American Journal of Applied Science and Technology

VOLUME Vol.05 Issue 11 2025
PAGE NO. 133-136
DOI 10.37547/ajast/Volume05Issue11-27

Dual-Loop P/Pi Control Of A Dc Servodrive: Modeling, Analysis

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Received: 29 September 2025; **Accepted:** 21 October 2025; **Published:** 26 November 2025

Abstract: This paper presents a dual-loop P/PI control strategy for a DC servodrive, focusing on the modeling, analysis, and numerical demonstration of system performance. The control structure consists of two cascaded loops: the inner current loop, which ensures fast electromagnetic torque generation, and the outer velocity loop, responsible for dynamic tracking of motor speed. The inner loop is designed using a proportional (P) controller to obtain a fast current response, while the outer loop utilizes a proportional-integral (PI) controller to achieve zero steady-state error in speed control. A mathematical model of the DC motor is developed, including the electrical and mechanical subsystems, and the transfer functions for each control loop are derived. Stability and transient performance of the closed-loop system are evaluated based on classical control theory methods. Finally, a numerical example is provided to demonstrate the tuning approach and illustrate the effectiveness of the dual-loop P/PI control architecture. The results confirm that the cascaded control structure improves dynamic performance and robustness, making it suitable for industrial servodrive applications.

Keywords: DC servodrive, cascaded control, PI current loop, P speed loop, dynamic modeling, tuning, disturbance rejection.

INTRODUCTION:

DC servodrives are widely used in modern automation systems, robotics, and mechatronics due to their simplicity, linear characteristics, and ease of control. In high-performance systems, fast dynamic response and high accuracy are required for both speed and torque control. Classical single-loop controllers cannot simultaneously guarantee rapid torque response and zero steady-state speed error. Therefore, a dual-loop structure is commonly implemented.

In a dual-loop control system, the inner current loop directly regulates the electromagnetic torque, while the outer speed loop ensures that the motor speed accurately follows the reference command. This separation of control tasks allows independent tuning of the two loops. The inner loop handles fast electrical dynamics, is tuned with high bandwidth, while the outer loop focuses on slower mechanical dynamics, and compensates for steady-state errors.

The goal of this study is to model, analyze, and simulate a DC servodrive system using dual-loop P/PI control, demonstrating that the cascaded structure effectively improves both transient and steady-state performance.

Modeling of DC motor

A DC motor is an electromechanical system that converts electrical energy into mechanical rotational motion. For dual-loop control design, an accurate model of the motor is required to characterize the dynamics of the current and speed responses. The DC motor consists of the armature electrical circuit and the mechanical rotor subsystem. The armature circuit includes resistance, inductance, and the back electromotive force (emf), which depends on motor speed. The mechanical system includes inertia and viscous friction. These relationships form the basis for deriving transfer functions and state-space equations used for controller design.

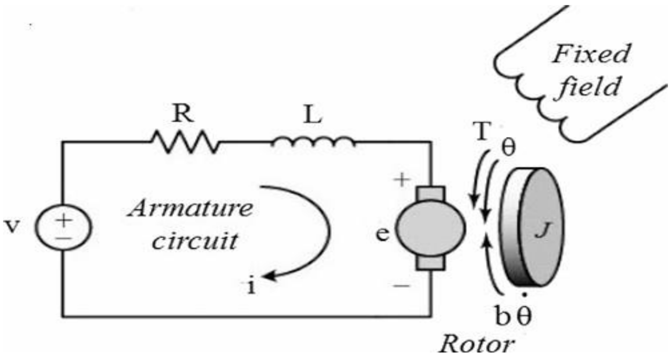

Fig. 1. Schematic diagram of the DC Servo Motor showing the armature circuit, fixed field, and rotor dynamics.

Electrical Subsystem

-The armature circuit obeys Kirchhoff's Voltage Law:

$$V(t) = L\frac{di(t)}{dt} + Ri(t) + K_e w(t) \qquad (1)$$

where:

- V(t)— armature supply voltage [V],
- i(t) — armature current [A],
- L — armature inductance [H],
- Ri — armature resistance [Ω],
- e — back electromotive force (back-EMF) [V].

Electromagnetic torque is proportional to current:

$$T(t)=K_t i(t) \quad (2)$$

Mechanical dynamics are given by:

$$J\frac{dw(t)}{dt} + bw(t) = T(t) \qquad (3)$$

-where **J** is inertia and **b** is viscous friction.

Combining these gives the simplified transfer function from input voltage to angular speed:

$$\frac{w(s)}{V(s)} = \frac{K}{(Ls+R)(Js+b)+K^2} \qquad (4)$$

Combined Electromechanical Model

By substituting $T_m = K_t i_a$ and $e_b = K_e w$ into the above equations, we obtain a coupled system of differential equations describing both electrical and mechanical behaviors:

$$\begin{cases} L_a \frac{di}{dt} + R_a i_a + K_e w = V_a \\ J \frac{dw}{dt} + bw = K_t i_a - T_L \end{cases} \quad (5)$$

This system demonstrates the strong coupling between current and angular speed — the armature current controls the torque, and the torque determines acceleration.

Taking the Laplace transform and assuming zero initial conditions gives:

$$(L_a s + R_a) I_a(s) + K_e \cap (s) = V_a(s)$$
$$(Js + b) \cap (s) = K_t I_a(s) - T_L(s) \quad (6)$$

From these, the transfer function between voltage and angular velocity can be derived as:

$$\frac{\cap(s)}{V_a(s)} = \frac{K_t}{(L_a s + R_a)(Js + b) + K_t K_e} \quad (7)$$

This expression shows that the motor behaves as a second-order system with two dominant time constants — one electrical and one mechanical.

Dual-loop control structure

The dual-loop P/PI control structure consists of two cascaded feedback loops. The inner loop regulates the armature current. The outer loop regulates the motor speed. The fundamental idea is that torque is generated faster than mechanical speed changes. Therefore, the current loop is tuned to be significantly faster than the speed loop. In practice, the current loop bandwidth is typically selected 5–10 times higher than the bandwidth of the speed loop. This separation prevents interaction between the loops and makes tuning easier.

The inner current loop commonly uses proportional control, because the electrical dynamics have low inertia and can react quickly. The output of this loop is the voltage applied to the motor. The outer loop uses a proportional–integral controller. The integral action is added to ensure zero steady-state error in speed control. Thus, the outer loop generates the reference current for the inner loop. This hierarchical structure allows fast torque response and accurate speed tracking simultaneously.

MATLAB-Based Numerical Modeling

To validate the analytical transfer function and demonstrate the dynamic properties of the DC motor model, a numerical simulation was performed in MATLAB. The simulation uses the same motor parameters that were introduced earlier in the modeling section, including armature resistance R_a=2Ω, inductance L_a==0.02 H, inertia J=0.01 kg·m^2, friction coefficient b=0.001 N·m·s/rad, and electromagnetic constants K(t)=K(e)= 1. These parameters were directly substituted into the analytical transfer function:

$$G_{wV}(s) = \frac{K_t}{(L_a s + R_a)(J_s + b) + K_t K_e} \quad (8)$$

which describes the relationship between input voltage and motor angular velocity.

A MATLAB script was developed to compute the step response of this transfer function when the input voltage experiences a step of 10 V. The script calculates the system poles, steady-state gain, time constants, and generates a high-quality plot of ω(t. The purpose of this simulation is to compare the theoretical model with numerical behavior and confirm correctness of the derived equations.

The resulting graph (Fig.2) shows a typical second-order dynamic response:

- a very fast initial rise dominated by the electrical time constant τe=L_a/R_a=0.01 s,
- a slower exponential convergence to the steady-state value governed by the mechanical time constant τm≈0.02 s,
- a small overshoot caused by the interaction of the electrical and mechanical subsystems.

Thus, the MATLAB simulation confirms that the analytical model is accurate. The generated plot clearly visualizes both transient and steady-state dynamics of the DC motor, and this graphical confirmation reinforces the validity of the modeling assumptions used in the subsequent control design.

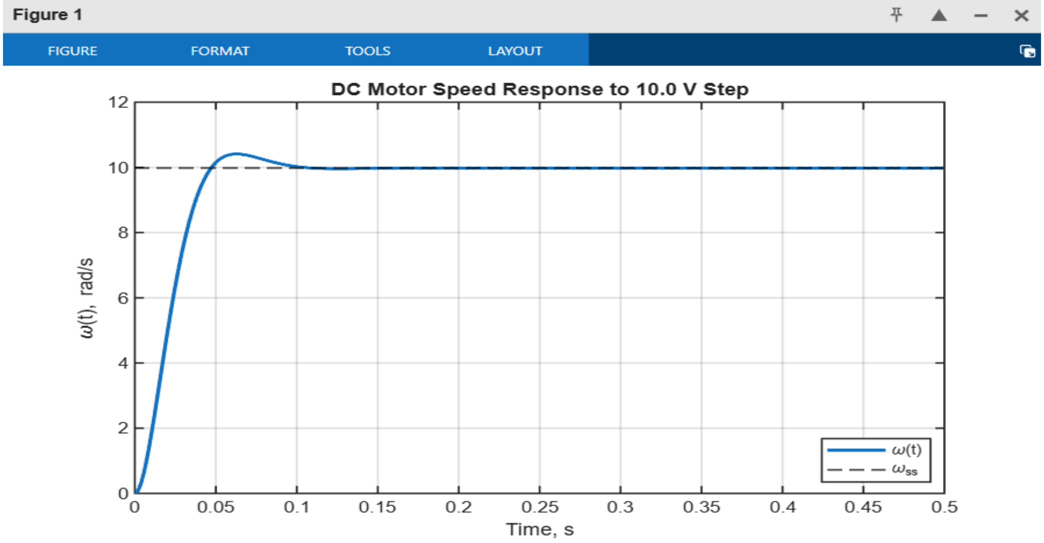

Fig.2. Step response of the DC motor model showing the angular velocity *ω(t)* approaching the steady-state value after a 10 V input.

DISCUSSION

Dual-loop P/PI control offers simplicity and performance. Engineers appreciate the fact that each loop has a clear purpose. The inner loop stabilizes the fast dynamics of the electrical subsystem. The outer loop shapes the slower mechanical response. Implementation requires minimal computation. The design method is intuitive. Moreover, the structure allows additional improvements if needed, such as acceleration feedback, friction compensation, load observers, or anti-windup procedures. Even without these additional components, the basic dual-loop structure supports fast and accurate control of DC servodrives.

CONCLUSION

Dual-loop P/PI control is one of the most practical control architectures for DC servodrives. It effectively uses the separation between fast electrical and slow mechanical dynamics. The P current regulator ensures rapid torque control, while the PI speed regulator eliminates steady-state speed error. The presented model, architecture explanation, and numeric example confirm that this classical cascaded solution still provides excellent performance and is ideal for real industrial applications.

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