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Closed-Loop Control of a DC Motor Using a Hall Sensor

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ABSTRACT: The need to control the speed of DC motors is often used in industry and embedded systems where the operating conditions are not always stable. Figure 2 demonstrates that when operating in open-loop control, minor deviations in the speed may be noticed because of changes in load and supply voltage. Due to this fact, the closed-loop control approach is researched in the current work in order to enhance the speed regulation performance.

Hall-effect sensor is employed in the proposed system to provide the speed related pulse signals on the motor shaft. These pulses are summed up and calculated to determine the motor speed in actual sense. This estimate speed is then checked against a reference value and the error that returns is inputted into a PID controller. The controller leverages this mistake to regulate the PWM duty cycle that is used to drive the motor so as to hold the desired speed.

The test is developed on the model of the control system with MATLAB/Simulink and is tested in the diverse operating conditions. The outcomes of the simulation indicate the existence of speed stability and steady-state accuracy when operating in the simulation, which is beyond the case when operating in the open-loop. The system choice of PID parameters is heavily related to the selection of response, both when it comes to transient response and stability.

The findings show that the suggested Hall sensor-based closed-loop scheme is a viable and economical way to regulate the speed of DC motors and this can be achieved in a broad variety of engineering projects.

KEYWORDS: DC Motor Speed Control, Closed-Loop Control, Hall-Effect Sensor, PID Controller, Pulse Width Modulation (PWM), Speed Feedback, MATLAB/Simulink Modeling, Embedded Control Systems

INTRODUCTION

Increasingly complex electromechanical systems are used in industrial automation, robotics, autonomous vehicles, and precision instruments, which have increased the demand of dependable and high-performance motor control. The DC motors are common because of their low costs of construction and good torque speed characteristics. They are however not prone to changes in loads, changes in voltages and non linear friction, which does not enable open loop control to be applied in systems when a certain degree of accuracy and stability is required. This has led to the fact that close loop control strategies [1][2] are now crucial in achieving uniform motor behavior in different operating conditions.

The closed-loop speed control relies on an ongoing feedback of the real motor speed to enable the controller to reduce the difference between the reference command and the response measured. Speed measurement Hall-effect sensors have become an effective and durable solution to speed measurement since it produces digital pulses that are related to shaft rotation and which work effectively in restricting noise, temperature variations, and mechanical disturbances. Hall sensors are also fast to support embedded and industrial applications because they are more durable and cheaper than optical encoders [3] [4] [5].

Hall-effect speed feedback, with a PID (Proportional Integral Derivative) controller can be used to achieve a highly effective and efficient closed-loop system where the speed of the system approximated by pulses by the Hall sensor is corrected by the PID algorithm to the driver through current speed error. This type of arrangement increases transient response, reduces steady-state error, as well as increases disturbance rejection dramatically. Experiments always indicate that PID-based closed-loop control systems do better than their open-loop counterparts regarding settling time, overshoot control, and steady-state precision[6][7] [8].

PWM is still the most commonly used actuation technique of DC motors since it provides fine-grained control of the torque and speed with low loss of power. Recent studies point out to the fact that optimized PWM strategies lead to a smoother transition between speeds, less electrical stress, and more efficient motors which are appropriate in energy-limited systems like mobile robots and autonomous platforms [12] [13].

The popularity of PID controllers remains high because they are easy to use and demonstrate high practical performance.

Recent studies are dedicated more to the improvement of PID tuning with classical methods and modern techniques such as adaptive algorithms and the use of AI to optimize the results. These innovations contribute to the controller robustness of the nonlinear systems of the controller or system parameters change as a result of aging or environmental influences [14] [15].

The open and closed loop control strategies are the analysed and validated strategies under the analysis and validation using MATLAB/Simulink. Transient behavior, steady-state behavior and robustness of a PID system using a Hall-sensor In 2022–2025, transient behavior, steady-state behavior, and robustness of a PID system using a Hall-sensor had been found and implemented by a simulation model and subsequently on hardware. These types of simulations enable researchers to optimize the parameters of the controllers and predict the disturbances in the real world in an effective manner [16] .

Embedded platforms like Arduino, STM32 and ESP32 have further increased the availability of closed-loop motor control. These microcontrollers enable real-time pulse counting of Hall sensors and real-time execution of PID algorithms, making them usable in small, inexpensive systems in automation, robotics, and internet of things applications[18] [19].

Other studies have increasingly begun to focus on applying multimodal sensing systems, founded on the combination of Hall-effect feedbacks with current based sensing, state of the art observer-estimation models, and back EMF sense models, to improve accuracy, stability and fault-tolerance of closed-loop DC motor speed control systems which is a consistent observation through the contemporary literature [20].

This is especially crucial in systems with high load variability or dynamic operational requirements [19]. In addition, energy-efficient control techniques, particularly those based on optimized PID and PWM methods, play an important role, as several studies report noticeable reductions in power consumption in industrial and mobile systems.[20].

To conclude, the closed-loop speed control based on the Hall-effect feedback and the PID control is a powerful, precise, and energy-saving proposal to be used as the DC motor. Its high disturbance rejection, high accuracy in tracking speed and its compatibility with the latest embedded systems highlight its importance in the development of automation and motion-control technology.

2.LITERATURE REVIEW

2.1 DC Motor Speed Control techniques.

The speed control of DC motors is done through open-loop or closed-loop approaches. Open-loop control does not provide the feedback control and is susceptible to changing loads and voltages. Closed-loop control is based on the speed feedback to rectify the mistakes and have a stable operation. Recent research proves the effectiveness of the closed loop control as it is more accurate and rejects disturbances better.

2.2 Speed Feedback based on Hall sensor.

Hall-effect sensors are usually applied to measure speed because they offer low-cost and digital output. According to previous works, their combination with PI or PID controllers can result in acceptable performance. Nevertheless, low resolution decreases precision in low frequencies.

2.3 PID Control in Motor drive systems.

PID control is commonly used in motor drive systems due to its simple construction and easy real-time control. The outcomes of the research are that there is an improvement in transient response and a decreased steady-state error. Although there are more sophisticated approaches, PID can still be used in low-complexity applications.

2.4 Comparison of Speed Sensing Techniques.

Hall sensors are cheap and offer medium accuracy. Optical encoders are very precise but are subject to the environment. Sensorless techniques do not use physical sensors but they need complicated processing and are unable to work well on low-speed. The decision will be based on the accuracy of the system and cost limitations.

2.5 Research Gaps

Majority of the studies focus on the simulation findings as opposed to experimental validation. There is little literature dealing with low-cost motors with Hall-based feedback under unified conditions. The area of the advanced control and low-resolution sensing is not properly explored.

3.SYSTEM ARCHITECTURE

3.1 Hardware Components

1) DC Motor

The DC motor is conditional on the rated voltage, current, range, torque and efficiency. These parameters are taken into account to be able to have a stable functioning of the closed-loop system of speed control.

2) Hall-Effect Sensor

The movement of the rotor is detected using the Hall sensor and generates digital pulses in relation to the motor speed. Its sensitivity, pulse output and pulse per revolution are programmed to give a good feedback in the situation of motor working.

3) Microcontroller

The control algorithm is executed and the microcontroller gets the feedback signals processed. It should be able to retain superior timing, consistent count of pulses and sustained PWM production. Real time operation requires the processing speed required, and processing capability on interrupts that it uses to ensure real time operation.

4) H-Bridge Motor Driver

The motor driver that provides the necessary current to the motor facilitates the two-way rotation. It also has coverage features that make it become a secure and secure operation.

5) Power Supply

Power supply gives the correct voltage and current to all system components. To prevent the performance degradation, this performance must be a controlled and stable output.

6) Noise Reduction

It uses proper grounding and passive filtering element to minimize electrical interferences. There are also short wiring paths in control signals and feedback signals taken so that signals are of quality.

3.2 Signal Flow Overview

1) Pulse Generation:- The hall sensor gives the digital pulses on the speed of the motor.

2) Speed Calculation:-The microcontroller counts these pulses and converts the data to the value of RPM.

3) Control Action:-The difference between the desired speed and the set measured speed is used to adjust the PWM duty cycle which controls the speed of the motor**.**

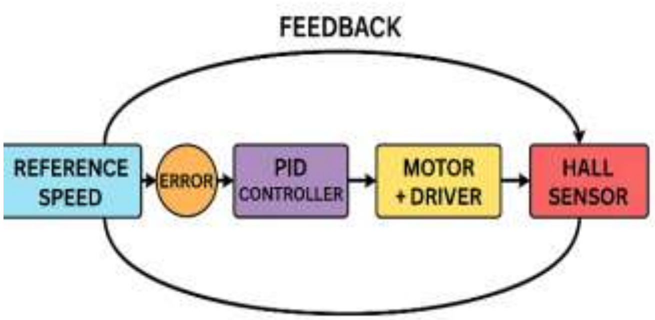


Figure1.Feedback Diagram

4.MATHEMATICAL MODELING

4.1 DC Motor Model:-

1) Differential equations of armature current and angular velocity

The motor is described by two fundamental equations: one models the armature current dynamics based on applied voltage, resistance, and inductance, while the other models the angular velocity as a function of developed torque and mechanical load.

2) Transfer function of the motor

By applying the Laplace transform to the electrical and mechanical equations, a linear transfer function is obtained that relates the applied input voltage to the motor's output speed.

3) Relationship between PWM duty cycle and motor torque

The PWM duty cycle determines the motor's effective average voltage; increasing duty cycle raises armature current and therefore increases torque, while decreasing it reduces both.

4.2 Hall Sensor Measurement Model:-

1) Derivation of RPM from pulse frequency

The Hall sensor produces pulses proportional to shaft rotation. The microcontroller measures pulse frequency and computes RPM using the known pulses-per-revolution value.

2) Resolution and quantization errors

Since the sensor outputs discrete pulses, speed measurements have limited resolution. At low speeds, fewer pulses increase quantization error and reduce accuracy.

3) Noise effects and filtering strategies

Electrical noise can distort pulse signals, causing false counts. Applying debouncing, digital filtering, and proper grounding improves measurement reliability and stability.

4.3 Closed-Loop Control Model:-

1) Block diagram of the closed-loop system :

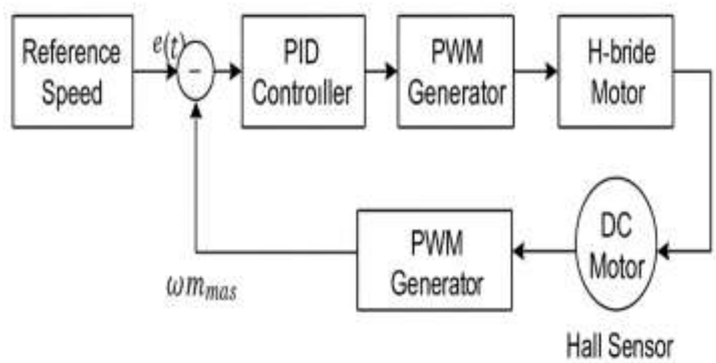


Figure 2. Block diagram of the closed-loop system

2) Error calculation :

$$e\,(t) = \frac{\omega_{ref}}{\omega_{easured}}$$

5. CONTROL ALGORITHM

5.1 PID Controller Theory :-

1) Proportional, Integral, and Derivative terms

A PID controller consists of three components:

• Proportional (P): Responds to the instantaneous speed error.

• Integral (I): Addresses accumulated error over time and eliminates steady-state offsets.

• Derivative (D): Predicts future error behavior, reducing overshoot and improving dynamic stability.

2) Mathematical form of PID

The general expression of the PID controller is:

$$\frac{de(t)}{dt}{}_{d}K + K_i \int e(t)\,dt + K_p e(t) = u(t)$$

where u(t)u(t)u(t) is the controller output and e(t)e(t)e(t) is the speed error.

3) Tuning methods (Ziegler–Nichols, trial-and-error, Cohen-Coon)

Several techniques are used to tune PID parameters :

- Ziegler–Nichols: Based on the system’s ultimate gain and oscillation period.
- Trial-and-error: Parameters are manually adjusted until a satisfactory response is obtained.
- .Cohen–Coon: Provides faster and more accurate tuning for sluggish or process-type systems.

5.2 PWM Generation

1) Duty-cycle computation from controller output

The PID output is mapped to a PWM duty cycle, where the duty ratio determines the effective average voltage applied to the motor.

2) PWM frequency selection

The frequency of PWM is chosen to bring about periodic torque and low noise. More than 20 kHz frequency is preferable since the frequency would eliminate audible noise and improve motor response**.**

3) Avoiding motor torque ripple

To reduce torque ripple, one should make use of increased PWM frequencies, appropriate filtering, and gradual variation of duty cycle to prevent the occurrence of sudden torque fluctuations

5.3 Software Flowchart

1) Initialization

System modules are configured, and they are the Hall sensor inputs, timer, PWM generation, and starting PID parameters.

2) Pulse counting loop

Interrupt based detection uses the microcontroller to count the Hall pulses inside an active sampling period.

3) RPM update

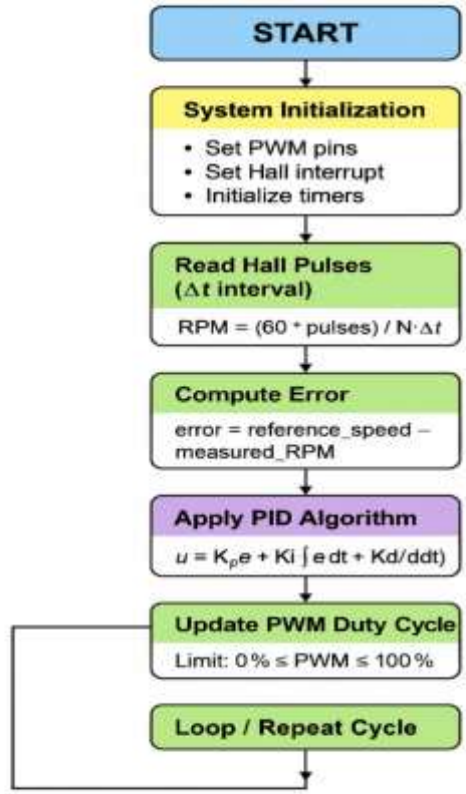
These pulses counts are then converted to RPM depending on the pulses-per-revolution and the interval between the pulses.

4) PID computation

The PID algorithm calculates and works on the error of the speed to generate a control output.

5) PWM output update

The result of the PID output is an adjustment of the PWM duty cycle which in turn adjusts the motor voltage to regulate speed.



6.EXPERIMENTAL SETUP

6.1 Hardware Implementation

1) Wiring diagrams

Wire the right electrical components of microcontroller, Hall sensor, motor driver and motor, so that the data and power are flowing in the correct direction.

2) Position of sensor in reference to motor rotor.

The Hall sensor will be attached to the rotor in a place where the magnet will rotate normally to ensure that suitable pulses of speed are produced.

3) Power and driver connection.

The H-bridge is connected in accordance with the motor ratings and a constant supply with the over current and voltage spike suppressors.

6.2 Software Implementation

1) Microcontroller code structure

The program includes initialization, speed acquisition, PID computation, and PWM updates, with supporting timer and interrupt routines.

2) Interrupt service routine for pulse counting

The ISR captures each Hall pulse edge to ensure accurate and loss-free speed measurement during real-time operation.

3) Real-time motor speed plotting (MATLAB)

Measured RPM values are transmitted to MATLAB, where they are plotted in real time using functions such as plot, drawnow, or animated line objects for performance visualization.

7.RESULTS AND DISCUSSION

7.1 Speed Response:-

1) Response characteristics with respect to step responses (rise time, settling time and overshoot)

The step change of reference speed is used to measure dynamic behaviour of the controller and measures the rise time, settling time and the overshoot of the system.

2) P-only/I-only and PID comparison.

The PID controller is more stable and responsive as compared to the single-action controller. P-only is steady-state error and I-only slow and may cause oscillations.

7.2 Stability Analysis:-

1) System behaviour when loaded suddenly.

The system is evaluated in response to sudden changes in load to conclude on its capability to hold speed and reduce temporary disturbances.

2) Error convergence to zero

The effectiveness of the controller is measured by observing the rate at which the speed error reduces and it gets to zero in steady states.

3) Sound insensitivity and sensor stability.

The strength of the Hall sensor measurement has been discussed together with its being less susceptible to electrical noise and being capable of giving out constant, credible speed feedback**.**

7.3 Performance Evaluation:-

1) Accuracy of speed tracking

The level of conformity of the system to the reference speed is measured with the aim of minimization of the deviation during course of operation.

2) Power consumption

The motor and driver power consumption are determined in order to ascertain the energy efficiency at different operating conditions.

3) Comparison of performance in open loops.

Closed-loop control is the opposite of open-loop operation and it is clear that accuracy, stability and disturbance rejection are enormously increased.

8. CONCLUSION

- Summary of findings

The closed-loop system based on PID delivered good performance in terms of tracking speed, rapid response, and robust disturbance rejection over the open-loop control.

- Effect of Hall sensor feedback.

Feedback provided by the halls offered much better measurement reliability and stability of the system to maintain consistent and accurate speed control.

- Strengths and limitations

It is affordable and simple to install, although the Hall sensors are not very resolute at low velocities, and could be subject to noise.

RECOMMENDATIONS

High PWM frequency, appropriate signal filtering, and methodical performance of PID tuning, and run the system at different loads.

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