system [28], [29].

For instructors, MATLAB/Simulink is a tool that supports effective lecture simulation design, allowing the creation of visual teaching models, from simple to advanced. For example, Aliane [30] developed a servo simulation interactive module using Simulink that helps students understand the structure and control feedback; Gelen and Ayasun [31] implemented a DC motor speed control model based on a power electronic converter; while Saghafinia [32] emphasizes the pedagogical effectiveness of teaching variable speed drive simulation using MATLAB/Simulink software. These studies indicate that incorporating simulation in training helps students be more active in learning, reduces reliance on expensive physical equipment, and expands virtual testing space [33]–[35].

Along with the development of simulation techniques, the trend of Real-Time Simulation and Hardware-in-the-Loop (HIL) is increasingly emphasized in technical training [36]–[39]. Thanks to the connectivity between MATLAB/Simulink and microcontrollers or boards such as dSPACE, Arduino, STM32, instructors can deploy real-time hands-on control models without the need for a real drive system [40], [41]. This helps students become familiar with the programming environment, control configuration, and signal processing – core skills in today's industry [42]–[44].

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Volume 38 No. 2s , 2025
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In recent studies, many universities around the world have implemented simulation-based teaching models and hands-on simulations, particularly in subjects such as *Electric Drive Systems*, *Power Electronics*, and *Control Engineering* [45]–[48]. The results showed that students who participated in the electric motor simulation using MATLAB/Simulink achieved 20–30% higher results on the controlling thinking tests compared to the traditional study group [49]. In addition, the application of simulation helps to standardize training content between technical institutions, reduce the disparity in laboratory equipment, and increase the ability of distance learning [50]–[52].

However, in Vietnam, the application of MATLAB/Simulink in teaching electric motor control is still limited. The main reasons come from the lack of standardized lecture models, difficulties in training lecturers and limitations in compatible hardware equipment [53], [54]. Some technical training institutions have begun to integrate simulation software into their curriculum, but mainly at the basic modeling level, which have not yet exploited the full potential of the Simscape, Control System Toolbox or Motor Control Blockset modules [55]–[57]. Therefore, it is necessary to have overview studies, develop teaching frameworks and simulation models suitable for the actual conditions of Vietnam [58]–[60].

Stemming from that context, this paper aims to research and propose the application of MATLAB/Simulink in teaching electric motor simulation and control at technical training institutions. Specifically, the study focuses on three main directions: (1) analysis of popular electric motor simulation models in MATLAB/Simulink; (2) develop illustrated lectures and simulated integrated teaching processes; (3) Evaluate pedagogical effectiveness through learner feedback. The research results are expected to contribute to improving the quality of automotive – electrical – control engineer training, and at the same time support digital transformation in technical education, in line with the development trend of STEM education and global simulation-based learning.

2. THEORETICAL BASIS

2.1. General introduction to simulation and control in technical teaching

In the context of today's digital transformation of education, the application of simulation tools in the training of technical engineers is increasingly becoming an inevitable trend. Simulation software such as MATLAB/Simulink, ANSYS, CarSim or LabVIEW allows learners to directly observe, analyze, and verify complex models in a virtual environment, thereby shortening the gap between theory and practice [4], [9]. In particular, for the automotive engineering industry, the strong development of electric vehicles (EVs) requires students to master the knowledge of electric motor control systems, energy management, and electronic drives [3], [7].

Numerous studies have shown that the use of simulation in technical training increases the level of conceptual understanding, improves systems thinking abilities, and develops design-analysis capabilities [10], [16]. MATLAB/Simulink is a standout tool in this field due to its intuitive modeling capabilities, high flexibility, and ability to integrate with hardware tools such as Arduino, dSPACE, or NI-ELVIS [12], [19].

2.2. MATLAB/Simulink and its applicability in technical education

MATLAB/Simulink, developed by MathWorks, is an engineering computing environment that combines programming, simulation, and control design [20]. Simulink, with its block diagram interface, enables the modeling of complex dynamic systems, including DC electric motors, asynchronous motors, permanent magnet synchronous motors (PMSM), and drive systems [22], [24].

In the field of engineering education, Simulink provides students with easy access to concepts such as feedback, PID control, vector control, and nonlinear control strategies [25]. Models can be built, run simulations, and fine-tune parameters quickly, thereby helping students to deeply understand the relationship between control signals and system response [27], [28].

A number of universities around the world such as *the Massachusetts Institute of Technology (MIT), the Technical University of Munich (TUM)* and *Chalmers University of Technology* have integrated MATLAB/Simulink in the training of subjects such as "Electric Motor Control", "Electric Drive Systems" and "Electric Vehicle Simulation" [31], [33], [36]. This proves the universality and high application value of this tool in technical teaching art.

2.3. Overview of electric motor control model

Electric motors are the heart of powertrains in electric and hybrid cars. The accurate simulation and control of motors such as DC, PMSM, and asynchronous (IM) motors helps students understand the electromechanical characteristics of each, as well as the system's ability to respond to changes in load, voltage, or control signals [35], [37].

The electric motor model in Simulink usually consists of three basic blocks: the electric part model (voltage – current equation), the mechanical part (torque – rotation speed), and the control block (PID, FOC, DTC or dim control) [39], [42]. These models can be combined with the "Power Electronics" block to simulate the inverter and the "Battery Model" to simulate the power source [43], [45].

The work of Singh et al. [46] and Yildiz [47] shows that teaching based on electric motor simulation in MATLAB/Simulink helps students quickly grasp the relationship between electromechanical theory and practical application. Furthermore, this method saves laboratory costs, reduces the risk of equipment damage and increases safety during training.

2.4. Simulation applications in control and automation training

One of the greatest advantages of MATLAB/Simulink is its ability to comprehensively simulate control systems, from simple control signal levels to adaptive control systems, neural networks, or model predictive control (MPC) [48], [50]. These models help students not only learn how to design controllers, but also evaluate system performance through parameters such as setting errors, transition times, and stability [51], [54].

In the study of Alkan et al. [55], the simulation of the vector control system for PMSM motors was applied as an integrated lesson between linear control theory, power electronics, and simulation techniques. Similarly, in technical training institutions in Vietnam such as Hanoi University of Science and Technology and Ho Chi Minh City University of Industry,

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ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

MATLAB/Simulink has been used in virtual labs to assist students in practicing controlling electric motors without the need for complex hardware [56]. [58].

2.5. The role of MATLAB/Simulink in digital transformation of technical education

The emergence of "virtual lab" and "simulation experiments" plays an important role in the digital transformation of education. Tools such as MATLAB/Simulink help create interactive learning environments, allowing students to test a variety of control configurations, record data, and analyze system performance [59].

In addition, the application of simulation also contributes to the development of students' scientific research capacity. According to research by Tan et al. [60], courses with integrated MATLAB/Simulink simulations help increase learners' creativity, logical thinking, and problem-solving abilities – key competencies in training the next generation of engineers.

3. RESEARCH METHODOLOGY

3.1. Research objectives and orientations

The main objective of this study is to evaluate the effectiveness and potential of applying MATLAB/Simulink software in teaching electric motor simulation and control, thereby proposing a suitable implementation model for technical training institutions in Vietnam. The selected method is interdisciplinary, a combination of digital simulation, technical pedagogical analysis and educational empirical evaluation [6], [13].

The general approach consists of four phases:

1. Theoretical analysis and selection of the right electric motor model for training (DC, PMSM, or IM).
2. Set up the simulation model on MATLAB/Simulink, including the electrical, mechanical, and control parts.
3. Integrate the model into a lecture or virtual lab for students to practice.
4. Assess students' learning effectiveness and level of understanding after applying the simulation.

3.2. Modeling Methods in MATLAB/Simulink

The process of modeling the electric motor system is carried out based on the basic electro-basic equations of each type of motor. For DC Motors, the model is built on the equation of armature voltage and electromagnetic torque:

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + e_b$$

$$T_e = K_t i_a$$

where *Va* is the armature voltage, *ia* is the current, *eb* is the reactive electromotive force, *Te* is the electromagnetic moment, and *Kt* is the torque constant [14], [21].

ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

The corresponding simulation blocks are created using standard blocks in the Simulink Library, including "Gain", "Integrator", "Sum", "Scope", and "Step Input". For PMSM or asynchronous motors, the "Simscape Electrical" blocks are used to simulate IGBT inverter circuits in detail [18], [26].

The control model is built using PID Controller, FOC (Field Oriented Control) or PWM modulation depending on the lesson level. The simulation was run for 10–20 seconds, allowing students to observe the response to speed, torque, and current in real time [30], [35].

3.3. Simulated Learning Environment Design

To increase interactivity in teaching, this study builds a multi-layered simulated learning environment, including:

1. Floor 1: Basic simulation (DC motor model, PID control).
2. Floor 2: Advanced simulation (PMSM, vector control).
3. Tier 3: Hardware integration (Arduino, NI-ELVIS, or dSPACE).

The model structure is designed in an open and flexible direction, allowing the instructor to add modules such as inverters, speed sensors, or signal filters [37], [41].

To ensure pedagogical effectiveness, the simulated environment is combined with interactive online lectures via MATLAB Live Script. Students are tasked with adjusting control parameters, recording responses, and discussing the results. This method not only helps them understand the nature of control but also forms analytical, self-learning and applied research competencies [42], [44].

3.4. Teaching effectiveness assessment methods

The evaluation of the effectiveness of the application of MATLAB/Simulink in teaching is carried out through two main groups of criteria:

1. Technical Effectiveness:
    1. Ability to accurately simulate mechanical-electrical properties.
    2. Response time, error setting, and system stability.
    3. Compatibility between simulations and experimental results (if any).
2. Pedagogical Effectiveness:
    1. Conceptual Understanding.
    2. Control system analysis capacity.
    3. Level of interest in learning and applicability.

The study used a side-by-side comparison method between two groups of students:

1. Group A studied according to traditional methods (theoretical lectures and hardware experiments).

Received: August 12 2025

Volume 38 No. 2s , 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

2. Group B learned through the integrated MATLAB/Simulink simulation.

Results were collected through a Likert questionnaire, theoretical test, and regression model analysis to determine the correlation between learning methods and attainment [46], [48].

3.5. Data verification and analysis methods

To verify the reliability of the simulation model, the motor specifications are derived from actual data (e.g. 12V DC motor, 100W power, 3000 rpm). The simulation results were compared with measurements from actual experiments using Arduino hardware and Hall speed sensors [50], [52].

Data analysis is performed using MATLAB tools such as "Curve Fitting Toolbox" and "Simulink Data Inspector". Quantitative indicators such as Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) were used to evaluate the error between the model and the reality [54], [56].

In addition, feedback from students and lecturers was analyzed using the Content Analysis method, which aims to identify factors affecting learning performance and technology adoption [57], [59].

3.6. Trial implementation at technical training institutions

The research model was piloted at the Faculty of Automotive Engineering Technology – Thanh Dong University, where students learned the module *of Automatic Control and Electric Drive System*.

The exercises are divided into three groups:

1. Control the DC motor by PID.
2. Control the PMSM with vector control.
3. Electric vehicle energy management simulation.

The duration of each lesson is 3–4 hours, including tutorials, simulation practices, and group discussions. After each lesson, students submit a simulation report, which presents the model structure, results, and evaluation of system performance. Lecturers score according to three criteria: simulation accuracy, analytical ability and technical presentation [60].

4. RESULTS AND DISCUSSION

4.1. Simulation model of electric motor control system on MATLAB/Simulink

The simulation system built on the MATLAB/Simulink platform consists of three main blocks: (1) the electric motor model, (2) the power converter and (3) the speed control block. The survey motor is an independent magnetic DC electric motor (DC Motor), which is simulated through the torque-velocity equation, while the control block uses a PID controller.

The main parameters of the model are presented in Table 1.

Table 1. DC Electric Motor Simulation Parameters

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ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

Parameter	Ampersand	Value	Unit
Armature Resistance	R	2.5	Ω
Armature Induction	L	0.01	H
Electromechanical constant	K	0.01	V·s/rad
Moment of inertia	J	0.01	kg·m²
Coefficient of viscosity of friction	B	0.001	N·m·s/rad
Supply Voltage	V	220	V

The model is built on the principle of closure between the motor block and the control block, which allows the observation of variations in speed, current, and torque over time.

When running the simulation under the condition of sudden change in load, the system responds quickly, the transit time is about 0.35 seconds, the stable fluctuation is less than 5%, proving the reliability of the model.

4.2. Evaluate the responsiveness of the PID controller

The system was tested with three different PID parameter values, corresponding to Ziegler–Nichols, Cohen–Coon calibration methods and manual adjustment. The results are summarized in Table 2.

Table 2. PID Controller Evaluation Results

Calibration method	Calibration method	Leap (%)	Static Deviation (%)
Ziegler–Nichols	0.42	7.5	1.8
Cohen–Coon	0.38	5.3	1.2
Manual Adjustment	0.35	4.9	0.9

From the simulation results, it can be seen that the PID is manually calibrated for the most optimal response with short transient times and small static deviations. This model can be used in illustrative lessons on speed feedback control and system stability in technical teaching.

4.3. Application of models in teaching

The MATLAB/Simulink model was tested in teaching "Electric Motor Control" for third-year students majoring in Mechatronics and Automotive Engineering.

After two semesters of application, the results of a survey of 80 students are shown in Table 3.

Table 3. Results of the Teaching Effectiveness Survey

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ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

Judging Criteria	Before Application (%)	After application (%)	Improvement (%)
Understand the structure of the control system	58.7	91.2	+32.5
Master the principles of PID	46.3	88.4	+42.1
Simulation and error handling skills	52.5	90.0	+37.5
Interest in learning	60.0	95.0	+35.0

The results show that the model helps students enhance their visual abilities, shorten the time it takes to understand abstract concepts, and improve their ability to practice simulations. Observing signal changes in real time helps learners quickly access modern control thinking [12], [24].

4.4. Comparison of simulations and real-world experiments

In order to evaluate the accuracy, the research team compared the simulation results with the actual experiment on the DC motor test suite (Quanser).

The combined results in Table 4 show that the average error between the two models is less than 5%, which is acceptable within the scope of the study.

Table 4. Comparison of simulation and experimental results

Parameter	Simulation results	Experimental results	Error (%)
Stable speed (rad/s)	142.3	145.0	1.86
Armature current (A)	2.47	2.52	1.98
Response Time(s)	0.36	0.38	5.26

The small error proves that the simulation model is highly reliable and can be a substitute for physical experiments during the initial training phase [9], [41].

4.5. Assessment of student and faculty satisfaction

A qualitative survey through a questionnaire with a 5-level Likert scale showed that 92.5% of students and 87.3% of faculty members appreciated the intuitiveness and applicability of the model.

The responses mainly focused on the advantages:

1. Easy to observe and calibrate control parameters.
2. It is possible to simulate multiple error scenarios or load changes.
3. Increase initiative and creativity in the learning process.

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ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

This confirms that MATLAB/Simulink is an effective tool in training future engineers, helping to shorten the gap between theory and practice [5], [33], [46].

.6. General Discussion

The research results show that the application of MATLAB/Simulink in teaching electric motor control brings three outstanding values:

1. Flexibility: Allows instructors to design lessons at levels from basic to advanced without the need for complex hardware.

2. Economy: Significantly reduce the cost of investment in laboratory equipment in the early stages of technical training institutions.

3. Practicality: The simulation model helps learners become familiar with the process of controlling, measuring, and optimizing the system before actual implementation.

These results are in line with the current trend of digital transformation in technical education [11], [19], [50]. In addition, the simulation method can be extended to other research objects such as BLDC motors, PMSM, or electric powertrains in electric cars in the future.

5. CONCLUSION

The study has developed and implemented a simulation model of an electric motor control system using MATLAB/Simulink software, and at the same time evaluated the pedagogical effectiveness of applying this model in teaching at technical training institutions. The results achieved can be summarized as follows:

1. Technically, the DC motor simulation model is set up with authentic electro-mechanical parameters, which allow for an accurate representation of the relationship between current, speed, and torque during operation. The simulation results showed that the average error compared to the experiment was only about 2–5%, proving the high reliability and applicability of the model in a technical training environment. In addition, the integration of PID, inversion, and variable load blocks makes it possible for learners to deeply analyze kinetic phenomena and the influence of control parameters on system response – something that traditional learning methods are difficult to do.

2. Pedagogically, the application of MATLAB/Simulink in teaching helps students gain a deeper understanding of the principle of feedback control, the law of signal variation, and the mechanism of interaction between the electrical and mechanical parts of the motor. The survey showed that students' level of comprehension, simulation ability, and interest in learning increased by an average of 30–40% compared to traditional teaching methods. Instructors also noted the ability to customize lectures, control the learning process and implement virtual experiments faster, and significantly reduce the cost of operating a physics laboratory.

3. In terms of practical application, the MATLAB/Simulink simulation model can be flexibly deployed at many levels:

1. Basic level: DC motor control PID simulation.

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ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

2. Advanced level: PMSM or DTC vector control simulation.

3. Extended level: combination of simulation and hardware (Hardware-in-the-Loop). This model can be integrated into modules such as *Automatic Control*, *Electric Drive*, *Power Electronics* or *Electric Car Drive System*, contributing to the modernization of the training program.

Thus, the study has proven that MATLAB/Simulink is an effective, flexible, economical teaching tool and in line with the current trend of digital transformation in technical education. The application of this tool not only helps to improve the quality of teaching but also creates a foundation for students to develop skills in research, design and control systems in the Industry 4.0 environment.

The application of MATLAB/Simulink in teaching simulation and control of electric motors is not only an inevitable trend of modern technical education, but also a practical, economical and effective solution in training conditions in Vietnam. This simulation model contributes to narrowing the gap between theory and practice, improve the quality of training of the new generation of engineers, and promote digital transformation in technical education, in line with the development orientation of the Industrial Revolution 4.0 and global STEM education.

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Received: August 12 2025

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ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

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Received: August 12 2025