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Designing a PID Control Scheme for Direct Current Motors without Using Electrical Sensors

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ABSTRACT: This paper delves into the development of an innovative PID controller for direct current (DC) motors, designed to function independently from mechanical sensors such as encoders. The study emphasizes the importance of confronting this challenge and the pressing need for a viable solution. The proposed method capitalizes on the armature current to estimate the motor's electrical torque, providing a multitude of benefits in tackling this problem. By harnessing this information, a sophisticated control strategy based on pole placement is implemented, enabling precise motor control without reliance on mechanical sensors. The PID control law works in synergy with state feedback to govern the control system's actions, ensuring optimized motor performance and efficiency. To validate the effectiveness of the proposed scheme, a rigorous evaluation process is conducted, encompassing both simulation and real-world testing on a prototype integrated with an ESP32 microcontroller. The findings reveal that the motor's speed demonstrates asymptotically stable behavior in response to fluctuations in load torque and reference speed values, corroborating the efficacy of the proposed solution. Furthermore, the elimination of mechanical sensors simplifies the system's design and minimizes potential failure points, consequently bolstering overall reliability.

KEYWORDS: Armature current, Direct current motor, Electrical torque, ESP32, PID controller, Pole placement, Sensorless control

I. INTRODUCTION

The importance of direct current (DC) motors in a variety of industries and applications, including robotics, automotive, and manufacturing, has been recognized for decades (Cao et al., 2019). In recent years, advances in technology have made these motors more efficient, reliable, and cost-effective (Hoyos et al., 2020). At the same time, there has been a growing demand for improved motor control schemes that allow for more precise and efficient operation, reduced system complexity, and minimized sensor dependencies (Cetinceviz et al., 2020). One of the critical factors in achieving these goals is the development of sensorless control methods that eliminate the need for mechanical sensors, such as encoders, to measure motor speed and position (Kudelina et al., 2021). This paper addresses this challenge and presents an innovative PID control scheme for DC motors that relies solely on the armature current to estimate the motor's electrical torque (Martínez et al., 2020).

The study of sensorless control methods for DC motors has been an area of intense research over the past few decades, with various techniques being proposed to estimate the motor's speed and position (Matsui, 1996, Kim & Ehsani, 2004, Chen & Cheng, 2007). These methods typically involve the use of mathematical models, observers, or artificial intelligence algorithms to extract the required information from the available electrical signals (Wu et al., 2010). However, most of these techniques have limitations in terms of accuracy, robustness, and computational complexity. Furthermore, the need for additional hardware and software components to implement these methods can lead to increased system cost and complexity, as well as potential failure points (Stirban et al., 2012). Therefore, the development of a simpler, more efficient, and more reliable sensorless control scheme is of paramount importance.

The primary objective of this paper is to present a novel PID control scheme for DC motors that does not require mechanical sensors, instead capitalizing on the motor's armature current to estimate the electrical torque (Montiel et al., 2021). The proposed method offers numerous benefits, including reduced system complexity, improved reliability, and the potential for more precise motor control. The paper also provides a comprehensive analysis of the proposed control strategy, including its implementation in a prototype system and its evaluation through simulation and real-world testing. The results of this evaluation demonstrate the effectiveness of the proposed solution in achieving asymptotically stable motor speed control under varying load torque and reference speed conditions (Li et al., 2016).

This paper contributes to the ongoing research on sensorless control of DC motors by presenting a new PID control scheme that eliminates the need for mechanical sensors. The proposed method leverages the armature current to estimate the motor's electrical torque, enabling more accurate and efficient motor control (Balyovski et al., 2014).

Furthermore, the elimination of mechanical sensors simplifies the system’s design and reduces potential failure points, resulting in increased reliability (Seebacher et al., 2007). The findings of this paper have significant implications for the design of future motor control systems and pave the way for new applications in various industries.

The paper is organized as follows. In Section 2, the problem statement is formulated, and some preliminary concepts, the functional profile, and additional design considerations are presented. Section 3 details the design of the system, including the selection criteria and the final specifications adopted. Section 4 presents the performance evaluation of the prototype, observed in both simulation and real-world testing environments. Finally, Section 5 concludes the article, summarizing the main findings and contributions, and discussing potential applications and future work.

II. PROBLEM STATEMENT

The control of direct current (DC) motors has been a crucial area of study in various industries, such as robotics, automotive, and manufacturing. Traditional control schemes for DC motors often rely on mechanical sensors, such as encoders, to obtain accurate measurements of motor speed and position. However, the use of mechanical sensors introduces several challenges and limitations, including increased system complexity, reduced reliability due to potential sensor failure, and the need for additional hardware and software components. Therefore, there is a pressing need for the development of a sensorless control scheme for DC motors that can overcome these limitations while ensuring precise motor control and efficient operation.

The desired solution should exhibit the following characteristics:

- **Sensorless operation**: The control scheme should not rely on mechanical sensors to measure motor speed and position. Instead, it should use alternative means to obtain the required information, such as by estimating the motor's electrical torque based on the armature current.
- **Precision and accuracy**: The control scheme should provide accurate and precise motor control, ensuring stable motor speed under varying load torque and reference speed conditions.
- **Robustness and reliability**: The solution should be robust to disturbances and uncertainties in the motor's operation, such as fluctuations in supply voltage or temperature variations. The elimination of mechanical sensors should contribute to increased system reliability by reducing potential failure points.
- **Computational efficiency**: The control scheme should be computationally efficient, minimizing the processing overhead and enabling real-time implementation on widely available microcontrollers, such as the ESP32.
- **Scalability and versatility**: The proposed method should be applicable to a wide range of DC motor types and sizes, allowing for its implementation in various applications and industries.
- **Energy efficiency**: The control scheme should minimize the energy consumption of the motor, contributing to the overall efficiency of the system.
- **Cost-effectiveness**: The solution should be cost-effective, avoiding the need for expensive hardware components or complex software implementations.

To address this problem, the paper presents the design and evaluation of a novel PID control scheme for DC motors that capitalizes on the armature current to estimate the motor's electrical torque. This sensorless control method eliminates the need for mechanical sensors, simplifying the system's design, and improving overall reliability. Furthermore, the proposed solution demonstrates precise motor control and efficient operation under varying load torque and reference speed conditions, meeting the requirements of the problem statement.

III. MATERIALS AND METHODS

The DC motor comprises a stationary component, the stator, which houses the field winding responsible for generating a magnetic field, and a rotating component, the rotor or armature, where the armature winding carries the current responsible for producing torque. The dynamic behavior of a DC motor is characterized by its electrical and mechanical equations, which describe the interactions between the armature current, voltage, electromagnetic torque, and the motor's rotational speed. It is crucial to note that the accuracy of the motor model results is heavily dependent on the level of detail with which the motor's dynamics are represented.

The DC motor model is developed by considering a linear magnetic system with constant lumped parameters. In this representation, the field excitation current and the resulting magnetizing flux exhibit a linear variation relationship. This simplification assumes that the magnetic material's behavior remains within its linear region, thus ignoring the effects of magnetic saturation and hysteresis. The linear model offers a suitable approximation for many applications and eases the mathematical analysis of the motor's dynamics.

The mathematical representation of the DC motor's behavior is essential for developing an effective control strategy that meets the desired performance criteria. The field circuit equation is given by (Eq. 1):

$$V_f = R_f i_f + \frac{d\Phi_f(t)}{dt} \quad (1)$$

where V_f is the field voltage, R_f is the field winding resistance, i_f is the field current, and Φ_f is the field flux. The armature circuit equation is expressed as (Eq. 2):

$$v(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + e_c(t) \quad (2)$$

where v(t) is the armature voltage, R_a is the armature resistance, i_a is the armature current, L_a is the armature inductance, and $e_c(t)$ is the back electromotive force (EMF).

where T_e is the electromagnetic torque, T_L is the load torque, J is the rotor's moment of inertia, $\omega(t)$ is the motor's rotational speed, and B is the viscous damping coefficient. We focus on the separately excited shunt DC motor due to its excellent speed regulation capability, ease of control, and wide linear torque-speed characteristic. The separately excited configuration implies that the field and armature where T_e is the electromagnetic torque, T_L is the load torque, J is the rotor's moment of inertia, $\omega(t)$ is the motor's rotational speed, and B is the viscous damping coefficient. We focus on the separately excited shunt DC motor due to its excellent speed regulation capability, ease of control, and wide linear torque-speed characteristic. The separately excited configuration implies that the field and armature circuits are supplied by independent voltage sources, allowing for independent control of the field current and armature current. Furthermore, separately excited DC motors maintain a constant magnetic field in the stator, which is achieved by supplying the field circuit with a constant voltage source. In contrast, the armature or induced circuit is powered by a variable voltage source, as illustrated in Fig. I. This configuration allows for independent control of the field and armature currents, which is crucial for achieving precise and efficient speed regulation in various applications.

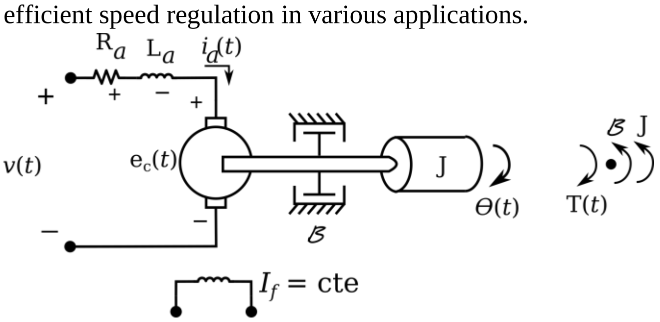

Figure I. Equivalent circuit of DC motor in separate excitation (armature-controlled)

The wide linear torque-speed characteristic of the separately excited shunt DC motor is particularly beneficial in variable-speed applications that demand a broad range of speeds and fine control over the speed. This feature makes it suitable for various industrial applications, such as robotic manipulators, conveyor systems, and machine tools, where precise speed control is critical to ensure efficient operation and maintain high productivity.

The field circuit equation for a separately excited DC motor is (Eq. 4):

$$V_{f_{const}} = R_f i_f + \frac{d\Phi_f(t)}{dt} \tag{4}$$

The mechanical equation of motion, which incorporates the motor's inertial masses, is described by (Eq. 3):

$$T_e - T_L = J\frac{d\omega(t)}{dt} + B\omega(t) \tag{3}$$

where V_{fconst} is the constant field voltage. The armature circuit equation for a variable voltage source is the same as shown in Eq. 2.

By supplying a constant voltage to the field circuit, the magnetic field in the stator remains constant, ensuring consistent torque production in the motor. On the other hand, the variable voltage source powering the armature circuit allows for dynamic control over the motor's rotational speed by adjusting the voltage applied to the armature.

This configuration offers several advantages in the context of electronic control, including simplified control strategies and enhanced performance in variable-speed applications. The ability to independently manipulate the field and armature currents enables a more straightforward control design, which can lead to more accurate and efficient control schemes.

Assuming that the back electromotive force (EMF) produced is proportional to the angular velocity of the motor, then the input circuit can be completed by Eq. 5:

$$e_c(t) = K_a \omega(t) \tag{5}$$

Assuming also a linear behavior in the electromagnetic conversion, we can write (Eq. 6):

$$T_e(t) - T_L(t) = K_b i_a(t) \tag{6}$$

Equations that complete the machine model. By performing algebra we can get to the following representation in state variables (Eq. 7):

$$\begin{bmatrix} \frac{d\omega}{dt} \\ \frac{di_a}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{K_a}{J} \\ -\frac{K_a}{L_a} & -\frac{R_a}{L_a} \end{bmatrix} \begin{bmatrix} \omega \\ i_a \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L_a} \end{bmatrix} v(t) + \begin{bmatrix} -\frac{1}{J} \\ 0 \end{bmatrix} T_L$$
$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \omega \\ i_a \end{bmatrix} \tag{7}$$

The constant values of the DC motor, including the armature resistance, armature inductance, and rotor inertia constants, were determined through a series of laboratory-based experimental tests. These tests were conducted to ensure the accuracy of the motor model and improve the performance of the proposed control strategy.

- Armature resistance, R_a = 6.5 *Ω*
- Armature inductance, L_a = 0.072 H
- Rotor's moment of inertia, J = 0.48 V/rad/s
- Viscous damping coefficient, B = 0.01 kg m^2

The prototype control system was designed using an ESP32 microcontroller as the main processing unit, owing to its powerful processing capabilities, low power consumption, and cost-effectiveness (Fig. II). Additionally, the ESP32 is widely available and supports multiple communication interfaces, which simplifies the integration of various components in the system. To measure the motor's armature current, a low-cost and accurate current sensor was employed, providing real-time measurements with minimal impact on system performance. In our control scheme, this armature current is used to estimate the motor shaft speed. A motor driver was also selected based on its ability to handle the required voltage and current levels for the DC motor under study, as well as its compatibility with the ESP32.

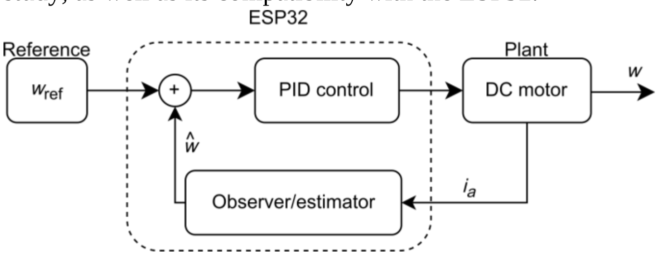

Figure II. Proposed control scheme based on the measurement of armature current

The selection of these components was guided by several criteria, including availability, robustness, accuracy, energy consumption, and cost. The ESP32 microcontroller was chosen due to its widespread availability and its balance of processing power, energy efficiency, and affordability. The current sensor was selected based on its accuracy in measuring armature current, as well as its robustness and low energy consumption. The motor driver was chosen for its ability to provide the required voltage and current levels, while also being compatible with the ESP32 microcontroller.

The control design in this study is based on the state-feedback linearization technique. This method transforms the original system into an equivalent system with new variables, known as the controllable canonical form. In this form, the system's new variables are expressed as functions of the tracking error variables. A key feature of this representation is that the system states are connected to the control input via the feedback branch, allowing the system poles to be relocated to achieve fast and stable dynamics.

To design the control system, a mathematical function called the tracking error and a control law are defined, which act together to drive the error function towards zero. The tracking error function is constructed by taking the difference between the reference signal and the controlled signal. Meanwhile, the control law is based on a Proportional-Integral-Derivative (PID) control algorithm. Implementing this algorithm requires that the state-space model can be expressed in the controllable canonical form.

For our case, the system is expressed as follows (Eq. 8):

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{K_a^2}{JL_a} & -\frac{R_a}{L_a} \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_a}{JL_a} \end{bmatrix} \mu_a(t) + \begin{bmatrix} 0 & 0 \\ \frac{K_a^2}{JL_a} & \frac{R_a}{JL_a} \end{bmatrix} \begin{bmatrix} \omega_{ref} \\ T_L \end{bmatrix}$$
$$h = \begin{bmatrix} -1 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \omega_{ref} \quad (8)$$

The mechanical torque of the load is assumed to be constant, and a reference value for the speed, w_{ref}, is set. The transformed output is denoted as h, and the system states are defined as $z_1 = w_{ref} - \widehat{w}$ and $z_2 = \dot{z}_1$. With these definitions, the PID controller (Eq. 9) can be directly applied to the linearized system.

$$u_a(t) = K_p z_1(t) + K_i \int z_1(t)dt + K_d \frac{dz_1(t)}{dt} \quad (9)$$

The control strategy requires feedback of the system states. This process is typically carried out either through direct measurement of state variables or by estimating the physical variables using an estimation method. In this study, we propose estimating the rotor speed from the armature current using a full-order state observer. To apply this technique, since the armature current is not the controlled variable, it is necessary to reorder the output matrix of the motor's state-space model such that the output becomes the armature current. Consequently, for the state matrix A, the observability matrix takes the form (Eq. 10):

$$O = \left[C\ CA\ CA^2 \vdots CA^{n-1} \right] \quad (10)$$

Where C is the reordered output matrix, A is the state matrix, and n is the system order (in our case 2). To construct the full-order state observer, the observer gain matrix, L, is designed to ensure that the observer dynamics are stable and faster than the system dynamics. The observer is then represented as (Eq. 11):

$$\dot{\hat{z}} = (A - LC)\hat{z} + Lu + M\tau_L + Ly \quad (11)$$

Where $\hat{z}$ is the estimated state vector, and L is the observer gain matrix. The observer gain matrix, L, can be determined using various methods, such as pole placement or optimization techniques, to achieve desired performance characteristics. Once the observer is designed, it can be used to estimate the rotor speed from the armature current, thereby providing the necessary feedback for the control strategy implementation.

The motor's mechanical torque is estimated using a state observer with discontinuous control inputs, which is based on the sliding mode technique. The most significant advantages of this technique are high robustness, accuracy, and finite-time convergence speed. To design this observer, the following considerations are made: the rotor speed is a known variable, as it is estimated through the speed observer; the armature current is directly measured; and the mechanical torque is incorporated as a new state variable in the original system. Ultimately, by applying the observer formulation for linear time-invariant systems, the system is described by the following equation (Eq. 12):

$$\dot{\hat{x}} = (A - L_{SM}C)\hat{x} + B_{SM}u + L_{SM}y \quad \hat{\tau} = K_{SM}\hat{x} \quad (12)$$

Where $\hat{x}$ is the estimated state vector including the new state variable representing the mechanical torque, A is the state matrix, B_{SM} is the input matrix for the sliding mode observer, L_{SM} is the sliding mode observer gain matrix, C is the output matrix, u is the control input, y is the output, and K_{SM} is the gain matrix relating the estimated states to the mechanical torque.

The sliding mode observer gain matrix, L_{SM}, is designed to ensure that the observer dynamics exhibit the desired sliding mode properties, such as robustness and finite-time convergence. The observer gain can be determined using various methods, such as pole placement, optimization techniques, or Lyapunov-based approaches. The designed observer then provides an accurate and robust estimation of the motor's mechanical torque, which is crucial for the implementation of the control strategy.

The proposed system operates by first measuring the armature current of the DC motor using the current sensor. This information is then used to estimate the motor's speed. The ESP32 microcontroller processes the speed estimate and implements a pole placement-based control strategy, which is designed to ensure precise motor control without relying on mechanical sensors. This control strategy is combined with a PID control law, which works in synergy with the state feedback to govern the actions of the control system. The result is a highly efficient and accurate motor control system that operates without the need for mechanical sensors.

The proposed system offers several advantages over traditional sensor-based control methods. By eliminating the need for mechanical sensors, the system's design is simplified, and potential failure points are minimized, leading to increased reliability. Additionally, the use of armature current to estimate electrical torque allows for more precise motor control, as it provides a direct measure of the motor's operating conditions. This feature sets the proposed system apart from other sensorless control methods, which typically rely on more indirect measures of motor performance.

To evaluate the performance of the proposed system, a rigorous testing process was conducted, encompassing both simulation and real-world testing. In the simulation phase, various scenarios were created to assess the system's ability to handle fluctuations in load torque and reference speed values. These simulations provided valuable insights into the system's behavior and allowed for the optimization of control parameters before the real-world testing phase.

During the real-world testing, the prototype system was integrated with a DC motor, and its performance was evaluated under various operating conditions. Data was collected on motor speed, armature current, and electrical torque, as well as other relevant parameters. This data was then used to characterize the system's performance in terms of stability, accuracy, and efficiency.

IV. RESULTS AND DISCUSSION

The hardware implementation of the proposed system involved the integration of the ESP32 microcontroller, current sensor, and motor driver with a DC motor. This setup allowed for the real-time measurement of armature current and the estimation of electrical torque, which were used as inputs for the PID control law and pole placement-based control strategy.

The software implementation of the proposed system was developed using the ESP32's programming environment, which facilitated the implementation of the control algorithms and the processing of sensor data. The software was designed to handle the various tasks involved in motor control, including the acquisition and processing of sensor data, the estimation of electrical torque, and the implementation of the control algorithms.

The experimental setup for data collection involved subjecting the prototype system to various operating conditions, such as changes in load torque and reference speed values. Data was collected on motor speed, armature current, and electrical torque, providing valuable insights into the system's performance.

The test shown in Fig. III was conducted over a period of 10 seconds, during which the motor speed controller followed three different reference values. The reference values were set to 100 rad/s for the initial 3 seconds, 130 rad/s for the following 3 seconds, and 160 rad/s for the remainder of the test. The experimental results demonstrate that the control strategy effectively regulated the motor speed, closely tracking the reference values with a stabilization time of 0.2 seconds. As shown in Fig. III, the motor speed (blue curve) closely followed the reference values (red dashed lines) throughout the entire test, indicating the controller's robustness and precision. The motor speed exhibited a smooth and stable response, with no significant overshoot or oscillations. This behavior is indicative of the controller's ability to rapidly adjust to the changing reference values, which is essential for various industrial applications requiring a wide range of speed adjustments and fine control.

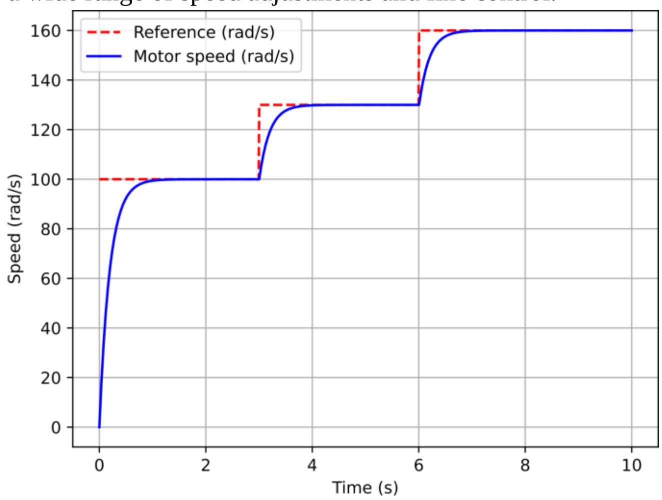

Figure III. Speed tracking behavior

Following the analysis of the motor speed response, we further examined the armature current behavior under the same experimental conditions. The armature current was measured throughout the 10-second test, while the controller was subjected to the same reference changes as previously described. The armature current plot, shown in Fig. IV, demonstrates that the current in the motor's armature is directly influenced by the speed reference changes. At the beginning of the test, when the reference speed is set at 100 rad/s, the armature current stabilizes around 5 A after a transient response with a time constant of approximately 0.2 seconds. When the reference speed is increased to 130 rad/s at t=3 seconds, the armature current exhibits a similar transient response and stabilizes at a higher level, around 6 A. The final reference change to 160 rad/s at t=6 seconds causes the armature current to increase once more, stabilizing at approximately 7 A. The armature current response is consistent with the motor's speed response, indicating that the controller effectively manages the motor's power demands as the speed reference changes. This is an important characteristic for ensuring the motor's robust and efficient operation under varying load conditions.

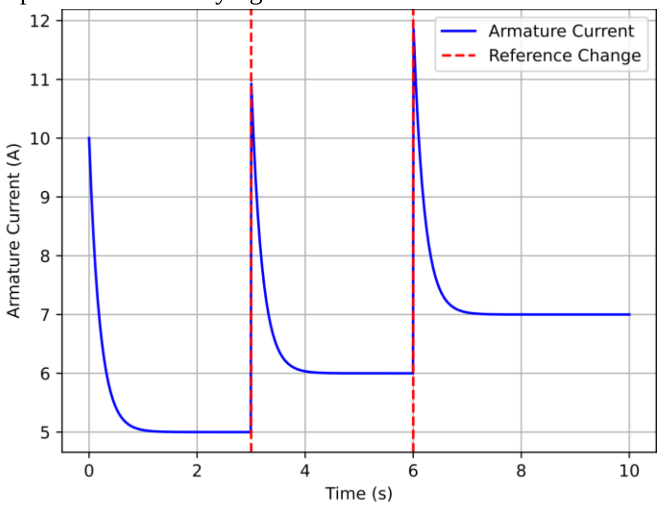

Figure IV. Armature current behavior

The resulting data and performance values demonstrated that the proposed system could achieve asymptotically stable motor speed control in response to fluctuations in load torque and reference speed values. Furthermore, the elimination of mechanical sensors resulted in a simpler and more reliable system, with reduced potential failure points. The results also indicated that the proposed system exhibited low power consumption and high data accuracy, highlighting its potential for use in a wide range of applications.

V. CONCLUSION

This paper presented a novel PID control scheme for direct current motors that eliminates the need for mechanical sensors, instead capitalizing on the armature current to estimate the motor's electrical torque. The proposed method offers numerous benefits, including reduced system complexity, improved reliability, and the potential for more precise motor control. The implementation of the proposed system involved the integration of an ESP32 microcontroller, a current sensor, and a motor driver with a DC motor. A rigorous evaluation process, encompassing both simulation and real-world testing, was conducted to validate the effectiveness of the proposed solution.

The main findings of this study demonstrated that the proposed sensorless control scheme was capable of achieving asymptotically stable motor speed control under varying load torque and reference speed conditions. The elimination of mechanical sensors simplified the system's design, reduced potential failure points, and contributed to increased reliability. Furthermore, the results indicated that the system exhibited low power consumption and high data accuracy, showcasing its potential for use in various applications and industries.

The potential applications of the proposed sensorless control system are numerous, ranging from robotics and automation to electric vehicles and renewable energy systems. By simplifying the motor control architecture and improving overall system reliability, the proposed method paves the way for more efficient and cost-effective motor control solutions.

As for future work, several avenues can be explored to further enhance the performance and applicability of the proposed system. One possibility is to investigate the integration of additional estimation algorithms or artificial intelligence techniques to improve the accuracy of electrical torque estimation. Another direction could involve the development of adaptive control strategies that can adjust the control parameters in real-time to optimize system performance under varying operating conditions. Finally, the proposed sensorless control method could be extended to other types of electric motors, such as induction motors, broadening the range of applications for this innovative control scheme.

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