

Simulation and Performance Analysis of a Buck Converter-Driven PMDC Motor Using PI Control

Prof. Sagar Bhaisare*, Aryan R. Dhore[†], Ashlesha R. Ghonmode[‡], Janvi L. Rangari[§],
Pallavi N Sharma[¶], Sakshi G. Ninawe^{||}, and Prachi N waghmare**

Department of Electrical Engineering
K.D.K College Of Engineering
Nagpur, Maharashtra, India

Email: *sagarbhaisare16@gmail.com, [†]dhorearyan414@gmail.com, [‡]ashleshghonmode@gmail.com,
[§]janvirangari44@gmail.com, [¶]pallavisharma9623@gmail.com, ^{||}ninawesakshi1@gmail.com, prachiwaghmare414@gmail.com

Abstract—In contemporary industrial environments, Permanent Magnet Direct Current (PMDC) machines have become the preferred choice for applications requiring precise torque linearity and high operational dependability. To guarantee optimal functionality when subjected to fluctuating mechanical loads, these systems necessitate highly resilient speed regulation architectures. This manuscript presents the initial phase of an in-depth investigation into a PMDC motor drive energized by a step-down DC-DC converter. This current study establishes a rigorous functional baseline by evaluating the standard Proportional-Integral (PI) control mechanism. Utilizing advanced MATLAB/Simulink environments for mathematical parametrization and behavioral modeling, the findings reveal the severe transient disturbances and mechanical stresses inherent to rigid mathematical PI frameworks. To resolve these documented instabilities, the integration of an advanced, rule-based Fuzzy Logic Controller (FLC) is proposed and theoretically outlined for the subsequent phase of this ongoing research.

Index Terms—Permanent Magnet Direct Current (PMDC) Motors, Speed Controllers, Proportional Integral (PI) Controller, Fuzzy Logic Controller (FLC), MATLAB Simulations, H-Bridge Chopper, Buck Converter.

I. INTRODUCTION AND HISTORICAL CONTEXT

The historical progression of industrial electromechanical control has been largely catalyzed by the urgent requirement to eliminate the massive power dissipation associated with primitive rheostatic controls

and linear voltage regulators [3], [13]. Modern industrial applications inherently demand elevated

efficiency, swift dynamic responses, and substantial torque capabilities [7].

To decisively resolve inherent hardware limitations, semiconductor-based electronic switching mechanisms powered by Pulse Width Modulation (PWM) converters were integrated, entirely superseding traditional resistance-centric control methods [6]. When coupled with contemporary solidstate drives, PMDC architectures present substantial operational benefits. They ensure outstanding reliability, strictly linear torque-to-speed ratios, swift acceleration profiles, and highly predictable performance metrics [4].

This paper represents the first half of a comprehensive two-part research initiative. The current scope is dedicated to establishing a functional baseline using a conventional Proportional Integral (PI) control strategy. Because standard PI controllers strictly require linear mathematical models, they often falter significantly when encountering sudden load shifts and parametric uncertainties [9]. By documenting these exact transient limitations, this paper sets the foundation for the subsequent implementation of a linguistic Fuzzy Logic Controller (FLC).

II. SYSTEM ARCHITECTURE AND MODELING

A robust PMDC configuration relies fundamentally upon the precise modulation of armature voltage via high-frequency PWM switching [10]. Architecturally, the proposed system harnesses a primary DC power source to energize a buck converter, which subsequently

routes its output through a DC link capacitor to fuel the H-Bridge chopper.

A. PMDC Motor Mathematical Dynamics

The dynamic armature voltage and mechanical rotation dynamics are mathematically expressed by:

$$V_a = E_b + I_a R_a + L_a \frac{dI_a}{dt} \quad (1)$$

$$T_e - J \frac{d\omega}{dt} + B\omega + T_L \quad (2)$$

Where the generated electromagnetic torque is $T_e = K_t I_a$ and the opposing back-EMF is $E_b = K_e \omega$.

The specific PMDC motor chosen features a rated voltage of 24 V, 3000 RPM, 1 Nm of torque, and a 4 A nominal current. The angular velocity translates to 314.16 rad/s, establishing a Back EMF constant (K_e) of 0.076 V/rad/s. To achieve the designated 1 Nm rated torque at the 4 A current threshold, the Torque Constant (K_t) is empirically adjusted to 0.25 Nm/A. Supplementary parameters to guarantee simulation fidelity include an armature resistance of $R_a = 0.05 \Omega$, inductance $L_a = 2$ mH, rotor inertia $J = 0.002$ kg · m², and a friction coefficient of $B = 0.0002$.

B. DC-DC Buck Converter Parametrization

The designated DC-DC conversion module is a step-down Buck architecture [1]. With an input of 36 V and an output of 24 V, the operational duty cycle (D) is calculated as 0.67 (or 67%). Assuming a switching frequency of $f_s = 20$ kHz alongside an allowable inductor ripple current of 30% of the load current ($\Delta I_L = 1.2$ A), the critical inductance (L) is computed as:

$$L = \frac{(V_{in} - V_{out}) \cdot D}{\Delta I_L \cdot f_s} \approx 335 \mu \text{ H} \quad (3)$$

A standardized commercial value of 330 μ H is adopted. To maintain a strict 1% output voltage ripple ($\Delta V_c = 0.24$ V), the smoothing capacitor is calculated as approximately 31 μ F, leading to the integration of a highly practical 47 μ F standard value into the model.

III. CONTROL METHODOLOGIES

A. Proportional-Integral (PI) Control Strategy

The fundamental operation of the PI loop is predicated upon identifying velocity discrepancies by constantly comparing a predefined reference target against the actual measured speed. For this specific

analytical framework, meticulous manual tuning produced a proportional gain (K_p) of 0.9 and an integral gain (K_i) of 0.001. However, standard PI frameworks strictly necessitate linear mathematical models, which inherently causes them to underperform when exposed to unpredictable non-linear system behaviors [9].

B. Proposed Solution: Advanced Fuzzy Logic Control (FLC)

To overcome the documented limitations of PI tracking, the subsequent phase of this research will implement a Fuzzy Logic Controller. Operating as an evolutionary leap beyond conventional Boolean logic, the FLC successfully emulates human cognitive assessment by processing data through fluid, conditional "If-Then" rule sets [2]. The raw numerical inputs ("error" and "change of error") will be mathematically mapped into linguistic descriptors, evaluated by a 49-rule Mamdani matrix, and defuzzified to provide critically damped PWM signals [8].

IV. MATLAB/SIMULINK IMPLEMENTATION AND RESULTS

To establish the comparative baseline for this ongoing project, the PI-regulated system was modeled with high fidelity using the MATLAB/Simulink environment.

A. Simulation of Buck Converter-Fed PMDC System

The simulated power stage incorporates the 36 V DC input, the 330 μ H inductor, and the 47 μ F capacitor in conjunction with the PMDC block. Fig. 1 delineates the Simulink architecture of the PI-regulated PMDC drive system, explicitly highlighting the step-down converter, the LC filter network, and the closed-loop feedback mechanism governing the PWM generation.

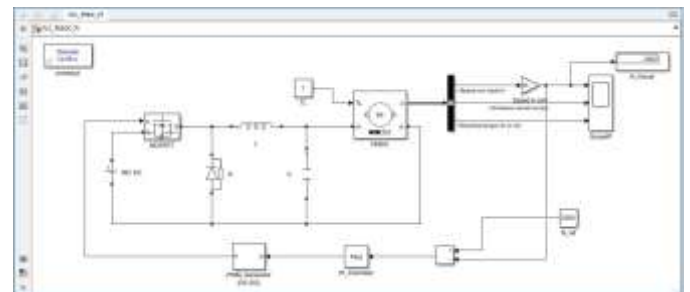


Fig. 1. Simulink architecture of the PI-regulated PMDC drive system, detailing the Buck converter power stage and error-driven feedback loop.

B. Waveform Analysis and Transient Limitations

The oscilloscope output captured in Fig. ?? explicitly illustrates the transient vulnerabilities of the motor under standard PI regulation.

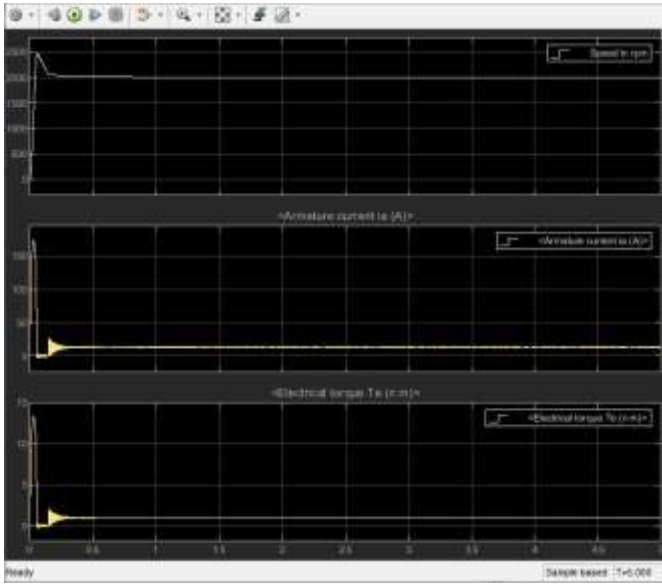


Fig. 2. Oscilloscope output under PI control: The top plot shows the underdamped Speed (rpm) response, while the lower plots reveal the severe transient spikes and chattering in Armature Current (A) and Electrical Torque (Nm).

Under PI control, the uppermost plot displays an underdamped velocity curve. The motor undergoes an initial surge to a peak overshoot of 2500 rpm before attempting to settle at the steady-state target of 2000 rpm, resulting in a settling delay that persists until approximately the 0.40-second mark. Concurrently, the unoptimized acceleration commands of the PI controller trigger a massive armature inrush current spike peaking at ~ 170 A. Because electromagnetic torque directly correlates with this current, the mechanical shaft is subjected to corresponding violent torque spikes peaking at ~ 13 Nm. Notably, visible chattering and ripple persist in both the current and torque signals until 0.40 seconds before finally smoothing out into a steady state.

TABLE I
PERFORMANCE METRICS OF THE PI CONTROLLER

Parameter	PI (Proportional-Integral) Value
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Settling Time	~0.40 seconds
Peak Speed Overshoot	2500 rpm
Peak Current (i_a)	~170 A
Peak Torque (T_e)	~13 Nm
Transient Behavior	Noticeable ripple/chattering

V. CONCLUSION AND SCOPE FOR FUTURE WORK
A. Phase I Conclusion

The exhaustive simulation of a closed-loop, buck-fed PMDC motor explicitly highlights the operational frailties of standard PI controllers. Despite meticulous mathematical modeling and manual tuning ($K_p = 0.9$, $K_i = 0.001$), the inflexible, linear methodology of the PI controller struggles with the realities of electromechanical dynamics. The empirical data confirms an underdamped speed profile characterized by extreme overshoot up to 2500 rpm, a prolonged ~ 0.40 s settling duration, and dangerous 170 A inrush currents. These aggressive initial control efforts induce violent torque spikes (~ 13 Nm) and noticeable chattering that place unnecessary cyclical stress on physical mechanical linkages.

B. Scope for Future Improvement (Phase II)

While the PI controller ultimately forces the PMDC motor into a steady state, its transient phase is undeniably volatile and sluggish. To mitigate these transient instabilities, the next phase of this ongoing research will prioritize the full integration and detailed analysis of the Advanced Fuzzy Logic Controller (FLC).

By leveraging linguistic "If-Then" rule bases rather than inflexible linear equations, the proposed FLC architecture is hypothesized to handle complex, non-linear motor characteristics far more effectively. Future work will simulate and benchmark the FLC against the PI baseline established in this paper, aiming to eliminate dangerous overshoot, compress settling times, drop peak inrush currents, and ensure a critically damped, mechanically safe system response.

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