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An Overview of Control Methodologies Applied for DC Motors

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Abstract

DC motors continue to play a fundamental role in numerous industrial, automotive, and commercial applications, due to their simple construction and ability to deliver accurate speed and torque control. In response to increasingly complex performance demands, broad control techniques were developed aiming at enhancing the adaptability and overall performance of DC motors under different operational conditions. This study provides critical overview of both classical, advanced and modern control strategies employed for DC motor systems. Classical controllers, such as the family of Proportional-Integral-Derivative (PID) controllers are widely employed due to their simplicity and reliable solutions for many tasks. Yet, advanced approaches including fuzzy logic, adaptive control and model predictive control (MPC) offer better and robust performance under load disturbances, nonlinearity, and dynamic uncertainties. The study also considers the role of power electronic components, such as H-bridge circuits in supporting efficient, precise and flexible regulation. This work aims to provide a critical appraisal of the operational strengths, inherent constraints, and implementation considerations of the key DC motor control techniques.

Keywords: DC motors, control methodologies, PID control, advanced control, H-bridge, motor control systems, classical control, adaptive control.

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نظرة عامة على منهجيات التحكم المطبقة على محركات التيار المستمر

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الملخص

تلعب محركات التيار المستمر دورًا محوريًا في مجموعة واسعة من التطبيقات الصناعية والتجارية وتطبيقات السيارات، نظرًا لبساطتها وموثوقيتها ودقتها في التحكم في السرعة وعزم الدوران. على مر العقود، طُوّرت منهجيات تحكم متنوعة لتحسين أداء هذه المحركات وكفاءتها وقابليتها للتكيف في ظل ظروف تشغيل مختلفة.

تقدم هذه الورقة نظرة عامة على استراتيجيات التحكم التقليدية والمتقدمة المستخدمة في أنظمة محركات التيار المستمر. توفر الطرق التقليدية، مثل وحدات التحكم التناسبية (P)، والتناسبية التكاملية (PI)، والتناسبية التكاملية المشتقة (PID)، البساطة وسهولة التنفيذ، مما يجعلها مناسبة للعديد من التطبيقات التقليدية. في المقابل. توفر تقنيات التحكم المتقدمة، مثل التحكم التكيفي، والمنطق الضبابي، والتحكم التنبؤي بالنماذج، استجابة ديناميكية محسنة، ومقاومة للاضطرابات، ومرونة في التعامل مع اللاخطية وعدم اليقين. بالإضافة إلى ذلك، يناقش البحث دور واجهات إلكترونيات الطاقة، مثل دائرة الجسر H، في تسهيل التحكم الدقيق.

تهدف هذه النظرة العامة إلى توفير رؤى حول نقاط القوة والقيود ومجالات التطبيق لكل منهجية، وتعمل كمورد قيم للباحثين والمهندسين الذين يسعون إلى تحسين أداء محرك التيار المستمر عبر حالات الاستخدام المتنوعة.

الكلمات المفتاحية: محركات التيار المستمر، منهجيات التحكم، التحكم التكاملي التفاضلي، التحكم المتقدم، جسر H، أنظمة التحكم في المحركات، التحكم الكلاسيكي، التحكم التكيفي.

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الكلمات المفتاحية: محركات التيار المستمر، طرق التحكم، المتحكم PID، التحكم المتقدم، القنطرة H، نظم المحركات، التحكم التقليدي، التحكم التكيفي.

1. Introduction

DC (Direct Current) motors constitute a foundational element in electromechanical systems due to their controllability, reliability, and structural simplicity. Their role is especially critical in applications where precise manipulation of speed, torque, or position is necessary, such as in automation, robotics, and embedded systems. However, to achieve consistent and optimized performance under real operational conditions, e.g. changes in load or input voltage variations, effective control strategies must be implemented. Consequently, understanding and revising control methodologies for DC motors are essential to enhancing both efficiency and system-level responsiveness.

The operation of DC motors is fundamentally governed by the interaction between magnetic fields generated by the armature and the field windings. Their dynamic behavior is significantly affected by parameters such as armature resistance, back electromotive force (EMF), and inductance. An effective control methodology is therefore required to regulate key performance variables, i.e. speed and torque. This is normally implemented by manipulating the applied voltage and/or current. Traditionally, both open-loop and closed-loop control systems have been employed for this purpose (Gupta, et al., 2017). However, with the growing demand for enhanced dynamic performance, more advanced control strategies have emerged, including Pulse Width Modulation (PWM), Proportional-Integral-Derivative (PID) control, fuzzy logic, and Model Predictive Control (MPC) (Rao & Saini 2016).

Conventionally, Pulse Width Modulation (PWM) is employed to regulate the average voltage delivered to the DC motor terminals. This method, while inherently straightforward, achieves a commendable balance between simplicity and efficiency, enabling effective speed control with minimal energy consumption (Babu, 2016). In contrast, more sophisticated control methodologies, such as Proportional-Integral-Derivative (PID) control, offer significantly greater precision by continuously adapting system inputs in response to real-time feedback, thereby ensuring that motor dynamics conform to stringent performance specifications

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even under varying operational disturbances in demand and load (Lee & Kim, 2019)

Moreover, techniques such as fuzzy logic control offers a highly effective approach for addressing the inherent nonlinearities and uncertainties commonly observed in DC motor systems. While adaptive control schemes, particularly, offer the advantage of real-time parameter tuning, allowing the system to respond intelligently to load and demand variations as well as motor characteristics alterations (Liu & Tsai, 2017).

The advent and progressive integration of Artificial Intelligence (AI) and Machine Learning (ML) algorithms have ushered in a new era of control strategies capable of autonomously enhancing motor performance. These intelligent systems facilitate adaptive optimization within complex and dynamic environments, reducing reliance on manual calibration and paving the way for self-regulating control architectures. Such innovations are poised to significantly extend the functional envelope of DC motor applications, especially in high-demand sectors such as robotics, electric mobility, and sustainable energy systems (Zhang & Xu, 2020).

This study overviews control methodologies employed in DC motor systems, encompassing both conventional approaches and modern techniques. It articulates the distinct advantages and limitations associated with each method, and offers informed perspectives on emerging research directions within this dynamic and rapidly advancing field.

1.1 Importance of DC Motor Control

DC motors control remains a critical aspect of modern systems, owing to their extensive deployment across industrial systems and technological applications. Both brushed and brushless variants are integral to systems where accurate speed, torque, and position regulation are essential. Achieving effective motor control is vital not only for reliable and stable system operation, but also for maximising energy efficiency and extending the operational lifespan of the motor. A thorough understanding of motor control principles is therefore indispensable for the design and optimisation of systems that depend on DC motor performance.

1.1.1 Precision in Speed and Torque Regulation

Accurate speed and torque regulation are central to effective DC motor control, particularly in applications demanding precise operation, such as robotics, automation, and electric vehicles. In

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robotic systems, accurate speed and torque control ensures reliable motion and task execution, while in electric vehicles, it has a direct impact on performance, range, and operational safety (Kose & Goknar, 2018) and (Lee & Kim, 2016).

1.1.2 Energy Efficiency

In the context of rising global energy demands, efficient motor operation has become increasingly vital. Conventional DC motors may suffer from energy dissipation when ineffectively operate under oscillatory load conditions. Advanced techniques, such as PWM devices and MPC, enhance efficiency by optimising voltage and current delivery. These approaches minimise energy waste and thermal dissipation, thereby supporting system sustainability, especially in energy-sensitive sectors such as electric vehicles, renewable energy, and industrial automation (Parker & Goh, 2019).

1.1.3 Load Adaptability and Stability

Maintaining stability under fluctuating load conditions remains a significant challenge in DC motor control. Closed-loop systems, which continuously adjust input based on feedback, offer a robust means of preserving consistent speed and torque. This is particularly essential in many industrial settings, for instance, conveyor systems and robotic arms, where load fluctuations can otherwise degrade performance. Effective load adaptation prevents overshoot and oscillation, thereby enhancing efficiency and reducing mechanical wear (Mota, & Garcia, 2017).

1.1.4 Minimization of Mechanical Wear and Tear

DC motors, especially brushed type, are disposed to wear over time. However, using effective control methods like PWM or PID can help in reducing the strain by limiting unnecessary high-speed operation, ultimately extending the motor's service life. When paired with sufficient control, both kinds of DC motors can operate with higher efficiency, smoother operation and less maintenance. In addition to higher durability and minimum machine stress (Tsai & Wu, 2019).

1.1.5 Cost-Effectiveness

Costs associated with DC motors can significantly be reduced by employing efficient control techniques. Control strategies, such PWM and adaptive control, would help in optimising power consumption by feeding motor with power more effectively and efficiently. In manufacturing environments, this translates directly into lower energy bills, improved reliability, and efficient production. Additionally, well implemented control strategies can

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prolong motor lifespan, minimizing maintenance and replacement expenses over time (Liu & Lin,2020).

1.1.6 Scalability in Complex Systems

In complex systems like robotics or automated manufacturing, DC motors often work together in coordinated motion. As these systems scale, control strategies must handle multiple motors efficiently. Techniques such as MPC and adaptive control offer the flexibility needed to manage large, distributed setups with precision (Martinez & Ruiz,2020).

1.1.7 Safety and Reliability

Reliable motor control is crucial in many applications where safety is critical; for instance, medical devices, aerospace systems, and automotive technologies. Advanced control methods help keeping motors operating within safe limits, protecting against issues like overheating, overloading, or excessive vibration and environment that could lead to system failure (Behrens & Ramos, 2015).

1.1.8 Integration with Modern Technologies

The growing adoption of technologies including Internet of Things (IoT) and Artificial Intelligence (AI) is reshaping the landscape of DC motor control. Their integration has enabled the development of intelligent control systems capable of real-time optimization, remote monitoring, and predictive maintenance. These advancements help in reducing unplanned downtime and improving system efficiency through out wide a range of applications (Goh & Choi, 2019).

2. Key Challenges in DC Motor Control

The utilisation of DC motors across broad applications, varying in complexity and functional demands, poses numerous technical challenges to control systems. Addressing these challenges is essential to achieve optimal performance, high reliability, and operational efficiency. Such difficulties stem from the intrinsic characteristics of DC motors, the variability in operating conditions, and the constraints of conventional control methodologies. This section delineates the principal challenges associated with the control of DC motors.

2.1 Nonlinear Dynamics of DC Motors

A major challenge in controlling DC motors stems from their inherently nonlinear dynamics, where the relationship between applied voltage and the resulting speed or torque is influenced by factors such as armature reaction, magnetic saturation, and load

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variations. Several physical phenomena contribute to the nonlinear behavior of DC motors, complicating the design of effective control strategies.

- **Back Electromotive Force (EMF)**: the voltage induced by the motor's rotation inherently opposes the applied voltage, introducing dynamic feedback that influences system behaviour.
- **Armature Resistance**: the resistance of the armature windings varies with temperature, thereby altering current flow and impacting performance consistency.
- **Magnetic Saturation**: at elevated current levels, the motor's magnetic field may enter saturation, distorting the linear relationship between power and torque.

These nonlinearities significantly hinder the development of controllers capable of maintaining accurate and stable operation under varying load and environmental conditions, particularly in high performance or precision dependent applications (Moreira & Almeida, 2008).

2.2 Parameter Variability and Uncertainty

The electrical parameters of DC motors, such as resistance, inductance, and back EMF, subjected to temporal variation due to factors including thermal effects, components ageing, and manufacturing tolerances. These fluctuations can lead to significant deviations in speed and torque output, as well as power efficiency. Moreover, external disturbances such as load variations and supply voltage fluctuations introduce additional uncertainty into system dynamics.

A central challenge lies in developing control strategies capable of compensating for these parameter variations without the need for continual recalibration. Techniques such as adaptive and robust control have been proposed to mitigate these issues; however, their implementation often entails increased algorithmic complexity and potential trade-offs between computational cost and system stability (Liu et al., 2014).

2.3 External Disturbances and Environmental Noise

DC motors are frequently exposed to external disturbances such as load fluctuations, mechanical vibrations, and electromagnetic interference (EMI), all of which can compromise system stability and control accuracy. For instance:

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- **Load variations** can cause deviations in motor speed, leading to trajectory tracking errors.
- **Electromagnetic noise** may disrupt sensor feedback, reducing the reliability of closed-loop control.

The design of controllers that capable of rejecting such disturbances while maintaining high performance is a significant challenge. Robust control strategies are commonly employed to reduce system sensitivity to these variations; however, their implementation often demands sophisticated algorithms and considerable computational effort (Park & Choi, 2016).

2.4 High-Speed Operation and Stability

Operating DC motors at elevated speeds introduces additional control and stability issues. At high rotational velocities, back EMF increases, complicating the regulation of speed and torque.

Mechanical resonance can emerge from interactions between motor inertia and structural dynamics, resulting in oscillations or instability.

Centrifugal forces may degrade mechanical integrity, particularly under extreme conditions.

Effective control under such conditions requires techniques that ensure system stability and suppress oscillatory behaviour. High-gain control, damping mechanisms, and model-based methods such as Model Predictive Control (MPC) are commonly employed. However, these approaches depend heavily on accurate dynamic models of the motor and the load (Mohan & Fernandes, 2020).

2.5 Complexity in Multi-Motor Coordination

Modern applications, for instance: robotics, electric vehicles, and automated manufacturing often involve multiple DC motors operating concurrently. When motors are coupled or synchronised, for example, in a robotic arm or a multi-wheel drive system, the control complexity increases substantially. Key challenges include:

- Motor synchronisation, ensuring coordinated operation in speed and torque.
- Decentralised control, which requires managing local control actions while accounting for inter-motor interactions.
- Load balancing, to distribute mechanical demands evenly and avoid overloading.

Addressing these issues involves the use of distributed control frameworks and coordination algorithms. Nevertheless, these

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solutions often entail complex mathematical formulations and demand substantial computational resources, which can limit their practicality in embedded or real-time systems (Brown & Sharma, 2019).

2.6 Control of Brushless DC (BLDC) Motors

While brushed DC motors are relatively simple to regulate, BLDC motors introduce unique challenges due to their reliance on electronic commutation. The absence of brushes enhances efficiency and longevity, but it necessitates advanced control strategies based on rotor position feedback. Typically acquired via hall sensors or inferred from back EMF. Major challenges include:

- Commutation control, requiring precise energisation sequences for smooth operation.
- Sensorless control, which aims to eliminate physical sensors while maintaining reliability and performance.
- Torque and speed regulation, often achieved through field-oriented control (FOC), a method that, although effective, is computationally intensive.

Despite these complexities, BLDC motors are increasingly preferred in high-efficiency and high-reliability applications (Low & Tan, 2019)

2.7 Operation in Variable Environmental Conditions

DC motors are frequently deployed in environments where temperature, humidity, and atmospheric pressure vary considerably. These environmental factors can significantly impact motor behaviour and control performance. For instance:

- Temperature fluctuations alter electrical resistance and inductance which reduce efficiency.
- High humidity can increase leakage currents and accelerate component degradation.
- Altitude-related changes in air density impair cooling, potentially leading to overheating.

Mitigating these effects requires the integration of temperature compensation algorithms, environmental sensing, and robust control mechanisms. However, these enhancements inevitably add to system complexity and design overhead (Zhuang et al., 2017).

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3. Types of DC motors

DC motors are widely utilised for numerous applications ranging from household appliances to industrial machinery. DC motors can be categorized in many ways. One category is based on the connection between the field winding and the armature (Nise, 2011). The major types include:

A) Separately Excited DC Motor

In a separately excited DC motor, the field winding is powered by an external source independent of the armature circuit. This configuration allows precise control of the motor speed and torque

Advantages: excellent speed control over a wide range; used in applications requiring precise speed regulation
Applications: industrial drives; electric propulsion systems

B) Self-Excited DC Motor

In self-excited motors, the field winding is connected to the armature circuit. These are subdivided into:

- **Shunt Wound DC Motor**: The field winding is connected in parallel (shunt) with the armature.

  Characteristics: Constant speed under varying loads; and moderate starting torque
  Applications: Lathes; Blowers; and Fans.

- **Series Wound DC Motor**: The field winding is in series with the armature.

  Characteristics: high starting torque; speed decreases as load increases.
  Applications: electric traction; cranes; and elevators.

- **Compound Wound DC Motor:**This motor combines both series and shunt field windings. It is further divided into:

  - **Cumulative compound motor**: Series and shunt windings assist each other.
  - **Differential compound motor**: Series winding opposes the shunt winding.

Applications: presses; conveyors; rolling mills.

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C) **Permanent Magnet DC Motor (PMDC):** There motors use permanent magnets to produce the field flux instead of field windings.

Advantages: simple and compact design; high efficiency at low loads

Disadvantages: limited field strength; demagnetization risk

Applications: toys; small appliances; and Automotive applications (e.g., windshield wipers, seat adjusters)

Table 1 represents a comparison between different types of motors. Each type of DC motor has unique characteristics that make it suitable for particular applications. Understanding their configuration and operational behavior is critical for selecting the right motor for a given task.

Table 1. Comparison table between different types of motors

Motor Type	Speed Control	Starting Torque	Applications
Separately Excited	Excellent	Moderate	Industrial drives
Shunt Wound	Good	Low	Fans, blowers, lathes
Series Wound	Poor	High	Cranes, elevators, traction
Compound Wound	Moderate	Moderate to High	Presses, conveyors
PMDC	Limited	Moderate	Toys, automotive devices

4. Mathematical modelling of DC motors

The mathematical modelling of DC motors entails formulating both the electrical and mechanical dynamic equations, which are subsequently expressed in Laplace domain or the state-space form. These models serve as the basis for the development of control strategies using classical techniques, including Proportional-Integral-Derivative (PID) controllers, root locus analysis, and frequency-domain methods. The specific form of the model depends on the motor configuration, with the most commonly studied types including:

- Separately excited DC motor (field excitation is independent of the armature).

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- Shunt DC motor (field winding connected in parallel with the armature).
- Series DC motor (field winding connected in series with the armature).

This explanation focuses on the separately excited DC motor, which is commonly used for control system design because it allows independent control of torque and flux.
The basic assumptions for modeling are as follows: the magnetic circuit is linear (no saturation); armature reaction is negligible; field flux is constant (due to separate excitation); the system is considered linear and time-invariant for classical control purposes.

4.1 Electrical Dynamics

i) Armature Circuit

Armature circuit is represented mathematically as follows:

$$V_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + e_b(t) \qquad (1)$$

Where:

$V_a(t)$ represents the applied armature voltage (V)

$i_a(t)$ denotes the armature current (A)

R_a is the armature resistance (Ω)

L_a refers to the armature inductance (H)

$e_b(t)$ represents the back electromotive force (EMF) (V)

ii) Back EMF

Back EMF can be represented mathematically as follows:

$$e_b(t) = K_e \omega(t) \qquad (2)$$

$$V_a(t) = R_a\, i_a(t) + L_a \frac{di_a(t)}{dt} + K_e \omega(t) \qquad (3)$$

Where:
K_e represents the back EMF constant (Vs/rad) and $\omega(t)$ is the angular speed of the motor (rad/s)

4.2 Mechanical Dynamics

Electromagnetic torque and Torque equations can be determined respectively as follows:

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$$T_m(t) = J\frac{d\omega(t)}{dt} + B\omega(t) \quad (4)$$

$$T_m(t) = K_t\, i_a(t) = J\frac{d\omega(t)}{dt} + B\omega(t) \quad (5)$$

Where:
$T_m(t)$ denotes the electromagnetic torque $(N \cdot m)$
J is the moment of inertia of the rotor $(kg \cdot m^2)$
B refers to the damping coefficient (viscous friction) $(N \cdot m \cdot s)$ $B\omega$ symbolises the angular velocity (rad/s)
K_t is the torque constant $(N \cdot m/A)$

4.3 Laplace Domain Representation

Taking Laplace transforms (assuming zero initial conditions) of equation 3 and 5, the electrical equation and mechanical equation respectively in s-domain, can be obtained as follows:

$$V_a(s) = R_a I_a(s) + L_a s\, I_a(s) + K_e \Omega(s) \quad (6)$$

$$K_t I_a(s) = Js\Omega(s) + B\Omega(s) \text{ and} I_a(s) = \frac{Js\Omega(s) + B\Omega(s)}{K_t} \quad (7)$$

4.4 Transfer Function Derivation

To obtain the transfer function based on the angular speed *Ω(s)* and the applied armature voltage *V_a(s)*, the mechanical equation (Equation 7) is substituted into the electrical equation (Equation 6), yielding:

$$V_a(s) = [R_a L_a s] I_a(s) + K_e \Omega(s)$$

$$V_a(s) = [R_a L_a s]\left(\frac{(Js+B)\Omega(s)}{K_t}\right) + K_e \Omega(s)$$

$$\frac{\Omega(s)}{V_a(s)} = \frac{K_t}{(L_a J)s^2 + (L_a B + R_a J)s + (R_a B + K_e K_t)}$$

This results a second order transfer function of the form represented by the following equation:

$$\frac{\Omega(s)}{V_a(s)} = \frac{K_t}{s^2 + a_1 s + a_o} \quad (8)$$

In many practical applications, the armature inductance L_a is sufficiently small to be neglected for the sake of simplification. Under this assumption, the transfer function relating the angular speed Ω(s) to the applied voltage $V_a(s)$ reduces to:

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$$\frac{\Omega(s)}{V_a(s)} = \frac{K}{\tau s + 1} \quad (9)$$

Where:

$$K = \frac{K_t}{R_a B + K_e K_t} \text{ and } \tau = \frac{R_a J}{R_a B + K_e K_t}$$

5. Classical techniques for DC motors control

Over the years, a range of control strategies has been developed for the DC motors regulation. Among the most widely adopted are classical control methodologies, including Proportional (P), Proportional-Integral (PI), and Proportional-Integral-Derivative (PID) controllers. These controllers are grounded in the principles of feedback control and utilise mathematical models of motor dynamics to achieve accurate regulation of speed or position.

Classical control approaches are valued for their simplicity, analytical transparency, and ease of implementation. Whether through analogue circuitry or digital platforms such as microcontrollers and programmable logic controllers (PLCs). Notably, when combined with pulse-width modulation (PWM) techniques, these controllers enable precise voltage control with improved energy efficiency in DC motor systems operation.

While modern control methods such as adaptive, fuzzy logic, and model predictive control have gained attention, classical control remains highly relevant. It continues to provide robust and cost-effective solutions, particularly in applications where system dynamics are well characterised and external disturbances are minimal (Ogata, 2010).

5.1 Open-loop control does not use feedback from the motor. Instead, it sends a predetermined voltage or current to the motor.

- **Advantages** include**,** simple implementation; and low cost.
- **Disadvantages** mainly include, no correction for disturbances or load variations, poor accuracy and stability.
- **Applications**, situations where precise control is not critical (e.g., toy motors, basic fans).

5.2 Closed-Loop Control (Feedback Control)

In a closed-loop control system, the actual output (speed, position, etc.) is measured and compared with the desired set-point. The error

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signal is used to adjust the input to the motor, improving performance and accuracy.

5.3 Overview of Classical Control Techniques

5.3.1 Proportional (P) Control

The proportional controller generates a control signal proportional to the error between the reference and the output. Although simple and easy to implement, a P controller generally cannot eliminate the steady state error and may result in high overshoot if not tuned properly (Nise, 2011)

5.3.2 Proportional-Integral (PI) Control

The addition of the integral term addresses the limitation of the P controller by accumulating the error over time. Thus it eliminats steady-state error. PI controllers are especially effective for speed control applications. PI controllers are widely implemented in industrial systems due to balance they provide between performance and simplicity (Gopal, 2002).

5.3.3 Proportional-Integral-Derivative (PID) Control

The PID controller adds a derivative term to improve transient response of the system. It predicts the future error trends and offers better performance. However, when deploying the derivative term appropriate filtering mechanisms may be required as to avoid oscillations my generated due to load or demand fluctuations. PID control is commonly applied in position control, robotics, and servo systems which utilize DC motors (Franklin et al., 2014)

5.3.4 Pulse-Width Modulation (PWM)

Pulse width modulation (PWM) is mostly combined with classical controllers to regulate the motor’s supply parameters. By rapidly switching the voltage on and off at high frequencies, PWM precisely controls the average power delivered to the motor. This technique is recognized for its energy efficiency and suitability for implementation on modern microcontrollers. Hence, it particularly favorable in embedded control systems. When integrated with PI or PID controllers, PWM enables smooth, precise, and stable DC motors control (Rashid, 2013).

Numerous studies have explored the implementation and performance of classical control strategies for DC motor regulation, both in simulation environments and practical, real world applications.

Hassan et al. (2017) conducted a comparative study of PID tuning methods such as Ziegler–Nichols and Cohen–Coon. They applied the PID controller to DC motor speed control and found that each

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tuning method had trade-offs in overshoot, settling time, and steady-state error, reinforcing the importance of proper tuning in classical control [30].

Faroqi et al. (2018) implemented a PID controller together with PWM on an Arduino Uno board for real-time DC motor speed control. The system achieved satisfactory performance with acceptable performance, demonstrating the feasibility of using classical controllers with modern technology.

Das and Biswas, (2020) compared traditional PID and Genetic Algorithm (GA) optimized PID controllers for a brushless DC motor (BLDC). While the GA-tuned controller offered improved performance, the classical PID controller also demonstrated good robustness and stability under varying load conditions.

Shneen et al. (2023) developed a PI controller-based DC–DC converter for DC motor speed control in MATLAB/Simulink. The system responded effectively to speed changes, confirming the practical value of PI control in power electronic interfacing.

Al-Bargothi et al. (2019) investigated the performance of fixed-gain PID and adaptive PID controllers incorporating Recursive Least Squares (RLS) adaptation. While the adaptive PID controller demonstrated enhanced disturbance rejection capabilities, the classical PID controller maintained reliable performance under nominal conditions, thereby affirming its suitability for systems with well-defined and predictable dynamics.

These studies highlight that, despite advances in adaptive control, classical controllers remain widely preferred for their simplicity, ease of tuning, and reliable performance across diverse operating conditions. Table 2 provides a comparative overview of various classical controller types.

Table 2: Comparative Analysis of Classical Controllers

Controller type	Strengths	Limitations
P	Fast response, simple design	Cannot eliminate steady-state error
PI	Eliminates steady-state error, good for speed control	Slower transient response, possible overshoot
PID	Excellent transient and steady-state performance	More complex to tune, noise sensitivity
PWM Integration	Digital-friendly, efficient, precise voltage control	Requires high switching frequency, nonlinear behavior at low duty cycles

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5.3.5 H-Bridge Circuit

The H-bridge circuit is a fundamental element in DC motor control, enabling bidirectional rotation and facilitating effective regulation of speed and torque. Its designation arises from the typical schematic configuration, which resembles the letter 'H'. Owing to its versatility, simplicity, and compatibility with both analogue and digital control systems, the H-bridge is widely employed in robotics, automation, electric vehicles, and various mechatronic applications. A single H-bridge component typically comprises four power switches, commonly MOSFETs, BJTs, or IGBTs, arranged such that activating complementary pairs permits current flow in either direction across the motor terminals. This bidirectional current flow is crucial for achieving both forward and reverse motor operation. Incorporating PWM into the switching control allows for precise adjustment of motor speed and torque.

As noted by Rashid (2013), the H-bridge is a standard topology in motor drive systems, offering comprehensive control over motor direction and speed through modulation of the applied voltage's duty cycle via PWM.

Numerous studies discovered the advantages of H-bridge drivers in: bidirectional control; PWM compatibility; compact design; suitability for embedded systems and cost effective and low cost IC availability. For instance, Renesas (2021) emphasized the significance of H-bridge integration in low voltage, high current motor control applications, highlighting their efficiency in reducing power losses and simplifying circuit layout in compact system designs.

5.3.6 H-Bridge in Practical Control Systems

- **Embedded Implementation**

Faroqi et al. (2018) implemented a PID controller within an Arduino-based speed control system, utilizing an L298N H-bridge motor driver. The configuration enabled smooth regulation of both speed and direction, demonstrating the effectiveness of H-bridge modules in real-time embedded motor control applications.

- **High-Efficiency and Protection Features**

Garg and Singh (2019) developed an enhanced H-bridge circuit incorporating flyback diodes, thermal shutdown, and short-circuit protection. Their findings indicated that the inclusion of integrated protection features significantly improved reliability and reduced failure rates in demanding industrial environments.

- **Motor Drive ICs**

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Integrated H-bridge driver ICs, such as the L293D, L298, and DRV8871, are widely employed in educational and prototyping contexts. According to Texas Instruments (2020), the DRV88xx series offers superior thermal efficiency and built-in protection mechanisms compared to earlier bipolar transistor-based H-bridge solutions.

5.3.7 H-Bridge Control with PWM

PWM is commonly employed with H-bridge circuits to regulate the effective voltage supplied to the motor. By varying the PWM duty cycle, motor speed can be adjusted without changing the input voltage.

Shneen et al. (2023) modelled a PI-controlled, PWM-fed DC-DC converter driving a motor through an H-bridge. The study demonstrated that the H-bridge enabled reliable bidirectional control, while the controller ensured stability under varying load conditions.

Table 3 presents a comparative analysis of H-bridge driver applications.

Table 3. Comparative analysis of H-Bridge driver applications

Type	Controller used	H-bridge role	Key outcome
Arduino-based robot	PID + PWM	Direction/speed control via L298N	Smooth motor control with low overshoot (Faroqi et al., 2018)
Industrial motor driver	Discrete Logic	H-bridge with protection and feedback	Improved thermal and short-circuit safety (Garg and Singh, 2019)
Simulated model	PI + PWM	DC motor bidirectional control	Effective speed regulation under load (Shneen et al., 2023)
Commercial motor IC	Built-in logic	Integrated H-bridge driver	Compact and efficient motor driver (Texas Instruments, 2020)

The literature consistently affirms the essential role of H-bridge circuits in DC motor control across both academic research and industrial applications. When combined with PWM and classical controllers, their performance is significantly enhanced. Specifically, in systems requiring precise speed and directional control. The availability of integrated H-bridge driver ICs has further simplified system development. However, to ensure reliable and efficient operation, careful consideration must still be given to

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switching methods, protection mechanisms, and thermal management.

6. Advanced Control Techniques for DC Motor Regulation

Although classical control methods, such as PID controllers, are widely adopted due to their advantages, yet they often prove inadequate in applications characterised by nonlinear dynamics, parameter uncertainties, external disturbances, and stringent performance demands. With growing integration of DC motors into advanced systems, such as robotic actuators, electric vehicles, aerospace platforms, and high-precision manufacturing, there is an increasing demand for more sophisticated control strategies that offer enhanced robustness, adaptability, and dynamic performance.

Advanced control strategies extend beyond linear feedback by incorporating real-time adaptation, machine intelligence, robust optimization, and predictive behaviour. These methods are particularly beneficial when:

- The motor parameters change over time, e.g., due to temperature or wear.
- The system is subjected to unmodeled dynamics or nonlinearities.
- External disturbances are unpredictable or time-varying.

6.1 Adaptive Control

Adaptive control adjusts controller parameters in real-time based on system behaviour, making it suitable for systems with uncertain or time-varying dynamics.
Adaptive control adjusts controller parameters in real-time based on system behaviour, making it suitable for systems with uncertain or time-varying dynamics.
Kumar and Singh, (2017) proposed a Model Reference Adaptive Control (MRAC) system for a DC motor that adjusted gains dynamically to match a desired model. The system achieved better robustness compared to fixed-gain PID controllers, especially under varying load conditions
Al-Bargothi et al., (2019) used a Recursive Least Squares (RLS)-based adaptive PID controller for speed control of DC motors. Their results showed faster convergence and better disturbance rejection compared to conventional PID systems.

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6.2 Fuzzy Logic Control (FLC)

Fuzzy logic controllers use linguistic rules to mimic human reasoning, making them highly effective in systems where precise modelling is difficult.

Kumbhar and Kulkarni (2016) developed a fuzzy logic-based controller for DC motor speed regulation. The controller was able to maintain speed under load variations better than a traditional PI controller and did not require a mathematical model of the system.

Khan and Iqbal (2019) compared PI and fuzzy controllers in real-time using Arduino-based hardware. The fuzzy controller showed reduced overshoot and improved stability in load transient conditions.

6.3 Neural Network-Based Control

Artificial Neural Networks (ANNs) learn from data and approximate complex nonlinear functions, making them ideal for real-time DC motor control without relying on exact plant models.

Ghazal and Abu-Rub (2015) designed a backpropagation ANN controller for speed regulation of a separately excited DC motor. The system demonstrated superior adaptability to parameter variation and nonlinear disturbances compared to PID.

Chen et al. (2020) implemented a hybrid neural-PID controller that adjusted PID parameters in real time using neural networks. This reduced tuning complexity and improved performance across a range of operating points.

6.4 Sliding Mode Control (SMC)

SMC is a robust nonlinear control method that forces the system trajectory to "slide" along a predefined surface, offering strong resistance to disturbances and parameter variations.

Rahman and Askar (2018) used a second-order sliding mode controller for speed control of a DC motor under variable loads. Compared to PI and fuzzy controllers, the SMC exhibited faster response and better robustness.

However, SMC can introduce a phenomenon called chattering, which may excite high-frequency dynamics or cause mechanical wear. Researchers like Utkin et al. (2017) have proposed higher-order SMC and boundary layer techniques to mitigate this issue.

6.5 Model Predictive Control (MPC)

MPC uses a model of the system to predict future outputs and optimize control actions over a moving time horizon. It is well-suited to multivariable systems with constraints.

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Kottayil et al. (2020) applied MPC to a DC motor drive and found it offered faster convergence and reduced control effort compared to PID, particularly when operating under input saturation and load changes. Although MPC provides excellent performance, it is computationally intensive and may not be ideal for low-cost, real-time applications unless implemented on capable hardware (e.g. FPGAs, DSPs). Summary comparative literature is tabulated in table 4.

Table 4:Comparative Literature Summary

Control method	Key benefits	Challenges	Typical application
Adaptive Control	Real-time tuning, robust to parameter variation	Complex design and stability analysis	Electric vehicles, aging systems
Fuzzy Logic Control	No need for precise models, robust to noise	Rule tuning is heuristic; lacks formal stability	HVAC systems, robotics
Neural Network Control	Learns nonlinear mappings, model-free	Requires training data, computational overhead	Prosthetics, autonomous vehicles
Sliding Mode Control	Strong disturbance rejection, fast response	Chattering issues, discontinuous control signal	Servo drives, military actuators
Model Predictive Control	Handles constraints, optimal multivariable control	High computational cost, needs accurate model	Industrial drives, power systems

The literature confirms that advanced control methodologies offer noticeable performance and improvements over classical approaches; particularly in applications involving nonlinearities, uncertainties, or high precision. While each method entails trade-offs, such as increased complexity, computational requirements, or implementation difficulty, their careful selection can greatly enhance the entire system performance.

Emerging research increasingly focuses on hybrid control strategies (e.g., fuzzy-PID, neural-fuzzy, adaptive-SMC), which seek to integrate the strengths of multiple techniques. These approaches aim to combine the simplicity and familiarity of classical control with the adaptability and accuracy of modern intelligent algorithms.

7. CONCLUSION

This study has reviewed a range of control strategies for DC motor

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regulation, from classical approaches such as P, PI, and PID, often combined with PWM, to more advanced methods including adaptive, fuzzy logic, neural networks, sliding mode, and model predictive control. Classical controllers remain widely used due to their simplicity, ease of tuning, and proven effectiveness in systems with well-understood, linear dynamics. However, their limitations become apparent in environments with nonlinearities, uncertainties, or time-varying parameters.

To overcome these challenges, advanced control techniques offer improved robustness, adaptability, and precision. Particularly in high-performance or dynamic applications. While such methods entail greater computational and implementation complexity, their benefits in accuracy, disturbance rejection, and real-time responsiveness are increasingly valued.

In conclusion, the choice of control strategy should be guided by the specific application requirements. Classical methods continue to serve reliably in many industrial and embedded systems. Whereas advanced and hybrid approaches are better suited to modern, adaptive, and high-precision applications.

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