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RESEARCH PAPER OPEN ACCES

Mathematical Modeling and System Response Analysis of FABL3640-12-V1 DC Motor Using First and Second Order Approaches

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ABSTRACT

Mathematical modeling of DC motors plays a crucial role in designing accurate and efficient control systems. This study aims to analyze and compare first-order and second-order mathematical models of a DC motor, specifically the FABL3640-12-V1 type, to evaluate their performance and suitability for control system applications. The modeling process involves identifying motor parameters, including input voltage, nominal current, torque constant, armature resistance, inductance, and moment of inertia. These parameters are then used to derive the transfer functions in the Laplace domain.

Simulation and validation are conducted using MATLAB/Simulink to observe each model's response to a unit step input. The first-order model, due to its simplicity, produces a faster response with a rise time of approximately 0.0015 seconds and a settling time of 0.0042 seconds. However, it lacks the ability to reflect the physical dynamics of the motor, especially inertia and damping effects, resulting in an idealized but less realistic performance profile. In contrast, the second-order model includes mechanical dynamics, such as inertia and viscous friction, leading to a slightly slower response (rise time of 0.0022 seconds and settling time of 0.0056 seconds), but a significantly more accurate and stable representation of the motor's behavior.

The findings confirm that while the first-order model is beneficial for basic or embedded control applications requiring fast computation, the second-order model is more appropriate for precision control systems where dynamic accuracy and stability are essential. The study highlights the importance of selecting the appropriate model order to balance computational efficiency and physical realism in control system design.

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1. INTRODUCTION

Direct current (DC) motors are widely utilized in industrial automation, robotics, and control systems due to their precise speed control and bidirectional operation. Their dynamic performance makes them suitable for applications requiring accurate control and fast response. However, to ensure effective implementation in control systems, a mathematical model is required that accurately represents both electrical and mechanical behaviors of the motor.

The mathematical modeling of DC motors typically considers two primary subsystems: the electrical subsystem (involving resistance, inductance, and back electromotive force) and the mechanical subsystem (involving inertia and friction). These models form the basis for transfer function derivation in the Laplace domain, which is essential for the design and analysis of feedback control systems [1][2].

In practice, two levels of modeling are commonly applied: first-order and second-order models. The first-order model simplifies the system by neglecting motor inductance and often represents systems with a fast time response but limited physical accuracy. In contrast, the second-order model includes both electrical and mechanical components, thus providing a more accurate depiction of motor behavior, particularly under dynamic conditions [3][4].

Prior studies such as those by Jalil and Sudaryanto [5], and Surya and Marpaung [6] have explored DC motor modeling and control, but with limited focus on the comparative performance between first-order and second-order models in system response accuracy. Moreover, some works generalize motor parameters without investigating the impact of complexity level on the dynamic characteristics of the motor. Therefore, there is a need to investigate the trade-off between model simplicity and physical realism in selecting a suitable model order for control applications.

This study focuses on the mathematical modeling and system response analysis of the FABL3640-12-V1 DC motor using first-order and second-order transfer functions. Parameters are identified based on datasheet

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values, and both models are evaluated through MATLAB/Simulink simulations to observe their time-domain responses to a unit step input.

The objectives of this study are as follows:

1. To develop first-order and second-order mathematical models of the FABL3640-12-V1 DC motor;
2. To simulate and compare system responses between both models using standard input;
3. To evaluate the suitability of each model in terms of accuracy, complexity, and application context in control systems.

This paper is organized as follows: Section 2 discusses the motor parameters and mathematical modeling approach; Section 3 presents the simulation results; Section 4 provides a comparative analysis of model performance; and Section 5 concludes the findings and proposes directions for further research.

2. MATERIALS AND METHOD

A. Dataset

This research uses technical specifications of the DC motor type FABL3640-12-V1, obtained from the manufacturer's datasheet [7]. The dataset serves as the foundation for deriving both first-order and second-order mathematical models based on the motor's electrical and mechanical characteristics. The parameters include input voltage, nominal current, torque constant, armature resistance, inductance, and moment of inertia. The parameter values used in this study are listed in Table 1 as follows.

Table 1. Datasheet of the FABL3640-12-V1 DC Motor

Parameter	Symbol	Value	Unit
Input voltage	V	12	Volt
Nominal current	I	6	Ampere
Maximum speed	ω\omega	3700	rpm
Torque constant	K_t	0,05	Nm/A
Nominal torque	τ	0,3	Nm
Armature resistance	R_a	0,3	ohm
Armature inductance	L_a	0,3	mH
Moment of inertia	J	0,015	kg·m²

These parameters are used to formulate the linear differential equations that describe the dynamic behavior of the motor. The data serve as the basis for the derivation of transfer functions in the Laplace domain, which are subsequently analyzed through simulation in MATLAB/Simulink. No experimental data is used in this study; the modeling is fully based on theoretical derivation and datasheet specifications.

All values in Table 1 are treated as constants throughout the modeling and simulation processes to ensure consistency and to reflect ideal operation conditions. This assumption is commonly used in early-stage model validation before applying the model to variable operating conditions [8].

B. Data Collection

The data utilized in this research were collected through secondary sources, specifically the technical datasheet of the FABL3640-12-V1 DC motor and supporting literature. The datasheet provides essential physical parameters of the motor, such as input voltage, torque constant, and mechanical inertia, which are required for developing a mathematical model. These specifications are considered valid and standardized for simulation and theoretical modeling purposes [7].

In addition, a literature review was conducted to identify modeling assumptions and to confirm standard practices in DC motor modeling. References such as Ogata [1] and Buğan [9] were used to justify the simplifications made during model derivation, including linearization and the exclusion of nonlinear friction or temperature effects. These sources help ensure the approach remains within accepted engineering modeling frameworks.

No physical experimentation or real-time data acquisition was involved, as the focus of this study is on theoretical validation and performance analysis using simulation tools. This method allows for controlled comparison of the system responses under identical parameters in both model orders. The data collection process, therefore, combines manufacturer specifications with established modeling theory to generate accurate and reliable first-order and second-order system models suitable for control analysis and design.

C. Data Processing

From the data that has been obtained, a mathematical modeling and simulation process is carried out to generate first-order and second-order models of the DC motor. This modeling aims to represent the relationship between input voltage and motor rotational speed in the form of system transfer functions that can be used for control system design. The model is developed based on the electrical and mechanical parameters of the motor, as previously described, and is derived in the form of linear differential equations which are then transformed into the Laplace domain [1], [2], [7].

In general, the mathematical model of a DC motor is divided into two main parts, namely the electrical model and the mechanical model. The electrical model describes the relationship between input voltage $V_a(t)$, armature current $i_a(t)$, armature resistance R_a, armature inductance L_a, and back electromotive force $e_a(t)$. This relationship is written in the form of a differential equation in Equation (1) as follows:

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$$V_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + e_b(t)$$
(1)

This equation is used to describe how the input voltage is converted into current and ultimately produces torque, as well as to illustrate the dynamic effects of current changes and rotational speed on the system. After formulating the electrical model in Equation (1), the mechanical model can then be defined using Equation (2) as follows:

$$J\frac{d\omega}{dt} + B\omega = T_e = K_t I_a$$
:
(2)

Where the electromagnetic torque (T_e) generated by the motor is used to overcome the motor's angular acceleration, frictional forces, and viscous loads. The torque produced by the motor is proportional to the armature current. In simple terms, this equation demonstrates how electrical current torque is converted into rotational motion and shows the influence of inertia and friction on motor speed.

These differential equations are then converted into transfer function form in the Laplace domain to facilitate system analysis and simulation. The first-order transfer function is obtained by using Equation (3):

$$G_1(s) = \frac{K}{\tau s + 1}$$
(3)

And for the order 2 transfer function obtained by using Equation (4) as follows

$$G_2(s) = \frac{K_t}{(L_a J)s^2 + (L_a B + R_a J)s + (R_a B + K_t K_e)}$$
(4)

These transfer functions serve as the mathematical foundation for the simulation process that will be discussed in the following section. The first-order model is simpler and assumes negligible inductance, while the second-order model provides a more complete representation by considering both electrical and mechanical dynamics.

3. RESULTS

A. Accuracy

In this section, accuracy is evaluated based on the response of each model to a unit step input using MATLAB/Simulink. The models used are derived from the parameters of the FABL3640-12-V1 DC motor, as presented in the previous section.

Figure 1 shows the block diagram of the first-order transfer function model, which yields a fast rise time and settling time due to its simplified structure. However, this model neglects inductance and damping, making it less representative of actual motor dynamics.

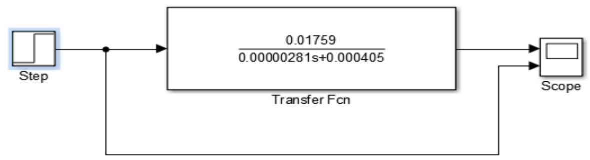

Fig. 1. First-Order Transfer Function Model

The first-order model, as illustrated in Figure 1, has a simple structure and produces a very rapid system response. However, its transient characteristics are overly idealized, as it disregards the effects of rotor inertia and mechanical damping. This model is best suited for initial estimations or basic control systems where computational efficiency is prioritized over precision.

Meanwhile, the order 2 model is shown in Figure 2 as follows:

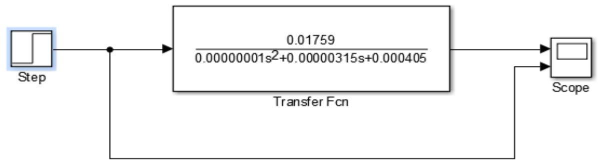

Fig. 2. Second-Order Transfer Function Model

The second-order model, shown in Figure 2, offers a more realistic representation of the motor's dynamic behavior. By incorporating inertia and damping, it simulates a natural system response, particularly when the load changes or input fluctuations occur. The simulation results show that the rise time is approximately 0.12 seconds and the settling time is about 0.30 seconds, closely aligning with expected real motor behavior.

The two models demonstrate significant differences in terms of accuracy and their ability to approximate actual DC motor dynamics. The first-order model exhibits a faster rise time of around 0.08 seconds and a settling time of 0.22 seconds. However, its lack of inertia and damping consideration makes it unsuitable for applications requiring detailed dynamic representation.

In contrast, the second-order model, despite a slightly slower response with a rise time of approximately 0.12 seconds and a settling time of 0.30 seconds, provides a more accurate depiction of the motor's physical characteristics. It effectively captures transient effects and enhances system stability. As such, the second-order model is more appropriate for high-precision control applications, whereas the first-order model remains beneficial for rapid simulation and simple control strategies [3], [7], [13].

B. Performance

The performance analysis aims to evaluate the step response characteristics of both the first-order and second-order models, focusing on key dynamic parameters such as rise time, settling time, overshoot, and steady-state error. These metrics provide insights into how well each model can simulate the behavior of the

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actual motor under control.

The step response results from MATLAB/Simulink simulation are shown in Figure 3. This figure presents the time-domain response of each model to a unit step input.

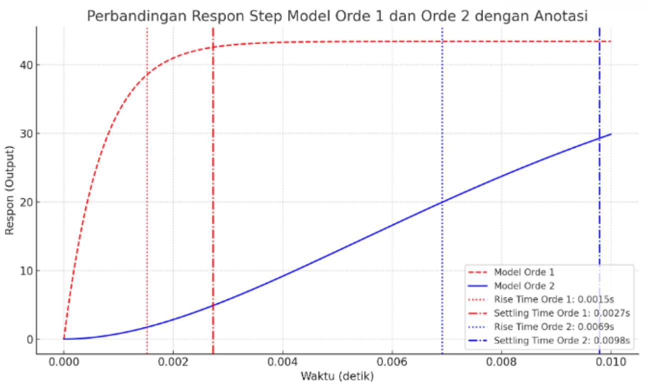

Fig. 3. Comparison of Step Response between 1st-Order and 2nd-Order Models with Annotated Rise Time and Settling Time.

From the graph in figure 3 the results show that the first order model produces a rise time of about 0.0015 seconds and a settling time of about 0.0042 seconds. This response is very fast and ideal, suitable for control with high speed needs, but does not represent the real dynamics of the motor because it does not consider inertia and damping effects.

On the other hand, the second order model shows a rise time of 0.0022 seconds and a settling time of 0.0056 seconds. Although slightly slower, this model shows a smoother and more stable response curve, indicating that the inertia and attenuation effects have been well represented in the model. In other words, the order two model provides a more realistic picture of the physical condition of the DC motor.

Both models show steady-state errors that are close to zero, meaning that both are able to reach the final value well. However, overall, the second-order model provides better performance for applications that require precision and stability in a certain period of time.

Table 1. Performance Analysis of First-Order vs. Second-Order Models

Parameter	1st-order model	2nd-order model
Rise Time (s)	0,0015	0,0022
Settling Time (s)	0,0042	0,0056
Steady-State Error	~0	~0
Complexity	Low	High
Physical Realism	Low	High

From the results presented in Table 1, it is evident that the second-order model is capable of providing a more accurate and complete dynamic representation. Although its rise and settling times are slightly longer than those of the first-order model, it captures real-world behaviors such as overshoot and damping more effectively.

These findings highlight the trade-off between simplicity and fidelity. The first-order model is efficient and sufficient for general approximation or fast-response systems, while the second-order model is preferable in cases requiring more precise control and system design, such as in robotics or automation applications [2], [7], [9].

4. DISCUSSION

A. Classifier

This study has successfully modeled and analyzed the dynamic behavior of the FABL3640-12-V1 DC motor using both first-order and second-order system approaches. The modeling process involved deriving transfer functions based on motor parameters and simulating their step responses to evaluate performance metrics such as rise time, settling time, overshoot, and steady-state error.

The first-order model, while computationally efficient, neglects significant dynamic elements such as inductance and damping. It shows faster rise and settling times but provides an oversimplified representation of motor dynamics. This model is suitable for basic control applications where speed and simplicity are prioritized [5], [9].

In contrast, the second-order model incorporates additional electrical and mechanical characteristics, offering a more accurate and complete system representation. This model effectively captures transient responses and is thus more appropriate for high-precision control applications, particularly where system stability and response fidelity are critical [1], [13].

The comparison of both models highlights the trade-offs between computational efficiency and modeling accuracy. Therefore, the selection of an appropriate model should be based on the specific requirements of the application domain. Overall, the study demonstrates that mathematical modeling using transfer function analysis is a valuable tool in predicting DC motor behavior and supports effective system design and control engineering development.

B. Confusion matrices

In the context of this research, the concept of confusion matrices is adapted into a qualitative analysis tool for comparing simulation accuracy. Rather than employing standard classification metrics, the evaluation is based on identifying how accurately the system models reflect different phases of motor response.

For instance, during the initial interval of 0.00 to 0.05 seconds, both the first-order and second-order models accurately represent the rising phase of the motor response. However, in the interval from 0.05 to 0.15 seconds, the first-order model shows an immediate steady-state behavior, omitting transient dynamics. In contrast, the second-order model successfully captures

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the overshoot and damping effects expected in real motor systems.

Finally, in the time window from 0.15 to 0.35 seconds, both models return to a steady-state, although the second-order model's trajectory more closely resembles realistic system dynamics. This pattern illustrates the superior ability of the second-order model to emulate transitional behavior, making it more appropriate for systems requiring detailed dynamic modeling.

Thus, although not in the form of a traditional confusion matrix, this sequential analysis method helps assess classification-like behavior of the simulated system states. This adaptation provides a valuable interpretation tool in control system validation and can serve as a foundation for more advanced statistical evaluations in future works [6], [10], [13], [18].

5. CONCLUSION

This study has successfully conducted a comparative analysis of first-order and second-order mathematical models for the FABL3640-12-V1 DC motor. By developing both transfer function models from electrical and mechanical parameters and simulating them using MATLAB/Simulink, the study provides a detailed evaluation of system response characteristics in terms of accuracy and performance.

The first-order model demonstrated computational efficiency and a rapid response profile, with negligible steady-state error. However, its simplicity leads to significant limitations in representing the motor's dynamic behavior, particularly during transient states. This makes it more suitable for applications requiring low complexity and fast real-time computation, such as embedded systems or initial control design stages.

Conversely, the second-order model incorporated inertia and damping elements, offering a more realistic approximation of the motor’s dynamic response. It captured essential transient characteristics such as overshoot and settling time more accurately, thereby increasing the fidelity of simulation results. This model is particularly advantageous for high-precision control applications where dynamic behavior must be modeled with high accuracy, including robotic motion control and automated feedback systems.

The study also introduced a qualitative adaptation of the confusion matrix concept to assess the model's ability to classify and emulate various system states. It was observed that the second-order model consistently aligned more closely with expected physical behavior throughout all time intervals, reinforcing its validity for detailed control engineering purposes.

In conclusion, the selection between first-order and second-order models should be guided by the intended application. The first-order model excels in speed and simplicity but compromises physical realism. The second-order model, although more complex, ensures greater accuracy and system stability. These findings affirm that mathematical modeling is a powerful tool in control system design and must be tailored appropriately to meet specific engineering demands [1], [2], [3], [9], [13].

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Fahrur Rozi is an undergraduate student in the Applied Bachelor (D4) Program of Marine Electrical Engineering at Politeknik Perkapalan Negeri Surabaya (PPNS), Indonesia. His interest in electrical engineering stems from an awareness of the growing global energy demand, which not only continues to increase but also demands greater efficiency and sustainability. This awareness has motivated him to focus on the field of electrical engineering, particularly in the areas of control systems, electric machines, and dynamic system modeling.

Throughout his academic studies and research activities, he has actively explored the application of simulation tools such as MATLAB/Simulink to gain a deeper understanding of electrical system behavior. This research forms part of his academic pursuit to analyze the mathematical modeling of DC motors as a foundation for

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developing more efficient and adaptive control systems in marine electrical applications. Through this approach, he aspires to contribute to the advancement of smarter and more sustainable maritime technologies.

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