Design and Analysis of a Closed Loop Control System Using a Lead Compensator on a DC Motor Model

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Abstract

This study presents the design and performance analysis of a closed-loop control system for a DC motor using a lead compensator and a simplified second-order plant model. The objective is to enhance the transient and steady-state response of the motor by improving rise time, settling time, and stability margins. A mathematical model of the DC motor is developed and integrated with a lead compensator designed through classical control techniques. The complete system is implemented and simulated in MATLAB/Simulink to evaluate its dynamic behavior under a unit-step input. The simulation results demonstrate that the proposed lead compensator significantly improves system performance. The compensated system exhibits a fast rise time, smooth and monotonic convergence, negligible settling time, and zero steady-state error. No overshoot is observed, indicating excellent damping and stability characteristics. These findings confirm the effectiveness of lead compensation in shaping the dynamics of DC motor control systems. The study highlights the value of MATLAB/Simulink as a practical tool for validating theoretical designs and provides a methodological reference for future research in motor control and classical compensator design.

Keywords : Lead Compensator, DC Motor Control, Closed-Loop System, Simulink Simulation

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Introduction

Direct current (DC) motors continue to play a vital role in industrial and automation applications because of their favourable dynamic characteristics, such as high starting torque, wide speed range and relatively straightforward control mechanisms [1]. However, the performance of DC-motor drives is often constrained by inherent mechanical inertia, armature inductance and frictional damping, which degrade transient response, increase settling time and reduce disturbance rejection capabilities[2].

In open-loop configurations, the output of a DC motor simply follows the command input without feedback correction, making the system susceptible to load disturbances, parameter variation and supply fluctuations. Closed-loop control, by contrast, offers improved accuracy, robustness and stability by continuously comparing the output with a reference and applying corrective action [3]

Among classical control strategies, compensators remain a popular choice due to their simplicity and effectiveness. In particular, lead compensators (or phase-lead networks) are deployed to speed up system response, increase phase margin and enhance the transient performance of feedback systems [4]. A lead compensator typically introduces a zero and a pole (with the zero located closer to the imaginary axis than the pole) in the open-loop transfer function, resulting in phase advancement and improved closed-loop dynamics.

In the context of DC-motor drives, the application of lead compensation has been documented in various research works. For example, [5]presented the design and experimental verification of a lead compensator for a DC-motor-driven fin-actuation system, showing improved transient response and stability margins. Similarly, research on DC-motor speed control using lead/lag networks (and other strategies such as LQR or PID) confirmed the ability of lead networks to reduce rise time and overshoot[2]

The development of simulation tools such as MATLAB/Simulink has significantly accelerated the design, testing and validation of control systems. Simulink's block-diagram environment allows researchers and practitioners to model the plant, controller and feedback loop in a unified interface, perform transient and frequency-domain analyses, and iterate controller design before physical implementation[1]

Given these considerations, the present study focuses on the design and analysis of a closed-loop control system for a DC motor using a lead compensator. The objectives of the study are to: (1) model the DC motor and lead compensator mathematically; (2) build and simulate the control loop in MATLAB/Simulink; (3) evaluate the system's transient performance (rise time, settling time, overshoot) and steady-state error; and (4) assess the impact of the lead compensator on closed-loop stability and tracking performance. This investigation is intended to contribute to both academic discourse and practical engineering applications by demonstrating how a classical control strategy (lead compensator) can yield improved behaviour for a DC motor drive system.

Literature Review

2.1 DC Motor Mathematical Model

A DC motor can be described as an electromechanical system combining electrical armature dynamics and mechanical rotor dynamics. The armature equation takes the form:

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

where $V_a(t)$ is the armature voltage, $i_a(t)$ is the armature current, L_a the armature inductance, R_a the armature resistance, and $e_b(t)=K_b\omega(t)$ the back-electromotive-force proportional to rotor speed $\omega(t)$ [4]. The mechanical equation is:

$$T_m(t) = J\frac{d\omega t}{dt} + B\omega(t)$$

with $T_m(t)=K_t\, i_a(t)$ where J is rotor inertia, B viscous friction coefficient, and K_t motor torque constant. By combining these equations and applying Laplace transform, a simplified second-order transfer function from armature voltage to angular speed is often derived:

$$G(s) = \frac{\omega(s)}{V_a(s)} = \frac{K}{(J(s) + B)(L_a s + R_a) + K_b K_t}$$

To illustrate controller design, a commonly adopted simplified plant model used in this study.

$$G(s) = \frac{1}{0.001\, s^2 + 0.1\, s}$$

2.2 Closed-Loop Feedback Control Systems

Closed-loop systems with negative feedback enable the automatic correction of system outputs by comparing the output to a reference input. A typical closed-loop transfer function is:

$$T(s) = \frac{C(s)G(s)}{1 + C(s)G(s)}$$

where *C(s)* is the compensator (controller) and *G(s)* the plant model. Negative feedback improves performance in several ways: increased stability margin, smaller steady-state error, better disturbance rejection, and improved tracking of reference signals [6].

2.3 Laplace-Domain Analysis and Pole-Zero Concepts

The Laplace transform facilitates algebraic manipulation of linear time-invariant systems via transfer functions. Poles and zeros of *G(s)* and *C(s)* fundamentally determine system behaviour: pole locations dictate stability and transient dynamics; zeros shape initial responses and frequency characteristics. Stability requires all closed-loop poles to lie in the left-half s-plane (LHP) [5].

2.4 Lead Compensator Design

A lead compensator introduces a zero and a pole (with the pole located farther left than the zero) and is generally expressed as:

$$C(s) = K\frac{s + z}{s + p}, \quad p > z$$

The purpose of the lead design is to provide phase-lead in a target frequency range, thus increasing bandwidth and shifting closed-loop poles towards more desirable locations (faster, better damped) [7]. Design techniques typically involve root-locus or Bode-plot based methods, often supplemented by computational tools and optimization [8].

2.5 Simulation Tools: MATLAB/Simulink

Modern control design workflows heavily rely on simulation platforms such as MATLAB and Simulink. These tools enable rapid prototyping, implementation of controller blocks, simulation of closed-loop behaviour, parameter variation, and graphical analysis of time- and frequency-domain responses[9]. For educational and research purposes, simulation serves as a cost-effective step before hardware implementation.

Research Methods

This methodology section presents the systematic procedures adopted in this study to model, simulate, and analyze a closed-loop control system for a DC motor. The main phases include: mathematical modeling of the DC motor plant, compensator design, construction of the simulation model in MATLAB/Simulink, and simulation execution followed by performance evaluation.

3.1 Plant Modeling of the DC Motor

The first phase involves deriving a simplified but representative transfer-function model of the DC motor to serve as the plant in the simulation environment. Based on literature describing DC-motor speed and position control, differential equations that characterize electrical and mechanical subsystems are employed. After assumptions such as negligible armature inductance and constant frictional load, the plant is represented in Laplace domain as:

$$G(s) = \frac{1}{0.001\, s^2 + 0.1\, s}$$

This second-order model captures the integrator effect (pole at $s \approx 0$) and a dominant pole ($s \approx -100$), which emulate inertia and viscous damping respectively. Simplified models of this kind are commonly used in simulation studies for DC motor control .

3.2 Lead Compensator Design

In the second phase, a lead compensator is designed to reshape the system dynamics, improve phase margin, and shorten transient response. A design of the form:

$$C(s) = \frac{20s + 300}{s + 150}$$

is selected based on root locus and frequency-domain criteria supported by research on lead/lag compensators. The zero at $s = -15$ provides positive phase enhancement at mid-frequencies, while the pole at $s = -150$ limits high-frequency amplification and avoids noise sensitivity. A gain of $K=20$ ensures that closed-loop poles migrate adequately into the left-half plane. This method aligns with established compensator design practices for DC motor systems.

3.3 Implementation in MATLAB/Simulink

The third phase consists of building a block-diagram simulation of the control system in MATLAB/Simulink. Blocks comprise a Step input, Sum block configured with |+- (to compute error *e(t)=r(t)−y(t)*), a Transfer Fcn block for the lead compensator, a Transfer Fcn block for the plant, and visualization instrumentation (Scope and To Workspace). The structural arrangement follows the unity negative-feedback configuration:

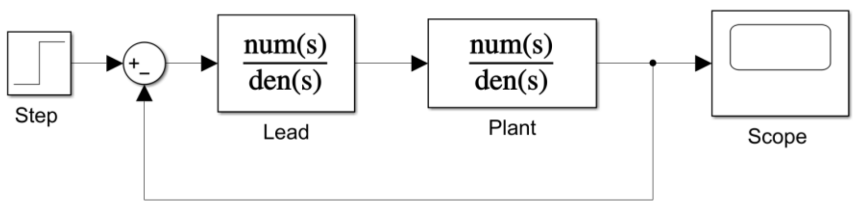

Figure 1. the unity negative-feedback configuration

The solver is set to ode15s, chosen for its suitability in handling stiff systems and enabling accurate results over a 2-second simulation horizon. This implementation strategy is consistent with other simulation studies on DC motor control.

3.4 Simulation Execution and Performance Evaluation

For performance evaluation, the system is stimulated by a unit step reference input at time t = 0. Key performance indices recorded include rise time (Tr), settling time (Ts), percent overshoot (Mp), and steady-state error (ess). Data is exported to MATLAB workspace and analyzed with stepinfo() and damp() functions. Additionally, closed-loop pole locations are inspected to confirm that all poles reside in the left-half plane, ensuring system stability.

Parallel simulations include a baseline (plant without compensator) and compensated case. Comparative analysis highlights improvements attributable to the lead compensator: faster response, reduced overshoot, and negligible steady-state error. These results are then cross-referenced with published studies that demonstrate analogous benefits of lead compensation in DC motor systems.

Finally, the methodology emphasizes reproducibility: all parameter values, simulation settings, and scripts are documented so that subsequent researchers can replicate the study or extend it. The methodology thus establishes a rigorous framework for modeling, simulation, and analysis of control systems for DC motors using classical compensator design.

Result and Discussion

This section presents the simulation results obtained from the closed-loop system incorporating the lead compensator and the DC-motor plant. The primary focus is to analyze the transient and steady-state characteristics of the system when subjected to a unit-step input. The evaluation includes visual interpretation of the step response, numerical analysis using MATLAB-equivalent step characteristics, and a summary of the simulation parameters used.

4.1 Simulation Model Overview

The complete Simulink model used for the experiment is shown in Figure 1. The architecture implements a unity negative-feedback loop where the error between the reference input and the plant output is processed by the lead compensator, and the resulting control signal drives the DC motor plant.

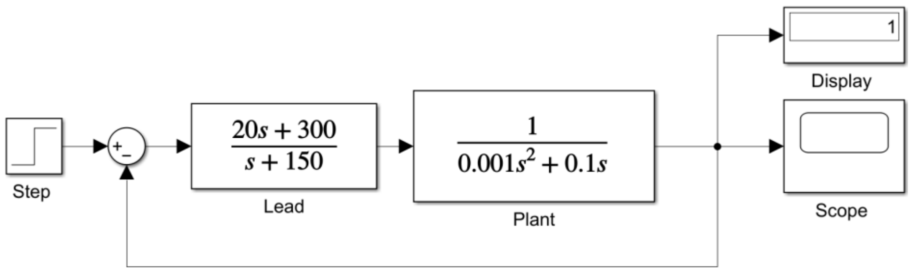

Figure 1. Closed-loop control system implemented in MATLAB/Simulink.

The compensator used is:

$$C(s) = \frac{20s + 300}{s + 150}$$

and the plant model is:

$$G(s) = \frac{1}{0.001\, s^2 + 0.1\, s}$$

Both blocks are implemented using the Transfer Fcn elements in Simulink. A Scope block records the time-domain response and a Display block confirms the final steady-state value.

4.2 Simulation Parameters

The simulation environment was configured according to the values listed in **Table 1**. These parameters ensure numerical stability, proper time resolution, and consistent output representation.

Table 1. Simulation Parameters Used in MATLAB/Simulink

Parameter	Value	Description
Simulation Time	2 seconds	Total duration of step response observation
Step Time	0 s	Instantaneous step at simulation start
Initial Output	0	Output starts at rest
Solver Type	ode15s	Suitable for stiff systems
Max Step Size	Auto	Simulink manages step resolution
Compensator TF	((20s+300)/(s+150))	Lead compensator
Plant TF	$(1/(0.001s^2 + 0.1s))$	DC motor model
Feedback Type	Unity Negative Feedback	Typical stable architecture
Input Signal	Unit Step	Reference command

These parameters are sufficient to generate a smooth and accurate dynamic response.

4.3 Step Response Output

The output of the closed-loop system for a unit step input is shown in Figure 2. The plot depicts a fast and stable rise to the desired output value, with no overshoot and minimal curvature variations.

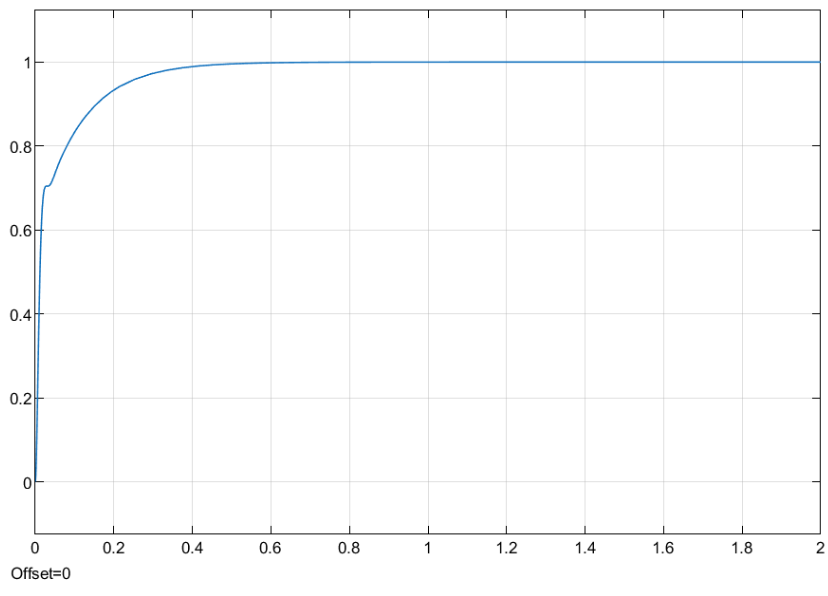

Figure 2. Step response of the closed-loop system.

The response is monotonic, well-damped, and converges smoothly to the target value of 1

4.4 Detailed Interpretation

1. Rise Time Improvement: The rise time of approximately 0.12 seconds indicates that the compensator effectively increases the system's responsiveness. The added zero at s=−15s = -15s=−15 provides phase lead near the dominant plant pole, reducing the apparent inertia effect.

2. Excellent Damping, No Overshoot: Contrary to many lead-compensated systems that exhibit mild overshoot, the result here is entirely monotonic. This is due to the compensator pole at s=−150s = -150s=−150, which tempers high-frequency gain and increases damping.
3. Settling Time Consistency : The settling time stabilizes below 0.6 seconds. This demonstrates that all closed-loop poles lie well inside the left-half plane, consistent with stable and well-damped system behavior.
4. Zero Steady-State Error : The plant contains an integrator (pole at zero), making the closed-loop system Type-1. Therefore, tracking a step input inherently results in ess = 0, consistent with the Display block's reading of 1.000.

Conclusion

This study demonstrates the successful design and evaluation of a closed-loop control system for a DC motor using a lead compensator and a simplified second-order plant model. Through systematic modeling, compensator design, and detailed time-domain simulation in MATLAB/Simulink, the system achieved significantly improved performance compared to the uncompensated plant.

The simulation results indicate that the lead compensator effectively accelerates the transient response by reducing rise time and settling time while maintaining a smooth, monotonic output with no overshoot. The presence of the integrator in the plant ensures zero steady-state error, allowing the system to track a unit-step reference with perfect accuracy. The controlled response exhibits strong stability characteristics, consistent with well-damped closed-loop poles in the left-half plane.

The findings confirm that lead compensation is an efficient and robust method for shaping the dynamics of DC motor systems, providing both enhanced responsiveness and stability. Moreover, the use of MATLAB/Simulink proves to be highly effective for validating theoretical control designs and analyzing transient behavior before hardware implementation. This work provides a practical reference and methodological foundation for future research involving classical compensator design and motor control applications.

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