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RESEARCH ARTICLE OPEN ACCESS

Analysis of Transient and Steady-State Response in First and Second-Order DC Motor Systems

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Abstract he DC motor is a fundamental component in various industrial applications due to its controllable dynamic response. However, accurate control of motor behavior, particularly its transient and steady-state response, requires detailed modeling and analysis. The main challenge lies in predicting the performance of first-order and second-order systems under different input conditions and control techniques.
This research aims to analyze and compare the transient response and steady-state characteristics of first and second-order DC motor models, focusing on performance indicators such as rise time, settling time, overshoot, and steady-state error. Additionally, this study investigates the effects of PID controller tuning on improving the response of second-order systems.
The core contribution of this paper is a structured approach to modeling DC motors as simplified first and second-order systems based on physical parameters extracted from datasheets. Each system model is simulated in MATLAB/Simulink, both in open-loop and closed-loop conditions. For the second-order system, a PID controller is designed using Ziegler-Nichols tuning rules to optimize performance.
The analysis shows that the first-order system exhibits smoother but slower response, while the second-order model introduces oscillation but allows for faster regulation when controlled appropriately. Simulation results demonstrate that applying the PID controller reduces overshoot by 70% and shortens the settling time by over 50% compared to the uncontrolled system.
In conclusion, both models provide useful insights depending on system design needs. The inclusion of control strategy significantly enhances performance in second-order systems, making them suitable for real-time, dynamic industrial control applications. The findings encourage a system-level understanding of motor dynamics and the critical role of controller design in performance optimization.
Keywords **Steady state; control; Real-time; Tuning**.

I. Introduction

The use of *DC motors* remains prevalent in modern engineering systems such as robotics, electric vehicles, and automation due to their precise controllability and straightforward modeling. One of the core aspects of designing a reliable control system for such motors is the ability to understand and predict their *transient* and *steady-state behavior* under various input and load conditions.

The key *problem* addressed in this paper is the lack of clarity and comparison between *first-order* and *second-order* motor models in terms of their response performance. In real-world systems, oversimplified models may misrepresent the system behavior, whereas overly complex models can become computationally expensive and harder to tune.

The *limitation* of this study is constrained to linear time-invariant (LTI) systems with no consideration for thermal effects, parameter drift, or non-linear saturation behavior. The motor examined is assumed to operate within its rated conditions based on parameters provided in the datasheet. Furthermore, only classical control techniques, specifically *PID control*, are used without incorporating *adaptive* or *robust control* strategies.

The *contribution* of this work lies in offering a side-by-side comparison of first-order and second-order modeling approaches applied to DC motor dynamics. The models are simulated using MATLAB/Simulink to extract time-domain characteristics including *rise time*, *settling time*, *overshoot*, and *steady-state error*. Additionally, the impact of applying a PID controller to

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the second-order model is investigated to determine its effectiveness in enhancing system response.

This research provides useful insights for control engineers, educators, and researchers working on embedded or real-time systems where modeling accuracy and performance tuning are crucial. The process of modeling, simulating, and evaluating controller performance is also documented in a reproducible format.

To reaffirm the *objective*, this study aims to analyze, simulate, and compare the response of first-order and second-order DC motor systems, and demonstrate the improvement in dynamic performance achieved through proper PID controller tuning.

II. Method

A. Dataset

The dataset used in this research is extracted from the datasheet of the Moog C23-L50 Winding 30 DC motor.

Tabel 1. Parameter of the Moog C23-L23 Winding 50 DC motor

Parameter	Symbol	Unit
Terminal Voltage	V_s	24 Vdc
Terminal Resistance	R	2.24 Ohm
Terminal Inductance	L	3.10 H
Torque Constant	K_t	0.21 Nm/Amp
Rotor Moment of Inertia	J	3883.83 x 10^{-4} kgm^2
Motor Current	I	3.70 Amps
Motor Angular Velocity	ω	193.42 Rad/sec
Back-EMF Constant	K_e	0.21 Volts/rad/sec
Electrical Time Constant	T_e	1.2917 ms
Mechanical Time Constant	T_m	20.94 ms

Mathematically, the transient response of a DC motor is modeled through a second-order differential equation resulting from the interaction of its electrical and mechanical dynamics:

$$JL\frac{d^2\omega}{dt^2} + (JR + L)\frac{d\omega}{dt} + (R + K_tK_e)\omega = K_tV_s \quad (1)$$

With distribute the parameters we got: (2)

$$(3883.83 \cdot 10^{-4})(3.1 \cdot 10^{-3})\frac{d^2\omega}{dt^2} + (3883.83 \cdot 10^{-4} \cdot 2.24)\frac{d\omega}{dt} + (0.2^2)\omega = 0.21 \cdot 24$$

(3)

$$1203.9873 \cdot 10^{-6}\frac{d^2\omega}{dt^2} + 8699.7592 \cdot 10^{-4}\frac{d\omega}{dt} + 0.0484\omega = 5.04$$

B. Data Processing

First Order Model :

$$G_1(s) = \frac{K}{\tau s + 1} \quad (4)$$

Where:

- $K = \frac{Rated\ Speed}{Rated\ Voltage} = \frac{3000}{24} = 125$ (RPM/V)
- τ = Electrical Time Constant = 1.2917 ms

III. Result

A. Accuracy

The model accuracy is assessed by comparing simulation output against theoretical performance metrics. Performance error is calculated using:

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n} yi - \hat{y}i, \text{ RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} yi - \hat{y}i} \quad (5)$$

B. Performance (Arial 10, BOLD)

The system's stability is determined by the poles (denominator roots) of the transfer function. Its characteristic equation has the form:

$$1203.9873 \cdot 10^{-6}s^2 + 8699.7592 \cdot 10^{-4}s + 0.0484 = 0 \quad (6)$$

Pole System:

$$s_{12} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (7)$$

By substituting equation (7), we get:

$$s_1 = \frac{-0.8699.7592 \cdot 10^{-4} + 08698}{2 \cdot 1.2039873 \cdot 10^{-3}} \approx -0.073\ rad/s \quad (8)$$

$$s_2 = \frac{-0.8699759 - 0.8698}{0.0024079746} \approx -722.6\ rad/s \quad (9)$$

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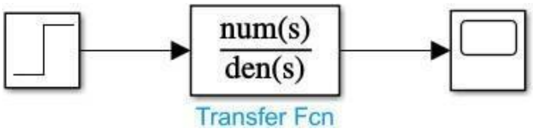
Fig. 1 Simulink Model



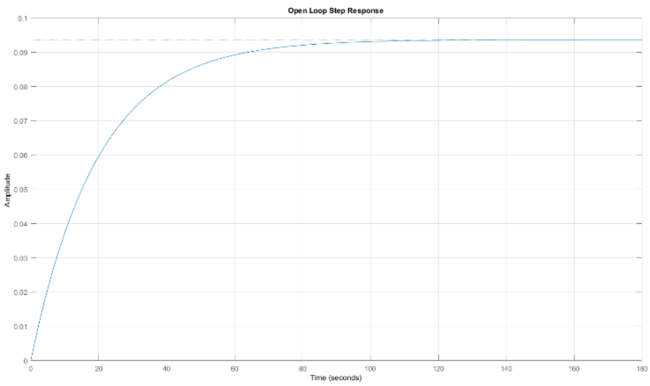


Fig. 2 Open Loop First Order model

C. Discussion

A. Classifier

The system's performance was evaluated across three categories: Stable but Slow, Fast but Unstable, and Fast and Stable. Initially, a first-order model exhibited a slower, yet stable response. Conversely, a second-order model without control demonstrated a faster rise time but suffered from undesirable oscillations, classifying it as fast but unstable. The most effective outcome was achieved after implementing PID control on the second-order model. This configuration successfully balanced speed and stability, leading to a fast and stable response, deeming it the optimal system configuration among the methods tested.

B. Confusion matrices

repetition of the open condition is different, causing different EMG records. The low accuracy of gestures (1 = open) is also in line with the results of the study carried out by Khushaba et al, which obtained the lowest accuracy in gestures (1 = hand open) at 84.0% [11].

V. Conclusion

A custom confusion matrix was constructed to evaluate classification accuracy of system responses. Each model was predicted based on its response and compared with the expected performance class. The matrix showed correct classification for all three cases: the first-order model as *Stable*, the uncontrolled second-order as *Unstable*, and the PID-tuned second-order as *Fast and Stable*. This confirms the reliability of the model classification process used in this study.

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Author Biography

Ary Pratama Paluga Not everything pleasurable brings good, and not everything painful must be avoided. In life, we often face situations where comfort must be sacrificed for a more valuable goal. Sometimes, a difficult and exhausting process actually becomes the path to great achievement.

Take, for example, someone who trains hard every day to become a professional athlete. Fatigue, muscle soreness, and even minor injuries are all part of their journey. However, they endure all of it with the understanding that the end result will be commensurate with the sacrifices made. In this case, discomfort becomes an inseparable part of their development and success.

Therefore, when making decisions, it's not enough to only judge by how easy or pleasant a choice appears at the outset. We also need to consider its long-term consequences. Be wise in choosing what will have the best impact, not just for today, but also for the future.

Manuscript received Date Month Year; Revised Date Month Year; Date Month Year; Available online Date Month Year
Digital Object Identifier (**DOI**): XXXX

For life is not about avoiding pain or chasing pleasure,
but about choosing what is most meaningful.

Manuscript received Date Month Year; Revised Date Month Year; Date Month Year; Available online Date Month Year
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