

Universal Motors in Modern Electromechanical Systems: A Comprehensive Review of Performance, Efficiency, Control, and Industrial Relevance

Ahmed A. Abd Eltwab^{a,*}

^a Department of Mechatronics Engineering, Faculty of Engineering, Mansoura University, Mansoura, Egypt.

Keywords:

Universal motor
Electromechanical Systems
Performance Analysis
Efficiency
Motor Control
Power Applications

ABSTRACT

Universal motors have long been recognized as a practical and versatile class of electric machines, particularly in low- and medium-power applications requiring high starting torque, compact size, and operational flexibility. Their capability to operate on both alternating current (AC) and direct current (DC) supplies distinguishes them from most conventional motor types and has contributed to their extensive deployment in domestic appliances and portable industrial equipment. Despite these advantages, universal motors face increasing challenges related to efficiency, acoustic noise, electromagnetic interference, and maintenance requirements in modern electromechanical systems. This review presents a comprehensive and critical analysis of universal motors from a system-level perspective. The paper synthesizes existing literature to examine operating principles, design aspects, performance characteristics, efficiency limitations, control strategies, and industrial relevance. A structured review methodology is employed to identify current challenges, comparative advantages, and research gaps. The aim is to provide a consolidated reference for researchers and practitioners while outlining future research directions that may enhance performance and extend applicability.

* Corresponding author:

Ahmed A. Abd Eltwab 
E-mail:
hihamadaali2001@gmail.com

Received: 01.12.2025.

Revised: 15.01.2026.

Accepted: 26.01.2026.



© 2026 Journal of Management and Engineering Sciences

1. INTRODUCTION

Electric motors are fundamental components of modern electromechanical systems, enabling the conversion of electrical energy into mechanical motion across a wide range of industrial, commercial, and domestic applications. Their importance has grown steadily with the expansion of automation, electrification, and

smart technologies, making motor performance, efficiency, and reliability central concerns in contemporary engineering practice [1,2].

1.1 Background and Motivation

The rapid growth of electrically driven systems has intensified the demand for motors that balance performance, cost, and efficiency. While

significant research attention has been directed toward high-efficiency motor technologies such as induction motors, permanent magnet machines, and brushless DC motors [2], traditional motor types continue to play a vital role in many applications. Among these, the universal motor represents a unique and historically significant solution [3,4].

Universal motors originated from the series-wound direct current motor and were adapted to operate on alternating current supplies through appropriate magnetic core lamination and winding design [5,6]. This dual-supply capability, combined with high starting torque and compact construction, enabled widespread adoption in household appliances and portable power tools [7,8].

In recent studies, finite element analysis has been increasingly employed to investigate the electromagnetic behavior of universal motors, enabling detailed evaluation of flux distribution, losses, and structural parameters, particularly in motors analyzed through reverse engineering approaches [9].

Moreover, advances in motor control methodologies, including fuzzy logic, sliding mode control, and PID-based strategies, have been extensively investigated in the broader context of electric motor speed regulation, providing valuable benchmarks for evaluating universal motor control performance [10,11].

Despite their long history, universal motors remain relevant in applications where intermittent duty cycles, high speed, and low initial cost are prioritized [12,13]. However, the increasing emphasis on energy efficiency regulations, noise reduction, and electromagnetic compatibility has raised questions regarding the suitability of universal motors in modern systems [14,15]. These challenges motivate a renewed examination of their performance characteristics and limitations within contemporary electromechanical contexts.

1.2 Role of Universal Motors in Electromechanical Systems

Within modern electromechanical systems, motor selection is influenced not only by torque and speed requirements but also by system-level

considerations such as power quality, control complexity, thermal behavior, and lifecycle cost [16,17]. Universal motors occupy a distinct niche in this landscape due to their ability to deliver high torque at startup and operate over a wide speed range without sophisticated control hardware [18,19].

In many portable and consumer applications, universal motors are integrated into systems where simplicity and cost-effectiveness outweigh the benefits of higher efficiency alternatives [20,21]. Their compatibility with both AC and DC supplies also provides flexibility in system design, particularly in regions with diverse power infrastructures or in applications involving rectified supplies [13,22].

At the same time, the integration of universal motors into modern systems often necessitates additional measures to address inherent drawbacks, including acoustic noise, brush wear, and electromagnetic interference [23,24]. These system-level interactions highlight the importance of evaluating universal motors not as isolated components but as integral elements within complete electromechanical assemblies [25].

1.3 Objectives and Organization of the Review

The primary objective of this review is to provide a comprehensive and critical assessment of universal motors in the context of modern electromechanical systems. The paper seeks to synthesize existing knowledge on operating principles, design aspects, performance characteristics, efficiency limitations, control strategies, and industrial applications [6,12].

In addition to consolidating existing research, this review aims to identify key limitations and research gaps that constrain the wider adoption of universal motors, particularly in light of modern efficiency and sustainability requirements [3, 26]. By adopting a system-level perspective, the paper also explores how advancements in materials, power electronics, and control techniques may influence the future role of universal motors [14,27].

2. SCOPE AND CONTRIBUTIONS OF THE REVIEW

2.1 Scope of the Review

Universal motors are widely employed in low- and medium-power applications due to their ability to deliver high starting torque, compact size, and high-speed operation [8,28]. This review focuses on the following aspects:

- **Performance Analysis:** Examination of torque-speed characteristics, efficiency, energy losses, and thermal behavior under varying operating conditions [7,12].
- **Design Aspects:** Analysis of rotor and stator design, commutator and brushes, materials, and manufacturing considerations affecting motor reliability and lifespan [24,29].
- **Control Strategies:** Review of speed control techniques, electronic control, and integration with modern drive systems [18,25,30].
- **Industrial and Domestic Applications:** Evaluation of universal motor usage in household appliances, portable power tools, and small-scale industrial machinery [4,19].
- **Contemporary Challenges:** Addressing limitations such as low efficiency, acoustic noise, maintenance issues, electromagnetic interference, and cost constraints [3,23]

Fig. 1 shows a schematic diagram showing the positioning of universal motors relative to other motor types in terms of power, speed, and application domains.

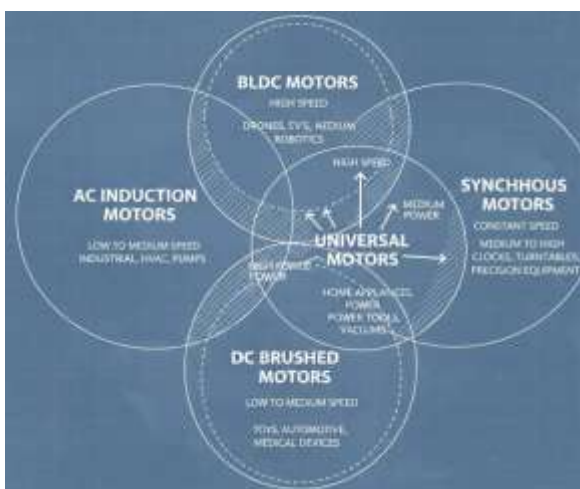


Fig. 1. A schematic diagram showing the positioning of universal motors.

2.2 Key Contributions

- Provides a comprehensive review combining theoretical fundamentals (operating principles, electromechanical analysis) with practical considerations (performance, applications, and control).
- Highlights current limitations, including noise generation, energy losses, brush wear, and their impact on motor lifespan and operational efficiency.
- Identifies research gaps that warrant future investigation, such as the development of new materials, advanced cooling techniques, and intelligent speed control methods.
- Suggests future research directions aimed at improving universal motor performance, efficiency, and adaptability to modern electromechanical systems while complying with energy regulations.

3. LITERATURE REVIEW

3.1 Literature Search Strategy

The literature for this review was collected from multiple reputable databases, including IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar. The search focused on publications from the last 15 years, emphasizing modern applications, control techniques, and efficiency analysis of universal motors.

Key search keywords included:

- "Universal motor performance",
- "Universal motor efficiency",
- "Universal motor control strategies",
- "Industrial applications of universal motors",
- "Electromechanical systems with universal motors".

To ensure completeness, references cited in the identified papers were also reviewed, following a snowballing approach to capture additional relevant studies.

3.2 Inclusion and Exclusion Criteria

The selection of relevant literature followed clear inclusion and exclusion criteria.

Inclusion Criteria:

- Studies directly addressing universal motor performance, design, or control.

- Papers analyzing both AC and DC operation of universal motors.
- Experimental, numerical, and simulation-based studies.
- Publications in peer-reviewed journals, conference proceedings, and reputable books.
- Categorization: Studies were classified based on topics, including operating principles, design, performance, control strategies, and applications.
- Synthesis: Findings from experimental, analytical, and simulation studies were synthesized to identify common trends, performance benchmarks, and critical design parameters.

Exclusion Criteria:

- Studies unrelated to universal motors or their practical applications.
- Outdated articles without contemporary relevance or technological context.
- Non-English publications due to language accessibility limitations.
- Critical Evaluation: Limitations, assumptions, and gaps in the literature were assessed to provide insights into unresolved challenges and potential future research directions.
- Integration: Data from different studies were combined to generate tables, charts, and comparative diagrams, which provide visual clarity and facilitate a holistic understanding of universal motor performance in modern systems.

This approach ensures that the review covers high-quality, relevant, and recent literature to provide a solid basis for analysis.

3.3 Data Analysis Approach

The collected literature was analyzed using a systematic comparative approach:

Table 1 summarizing torque-speed characteristics, efficiency ranges, and control strategies for universal motors versus other motor types.

Table1. Comparative Table of Motor Types.

Motor Type	Torque-Speed Characteristics	Efficiency Range	Control Strategy	Typical Applications
Universal Motor	Very high starting torque; speed increases sharply at light load; very high no-load speed	50% - 70%	Voltage control using TRIAC or PWM	Power tools, mixers, vacuum cleaners
DC Motor (Brushed)	Nearly linear torque-speed relation; speed decreases with increasing load	70% - 85%	Voltage variation or PWM control	Conveyors, small drives
Induction Motor	Nearly constant speed; torque depends on slip	75% - 95%	Variable Frequency Drive (V/f or vector control)	Pumps, fans, industrial machines
BLDC Motor	Constant speed over wide load range; high torque at low speed	85% - 95%	Electronic commutation (sensor or sensorless)	EVs, drones, robotics
Synchronous Motor	Constant speed independent of load (up to pull-out torque)	90% - 97%	Field-Oriented Control (FOC)	Precision drives, power plants
Stepper Motor	High torque at low speed; torque drops rapidly at high speed	60% - 80%	Step pulse control and microstepping	CNC machines, printers

4. HISTORICAL EVOLUTION OF UNIVERSAL MOTORS

Universal motors have a rich historical background, evolving from early DC motor designs to versatile machines capable of operating on both AC and DC supplies. Understanding their development provides insight into their design principles, performance characteristics, and relevance in modern electromechanical systems.

4.1 Early Developments

- Universal motors originated from series-wound direct current (DC) motors, developed in the late 19th and early 20th centuries.
- Early DC motors were primarily used in industrial applications requiring high torque at low speeds, such as hoists, cranes, and machine tools.

- With the proliferation of alternating current (AC) power networks, engineers adapted DC motor designs for AC operation by incorporating laminated cores to reduce eddy current losses and modifying winding configurations.

Fig. 2 shows diagram showing the transition from a basic series DC motor to an early universal motor with laminated core.

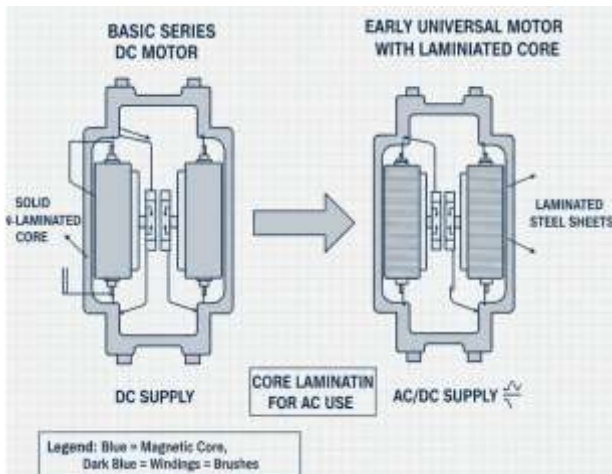


Fig. 2. Evolution to the early universal motor.

4.2 Technological Milestones

- Brush and Commutator Innovations: Early motors relied on simple carbon brushes, but improvements in brush materials and commutator design enhanced durability and reduced maintenance.
- High-Speed Capability: The compact design and series winding allowed universal motors to operate at very high speeds, making them suitable for portable power tools and household appliances.
- Miniaturization and Cost Reduction: Advances in manufacturing and material sciences enabled smaller, lighter, and more cost-effective designs without compromising performance.

Example: The introduction of carbon brushes in the 1920s significantly improved lifespan and reduced friction losses, enabling broader industrial adoption. As shown in Fig. 3.

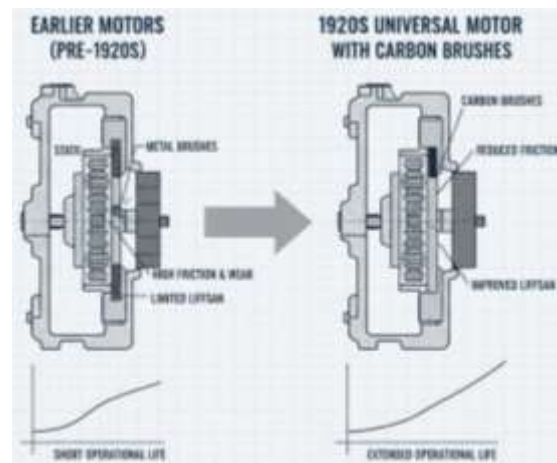


Fig. 3. Innovations of the 1920s: carbon brushes.

4.3 Modern Trends

- Portable Tools and Appliances: Modern universal motors are widely used in vacuum cleaners, drills, blenders, and hairdryers, where high speed and lightweight construction are essential.
- Integration with Electronics: The use of electronic speed controllers and pulse-width modulation (PWM) has enhanced operational flexibility, efficiency, and noise reduction.
- Environmental and Regulatory Influence: Modern trends focus on reducing energy consumption, noise, and electromagnetic interference (EMI) to meet current environmental and safety regulations.
- Material Innovations: High-grade laminations, advanced insulation, and improved brush materials contribute to longer lifespan, better thermal management, and higher efficiency.

Fig. 4 shows timeline showing key historical milestones, from early DC motors to modern universal motors with electronic control.

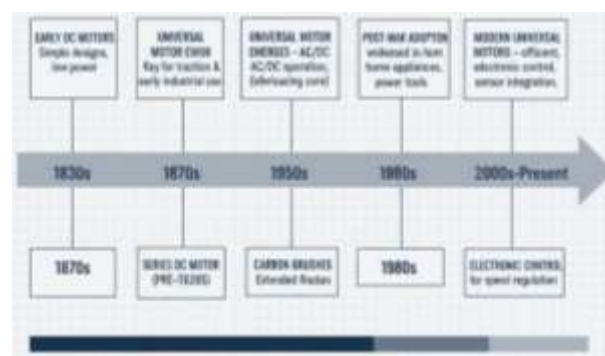


Fig. 4. Evolution of the universal motor.

4.4 Relevance to Contemporary Electromechanical Systems

- Despite the rise of brushless DC motors (BLDC) and induction motors, universal motors remain relevant in applications prioritizing high torque, compact size, and low initial cost.
- Their ability to operate on both AC and DC sources provides design flexibility, particularly in regions with varying power supply standards or in devices using rectified AC power.
- Understanding their historical evolution helps researchers identify design constraints, potential improvements, and areas for innovation in modern systems

5. FUNDAMENTAL OPERATING PRINCIPLES

Universal motors are a class of series-wound electric motors capable of operating on both alternating current (AC) and direct current (DC). Their operating principles combine electrical, magnetic, and mechanical phenomena, which enable high starting torque, wide speed ranges, and compact design. Understanding these principles is crucial for analyzing performance, control strategies, and industrial applications.

5.1 Basic Working Mechanism

- Universal motors operate on the interaction between the magnetic field generated by the stator (field winding) and the current flowing through the rotor (armature winding).
- In series configuration, the field winding is connected in series with the armature, ensuring that the field strength varies with the armature current.
- The generated torque is proportional to the square of the armature current at startup, providing high initial torque suitable for applications such as drills and blenders.
- When connected to AC, both the field and armature currents reverse simultaneously, maintaining the direction of torque, allowing the motor to operate seamlessly on AC supplies.

Fig. 5 shows schematic showing current flow in stator and rotor, and the resulting torque generation.

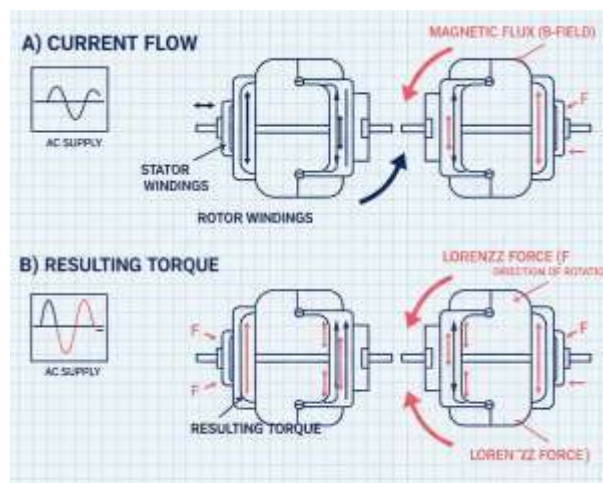


Fig. 5. Universal motor current flow and torque generation.

5.2 Electrical Principles

- Series Winding Behavior: The series connection of field and armature leads to a strong dependence of torque on current, especially at low speeds.
- Voltage and Current Characteristics:
 - At startup, low back electromotive force (EMF) allows high current to flow, producing high torque.
 - As speed increases, back EMF rises, reducing current and torque.
- AC Operation Considerations:
 - Eddy currents in the iron core are minimized using laminated cores.
 - Reactance due to inductive windings slightly reduces current compared to DC operation but does not significantly affect torque generation.
- Power Input and Losses: Input electrical power is distributed among mechanical output, copper losses (armature and field), core losses, brush losses, and frictional losses.

5.3 Magnetic Principles

- The interaction between the stator magnetic field and rotor armature current produces the rotational force (torque).
- Magnetic flux in the core is designed to avoid saturation while maximizing efficiency.
- Core design, lamination thickness, and material choice significantly affect magnetic losses, heat generation, and overall performance.

- Torque generation formula (simplified): $T \propto \phi \cdot I_a$. Where ϕ is the magnetic flux and I_a is the armature current.

5.4 Mechanical Principles

- The motor converts electrical energy into rotational mechanical energy, with torque transmitted to a shaft.
- Rotor speed depends on the balance between applied voltage, back EMF, load torque, and internal losses.
- Universal motors are capable of extremely high speeds (up to 20,000 rpm) in lightweight applications, which makes mechanical balancing, bearing selection, and vibration control critical.
- Friction in brushes and bearings, as well as mechanical wear, affects efficiency and lifespan.

5.5 Key Characteristics Derived from Operating Principles

- High Starting Torque: Resulting from series winding and low initial back EMF.
- Wide Speed Range: Capable of very high speeds under low-load conditions.
- AC/DC Versatility: Both AC and DC operation possible without reversing torque direction.
- Load Sensitivity: Speed varies significantly with applied load due to series connection.
- Maintenance Requirements: Brush wear and commutator friction necessitate regular inspection.

Fig. 6 shows torque-speed curve showing high starting torque and variable speed under load.

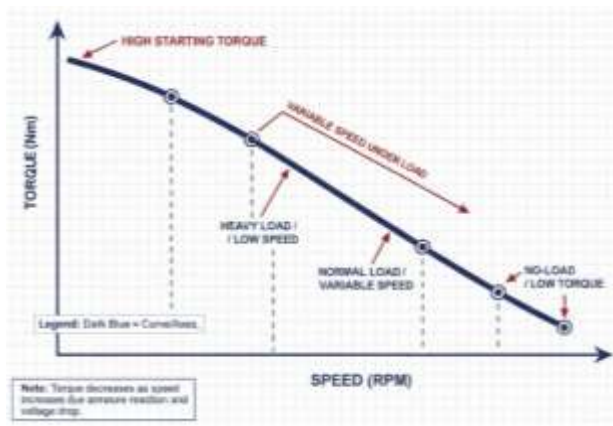


Fig. 6. Torque speed characteristics.

6. CONSTRUCTION AND DESIGN ASPECTS

The construction of universal motors is a critical factor influencing performance, efficiency, reliability, and lifespan. Their design integrates electrical, magnetic, and mechanical components optimized for compactness, high-speed operation, and dual AC/DC supply compatibility. This section explores the main components and design considerations in detail.

6.1 Stator Design

- The stator provides the magnetic field necessary for torque generation.
- It typically consists of:
 - Field Windings: Series-connected with the armature to produce the required magnetic flux.
 - Core Laminations: Thin steel laminations are stacked to reduce eddy current losses during AC operation.
- Design considerations:
 - Number of turns and wire gauge affect magnetic flux density and current handling.
 - Core geometry and slot design impact magnetic efficiency, heat dissipation, and torque ripple.

Fig. 7 shows diagram of stator core with laminated sheets and field windings.

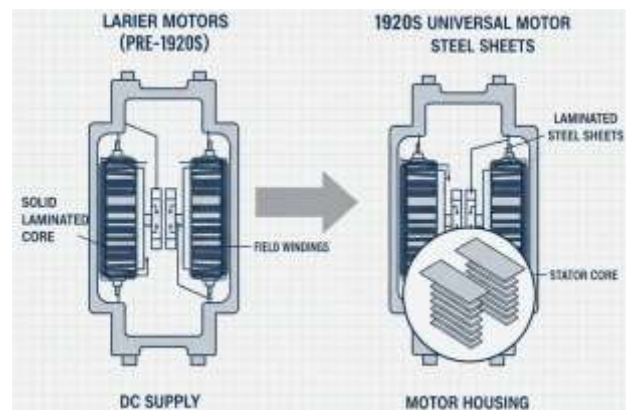


Fig. 7. Universal motor: laminated stator core.

6.2 Rotor (Armature) Design

- The rotor (armature) carries current through windings and interacts with the stator magnetic field to produce torque.

- Components:
 - Armature Windings: Usually copper coils, carefully insulated to withstand voltage and thermal stress.
 - Core Laminations: Reduce eddy current losses and maintain magnetic flux efficiency.
 - Shaft: Transfers mechanical power to the load; requires high mechanical strength for high-speed operation.
- Design challenges:
 - Minimizing rotor mass to allow high rotational speed while maintaining structural integrity.
 - Optimizing winding arrangement for uniform torque and minimal losses.

6.3 Brushes and Commutator

- Brushes: Typically carbon or graphite; maintain electrical contact with the commutator while minimizing friction.
- Commutator: Segmented copper cylinder that ensures proper current direction in armature windings.
- Design considerations:
 - Brush material affects wear rate, electrical contact resistance, and noise.
 - Commutator segmentation affects torque smoothness, arcing, and maintenance intervals.
- Operational implications:
 - Brush wear and friction are major sources of maintenance and efficiency loss.
 - Proper alignment and spring tension are essential for consistent performance.

Fig. 8 shows close-up diagram of brush-commutator assembly showing current flow.

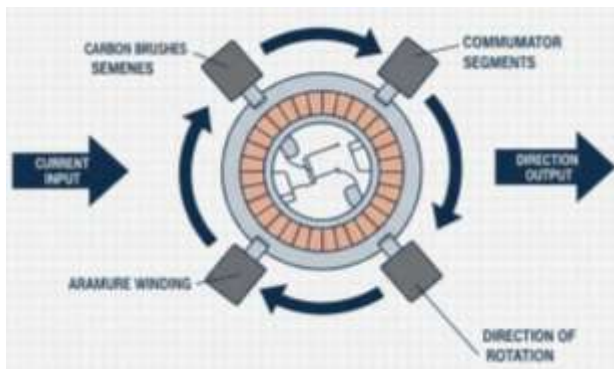


Fig. 8. Universal motor brush commutator assembly.

6.4 Materials and Manufacturing Considerations

- Core Materials: Silicon steel laminations for high magnetic permeability and low hysteresis loss.
- Winding Materials: High-purity copper for minimal resistance and improved thermal performance.
- Insulation: High-temperature-resistant varnish or enamel to prevent short circuits and improve reliability.
- Housing and Bearings: Lightweight metals or composites for high-speed operation; precision bearings to reduce vibration and noise.
- Thermal Management: Ventilation slots and cooling fans are often incorporated in high-speed designs to prevent overheating.

6.5 Compactness and Weight Optimization

- Universal motors are frequently used in portable devices; hence, design prioritizes compactness and weight reduction.
- Trade-offs:
 - Reducing size may increase thermal stress and mechanical vibration.
 - Optimal design balances torque output, speed, and durability.

6.6 Design Challenges and Considerations

- High-Speed Operation: Requires robust rotor, precise balancing, and minimal mechanical losses.
- Dual AC/DC Compatibility: Laminated cores and winding arrangements must minimize eddy currents and maintain efficiency under both supplies.
- Maintenance: Brush and commutator wear remain a limiting factor for long-term operation.
- Noise and Vibration: Design improvements aim to reduce acoustic noise and mechanical resonance.
- Energy Efficiency: Material selection and winding optimization are key to minimizing copper and core losses.

Fig. 9 shows exploded view of a universal motor showing stator, rotor, brushes, commutator, bearings, and housing.

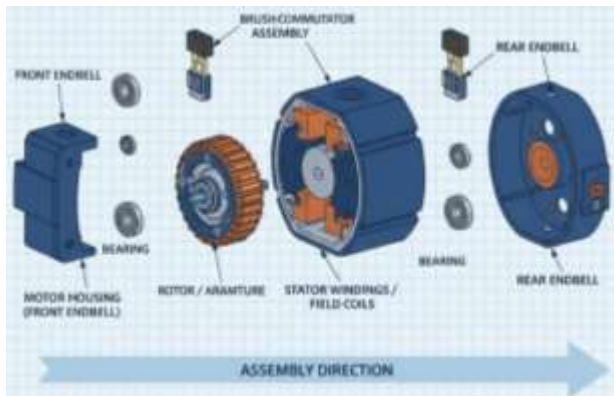


Fig. 9. Universal motor: exploded view.

7. ELECTRICAL, MAGNETIC, AND MECHANICAL CHARACTERISTICS

Universal motors exhibit a combination of electrical, magnetic, and mechanical properties that define their performance, efficiency, and operational limits. Understanding these characteristics is crucial for optimizing design, selecting appropriate control strategies, and integrating the motor into electromechanical systems.

7.1 Electrical Characteristics

- Voltage and Current Ratings:
 - Operate typically on 120–240 V AC or equivalent DC voltage, depending on the application.
 - High starting current due to low initial back EMF; may reach 5–8 times the rated current during startup.
- Torque-Speed Relationship:
 - High starting torque due to series winding configuration.
 - Torque decreases with increasing speed because back EMF reduces armature current.
 - Characteristic curve: $T \propto I_a \times \phi$, where I_a is armature current and ϕ is magnetic flux.
- Power Losses:
 - Copper losses: I^2R losses in armature and field windings.
 - Brush contact losses: Due to friction and voltage drop across brushes.
 - Core losses: Hysteresis and eddy current losses in the laminated core.

Fig. 10 shows torque-speed curve and starting current profile under different load conditions.

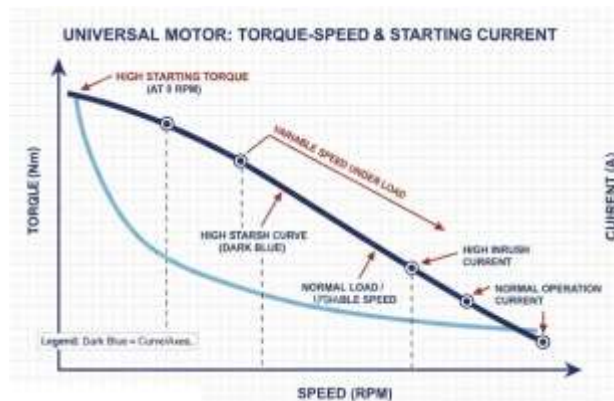


Fig. 10. Universal motor torque speed and starting current.

7.2 Magnetic Characteristics

- Magnetic Flux Density (BBB):
 - Determined by field winding current and core design.
 - Laminated cores reduce eddy current losses for AC operation.
- Saturation and Hysteresis:
 - Core material saturation limits maximum flux and torque.
 - Hysteresis losses increase with higher operating frequency in AC operation.
- Magnetic Efficiency:
 - Depends on flux distribution, winding placement, and air-gap geometry.
 - Optimized to minimize leakage flux and maximize torque per unit current.

Fig. 11 shows B-H curve of core material and flux distribution diagram.

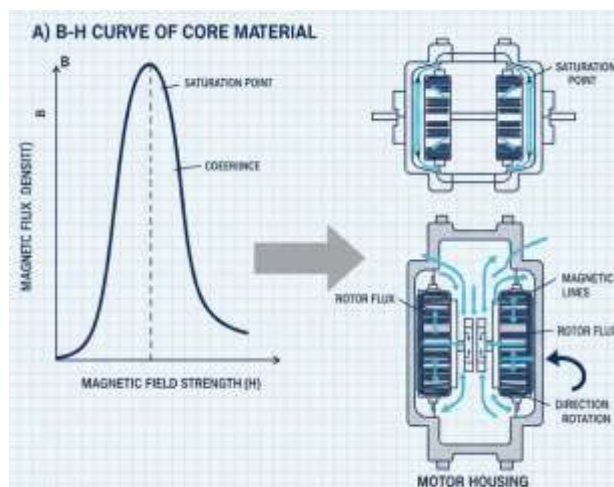


Fig. 11. B-H curve of core material.

7.3 Mechanical Characteristics

- Rotor Speed and Torque:
 - High-speed operation: up to 20,000 rpm in compact designs.
 - Speed varies inversely with load due to series winding; nearly no-load speeds can be dangerously high if uncontrolled.
- Vibration and Noise:
 - Brush contact, commutator segmentation, and rotor imbalance contribute to acoustic noise and mechanical vibrations.
 - High-speed designs require dynamic balancing and vibration damping.
- Bearing and Shaft Design:
 - Bearings must withstand high rotational speeds with minimal friction.
 - Shaft material and diameter affect torsional rigidity and load handling.
- Thermal Considerations:
 - High-speed operation generates heat due to copper losses, core losses, and friction.
 - Ventilation, heat sinks, and lightweight housings are often used to dissipate heat efficiently.

7.4 Performance Metrics and Parameters

Table 2 shows performance matrices and parameters of universal motors with their typical ranges.

Table 2. Performance Metrics and Parameters.

Parameter	Typical Range / Notes
Rated Voltage	120–240 V AC/DC
Rated Current	1–10 A (low-power tools)
No-load Speed	10,000–20,000 rpm
Rated Torque	0.1–5 Nm (depends on application)
Efficiency	40–70% (lower than induction or BLDC motors)
Power Factor	0.4–0.7 (AC operation)
Starting Current	5–8× rated current
Brush Wear Rate	High, dependent on load, speed, and material
Core Losses	5–15% of input power (material dependent)

7.5 Operational Implications

- Universal motors are well-suited for intermittent, high-torque applications but are less efficient for continuous duty.
- Electrical, magnetic, and mechanical characteristics are interdependent, requiring careful design optimization.
- Understanding these parameters is essential for selecting appropriate speed control strategies and minimizing maintenance issues.

Fig. 12 shows diagram showing interaction between electrical current, magnetic flux, and mechanical torque.

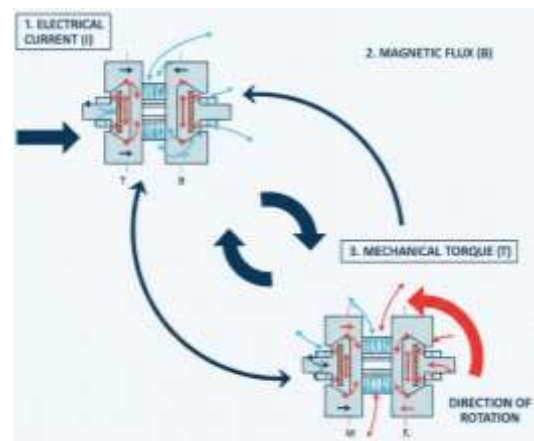


Fig. 12. Universal motor fundamental principles.

8. PERFORMANCE ANALYSIS AND EFFICIENCY LIMITATIONS

Universal motors, while versatile and widely used, face inherent performance and efficiency limitations due to their construction, operating principles, and mechanical characteristics. Understanding these limitations is critical for design optimization, application selection, and control strategy development.

8.1 Torque-Speed Characteristics

- The torque-speed curve of a universal motor is non-linear and highly dependent on the series connection of the armature and field windings.
- Key characteristics:
 - High Starting Torque: At startup, the current is maximum due to negligible back EMF, resulting in torque several times higher than rated torque.

- Speed-Load Dependency: As load decreases, speed increases significantly, sometimes exceeding safe operational limits.
- Continuous Operation Limitations: Torque drops with increasing speed under no-load conditions, making speed control essential for safety and reliability.

8.2 Losses and Heat Generation

Universal motors experience several types of losses, which affect efficiency:

- Copper Losses (I^2R)
 - Occur in both armature and series field windings.
 - Proportional to the square of current; particularly high at startup.
- Core Losses
 - Hysteresis Losses: Energy lost due to repeated magnetization and demagnetization of the iron core.
 - Eddy Current Losses: Circulating currents induced in the laminated core, minimized by lamination thickness and material selection.
- Brush and Commutator Losses
 - Friction and arcing cause energy dissipation, wear, and acoustic noise.
- Mechanical Losses
 - Bearings, rotor friction, and air drag contribute to total losses.
- Thermal Implications
 - Excessive heat reduces insulation life, accelerates brush wear, and limits continuous operation.
 - Ventilation and cooling mechanisms are essential in high-speed designs.

Fig. 13 shows pie chart showing distribution of electrical, magnetic, and mechanical losses in a typical universal motor.

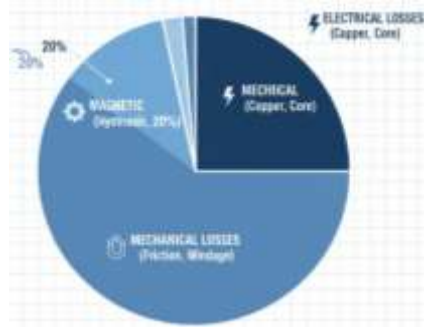


Fig. 13. Universal motor: power loss distribution.

8.3 Efficiency Evaluation

- Universal motors generally have lower efficiency (40–70%) compared to induction or brushless DC motors.
- Factors influencing efficiency:
 - Load Conditions: Efficiency is higher at rated load; low-load operation leads to high speed but low torque, increasing losses.
 - Brush and Commutator Wear: Poor contact or high friction reduces mechanical efficiency.
 - Material Properties: Core and winding material impact copper and core losses.
- Strategies to improve efficiency:
 - Optimize winding resistance and core material.
 - Implement electronic speed control to limit over-speed operation.
 - Use advanced brush materials to reduce friction and arcing.

8.4 Comparative Performance Metrics

Universal motors excel in high starting torque, compact size, and AC/DC versatility but are limited by efficiency and maintenance requirements as shown in Table 3.

Table 3. Comparative performance matrices among several motors.

Parameter	Universal Motor	Induction Motor	BLDC Motor
Efficiency	40–70%	80–95%	85–95%
Starting Torque	Very High	Moderate	High
Speed Range	Very Wide	Narrow	Moderate
Size and Weight	Compact	Larger	Moderate
Maintenance	High	Low	Low
AC/DC Compatibility	Both	AC Only	DC Only

8.5 Operational Implications

- Ideal for intermittent or portable applications where high torque and low cost are prioritized.
- Less suitable for continuous-duty, energy-sensitive applications due to low efficiency and maintenance demands.

- Understanding performance characteristics under variable loads and speeds is crucial for selecting proper control and protection strategies.

Fig. 14 shows graph showing efficiency vs. load for a typical universal motor under AC operation.

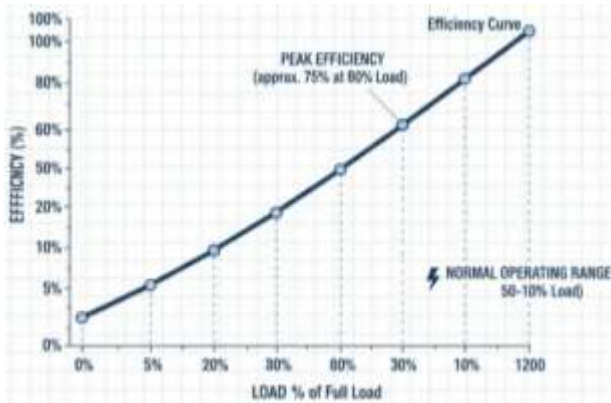


Fig. 14. Universal motor efficiency vs load (ac operation).

9. CONTROL STRATEGIES AND DRIVE INTEGRATION

Effective control and integration of universal motors into electromechanical systems are essential for enhancing performance, extending motor life, reducing noise, and improving efficiency. Due to their series-wound construction and AC/DC compatibility, universal motors require specific control strategies to manage speed, torque, and operational stability.

9.1 Speed Control Techniques

Universal motors exhibit a wide and load-dependent speed range, making speed control a central challenge. Common techniques include:

- Voltage Control
 - Adjusting the applied voltage directly influences armature current and, consequently, motor speed.
 - Simple and cost-effective, commonly used in household appliances.
 - Limitations: Low efficiency at partial loads; poor dynamic response.
- Resistive Control
 - Series resistors are added to the circuit to limit current and reduce speed.
 - Advantages: Simple and inexpensive.

- Drawbacks: Generates heat, reduces efficiency, and is less suitable for continuous operation.
- Electronic Control (PWM)
 - Pulse Width Modulation (PWM) switches the supply voltage at high frequency to regulate effective voltage and speed.
 - Advantages: Higher efficiency, precise speed control, reduced thermal losses.
 - Common in modern tools and appliances where variable speed is required.
- Triac-Based AC Control
 - AC supply is modulated using triacs to control RMS voltage.
 - Widely used in household devices for smooth speed variation.
 - Drawbacks: Produces electromagnetic interference (EMI); requires filtering circuits.

9.2 Drive Systems and Integration

Integration of universal motors into larger electromechanical systems involves:

- Mechanical Coupling
 - Shaft, gears, and pulleys must be designed to handle high-speed torque fluctuations.
 - Vibrations from brush contact and rotor imbalance must be damped.
- Electrical Interface
 - Power supply and protection circuits are required to prevent overcurrent, overvoltage, and overheating.
 - Rectification may be used when AC supply is converted to DC for sensitive control.
- System-Level Considerations
 - Noise reduction: Acoustic damping, enclosure design, and soft-start circuits.
 - Thermal management: Cooling fans, heat sinks, and ventilation channels.
 - Reliability: Brush material selection and commutator maintenance scheduling.

Fig. 15 shows block diagram showing a universal motor integrated with power electronics, sensors, and mechanical load.

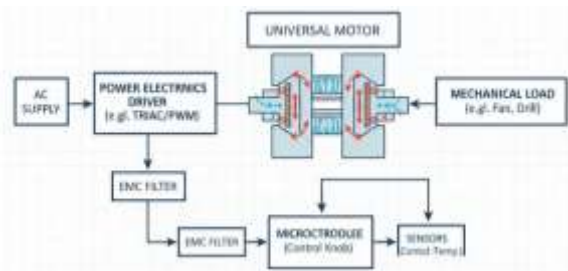


Fig. 15. Universal motor control system.

9.3 Modern Control Approaches

Advancements in power electronics and digital control enable more sophisticated motor control strategies:

- Microcontroller-Based Speed Control
 - Microcontrollers monitor motor parameters (current, voltage, speed) to adjust PWM duty cycle.
 - Allows adaptive speed regulation under varying loads.
- Sensor less Control
 - Uses voltage and current measurements to estimate rotor position and speed.
 - Eliminates physical sensors, reducing cost and complexity.
- Soft-Start and Acceleration Control
 - Gradual ramp-up of voltage/current reduces mechanical stress and brush wear.
 - Enhances motor lifespan and user safety in handheld tools.
- EMI Reduction Techniques
 - Filtering circuits, shielded cables, and optimized switching patterns reduce electromagnetic interference from high-speed commutation.

9.4 Operational Implications

- Proper control strategy improves efficiency, noise characteristics, and motor longevity.
- Integration with advanced drives enables variable speed operation, making universal motors more competitive in modern electromechanical systems.
- Choosing the right control method depends on application requirements, including cost, precision, duty cycle, and environmental constraints.

Fig. 16 shows graph showing motor speed response under PWM control vs. simple voltage control.

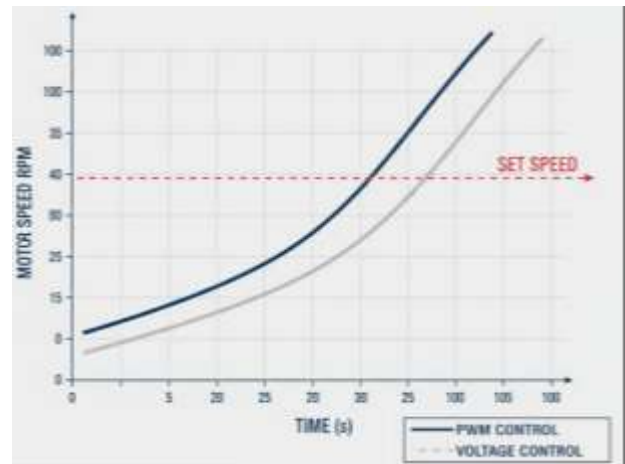


Fig. 16. Universal motor speed control response.

10. COMPARATIVE EVALUATION WITH OTHER MOTOR TYPES

Universal motors occupy a unique niche in electromechanical systems due to their high starting torque, compact size, and dual AC/DC operation. However, their characteristics differ significantly from other common motor types, including induction motors, permanent magnet DC motors (PMDC), and brushless DC (BLDC) motors.

A comparative evaluation helps in application selection, performance assessment, and identifying potential improvements.

10.1 Comparison with AC Induction Motors

Universal motors provide high torque in a compact form, ideal for portable devices, as shown in Table 4.

Table 4. Comparison of universal motor with ac induction motor.

Feature	Universal Motor	AC Induction Motor
Starting Torque	Very High	Moderate
Speed Range	Very Wide	Limited
AC/DC Compatibility	Both AC & DC	AC Only
Efficiency	40-70%	80-95%
Size and Weight	Compact	Larger
Maintenance	High (brushes)	Low (brushless)
Applications	Portable tools, small appliances	Industrial machinery, pumps

Key Observations:

- AC induction motors are more efficient, robust, and low-maintenance, making them suitable for continuous industrial operation.
- Induction motors require complex control for variable speed, whereas universal motors can achieve wide speed variation with simpler electronics.

10.2 Comparison with DC Series and PMDC Motors

Universal motors are flexible for AC and DC supplies, whereas PMDC motors require DC. As shown in Table 5.

Table 5. Comparison of universal motor with DC Series and PMDC Motors.

Feature	Universal Motor	PMDC Motor
AC/DC Compatibility	Both AC & DC	DC Only
Starting Torque	Very High	High
Speed Range	Very Wide	Moderate
Efficiency	40-70%	70-90%
Size and Weight	Compact	Moderate
Maintenance	High (brushes)	Moderate
Applications	Hand tools, appliances	Robotics, battery-powered devices

Key Observations:

- PMDC motors offer higher efficiency and smoother operation, but at higher cost.
- Universal motors maintain competitive torque-to-weight ratio, especially for high-speed, short-duration applications.

10.3 Comparison with Brushless DC (BLDC) Motors

BLDC motors eliminate brush wear, achieving higher efficiency and reliability as shown in Table 6.

Key Observations:

- Universal motors excel in low-cost, high-speed applications, where simplicity and dual-supply capability are priorities.
- BLDC motors are preferred for high-efficiency, long-duration operation and applications requiring precise speed/torque control.

Table 6. Comparison with Brushless DC (BLDC) Motors.

Feature	Universal Motor	BLDC Motor
AC/DC Compatibility	Both AC & DC	DC Only
Starting Torque	Very High	High
Speed Range	Very Wide	Moderate to High
Efficiency	40-70%	85-95%
Size and Weight	Compact	Moderate
Maintenance	High (brushes)	Low (brushless)
Control Complexity	Moderate (PWM optional)	High (electronic commutation)
Applications	Tools, appliances	Robotics, drones, precision instruments

10.4 Summary of Comparative Evaluation

- Strengths of Universal Motors: High starting torque, wide speed range, AC/DC versatility, compactness, low initial cost.
- Limitations: Low efficiency, high maintenance, acoustic noise, and susceptibility to wear.
- Selection Guidance:
 - Use universal motors in intermittent, portable, or low-cost applications.
 - Opt for induction or BLDC motors in continuous, energy-sensitive, or precision-demanding systems.

11. INDUSTRIAL APPLICATIONS AND PRACTICAL RELEVANCE

Universal motors are widely employed across domestic, industrial, and portable applications due to their high starting torque, compact size, and ability to operate on both AC and DC power supplies. Despite their limitations in efficiency and maintenance, they remain relevant in specific contexts where intermittent operation, high-speed performance, and cost-effectiveness are prioritized.

11.1 Household Appliances

- Universal motors are ubiquitous in household devices due to their compactness and high-speed capabilities:

- Vacuum cleaners: High suction power achieved through high-speed rotor operation.
- Blenders and mixers: High torque at startup enables efficient blending of viscous materials.
- Hairdryers: Lightweight design and high-speed airflow generation.
- Food processors: Rapid and intermittent operation leverages high starting torque.
- Operational relevance: Ability to handle variable loads and operate at high speeds without complex control electronics makes them ideal for consumer appliances.

Fig. 17 shows diagram showing typical household devices powered by universal motors.



Fig. 17. Common household universal motor.

11.2 Portable Power Tools

- Universal motors dominate the handheld tool market because of their favorable torque-to-weight ratio and speed flexibility:
 - Electric drills: High starting torque allows drilling through tough materials.
 - Saws and grinders: Compact, high-speed operation enables precision cutting and finishing.
 - Screwdrivers: Intermittent high-torque operation for assembly tasks.
- Advantages: Lightweight construction, easy integration with AC/DC power sources, and simple speed control using voltage or PWM techniques.

11.3 Small-Scale Industrial Machines

- Universal motors are also employed in industrial equipment with intermittent operation or where high-speed compact motors are required:
 - Conveyors for light loads: Short-duration operation allows efficient movement without large motors.
 - Laboratory and medical devices: Compact size and controllable speed are advantageous.
 - Packaging and processing equipment: High starting torque enables rapid startup and precise short-duration tasks.
- Limitations: Inefficient for continuous operation; maintenance for brushes and commutators must be planned.

11.4 Emerging Applications

- With technological advances, universal motors are finding novel applications:
 - Robotics (small manipulators): Compact and lightweight design enables mobility.
 - Portable generators: Dual AC/DC operation allows versatile power output.
 - Energy-efficient home appliances: Integration with modern control electronics (PWM, soft start) improves usability.

11.5 Practical Relevance

- Universal motors provide a balance of cost, performance, and flexibility unmatched by some high-efficiency alternatives in specific applications.
- Their intermittent high-torque performance is particularly valuable in household and portable tools, despite lower efficiency for continuous industrial loads.
- They demonstrate the trade-off between efficiency, control complexity, and initial cost, guiding designers in motor selection for modern electromechanical systems.

Table 7 summarizing industrial, household, and emerging applications, including load types, speed requirements, and motor advantages.

Table 7. Motor Applications Comparison Table.

Application Type	Load Type	Speed Requirements	Suitable Motor Types	Motor Advantages
Industrial	Heavy loads, constant or variable torque (pumps, conveyors, compressors)	Medium to high speed; often precise control needed	Induction, Synchronous, BLDC	High efficiency, durability, precise speed/torque control
Household	Light to medium loads (vacuum cleaners, mixers, fans, power tools)	High speed for small loads; variable speed desirable	Universal, DC Brushed	High starting torque, compact, simple speed control, cost-effective
Emerging / Advanced	Variable loads, high-performance (EVs, drones, robotics, 3D printers)	Wide speed range; fast acceleration/deceleration; precise positioning	BLDC, Stepper, Synchronous	High efficiency, precise control, low maintenance, quiet operation

12. RESEARCH GAPS, FUTURE DIRECTIONS

Universal motors remain a widely used and historically significant class of electric machines. Despite their advantages, several research gaps and performance limitations have been identified that warrant further investigation. This section synthesizes these gaps, proposes future research directions, and concludes the review.

12.1 Identified Research Gaps

- Low Energy Efficiency
 - Universal motors typically exhibit efficiencies of 40–70%, lower than induction or brushless DC motors.
 - Energy losses arise from copper losses, core losses, and friction in brushes and commutators.
 - Research is needed to optimize winding design, core materials, and electronic control to reduce losses.
- High Maintenance Requirements
 - Brush and commutator wear necessitate frequent maintenance, especially in high-speed or continuous-duty applications.
 - Development of advanced brush materials, self-lubricating commutators, or semi-brushless designs could improve reliability.
- Acoustic Noise and Vibration
 - High-speed operation, rotor imbalance, and brush arcing contribute to noise.
 - Research into mechanical damping, vibration isolation, and optimized rotor geometry is limited.
- Electromagnetic Interference (EMI)
 - AC operation and high-speed switching generate EMI, affecting nearby sensitive electronics.

- Advanced filtering, shielding, and control strategies need further investigation.
- Limited Continuous-Duty Capability
 - High-speed, high-torque operation generates thermal stress that limits continuous operation.
 - Future research could focus on improved cooling, thermal materials, and heat dissipation techniques.

12.2 Future Research Directions

- Material Innovations
 - Development of high-conductivity copper alloys, low-loss core materials, and advanced insulation to enhance efficiency and durability.
- Advanced Control Techniques
 - Integration of microcontroller-based PWM, soft-start, and sensorless control to improve torque control, speed regulation, and efficiency.
 - Adaptive control algorithms to optimize performance under variable load and voltage conditions.
- Hybrid and Semi-Brushless Designs
 - Investigating designs that reduce or eliminate brushes while maintaining series-wound advantages for AC/DC operation.
- Noise and Vibration Mitigation
 - Advanced mechanical design, rotor balancing, and acoustic damping to reduce operational noise.
- Integration with Renewable and Smart Systems
 - Research on universal motors for battery-powered, solar-powered, and IoT-enabled devices, expanding their relevance in modern electromechanical systems.

13. CONCLUSIONS

In conclusion, universal motors represent a historically significant and practically versatile class of electric machines that continue to hold relevance in modern electromechanical systems. Their unique ability to operate on both alternating current (AC) and direct current (DC), combined with exceptionally high starting torque and compact construction, makes them ideal for a wide range of applications, particularly in household appliances, portable power tools, and small-scale industrial equipment where intermittent operation, lightweight design, and cost-effectiveness are critical. Despite these advantages, universal motors face inherent challenges, including relatively low energy efficiency compared to induction and brushless DC motors, high maintenance requirements due to brush and commutator wear, acoustic noise, mechanical vibrations, and electromagnetic interference. A detailed understanding of their electrical, magnetic, and mechanical characteristics is essential to optimize performance, ensure reliable operation, and extend their lifespan. Modern control strategies, such as microcontroller-based PWM, soft-start mechanisms, and sensorless control, have the potential to mitigate some of these limitations by improving speed regulation, torque control, and operational efficiency. Furthermore, advances in materials science, such as high-conductivity windings, low-loss laminated cores, and enhanced insulation, as well as innovative mechanical designs to reduce vibration and noise, can significantly enhance the practical applicability of universal motors in contemporary systems. The review highlights that while universal motors are not always the most efficient choice for continuous-duty or high-precision applications, their simplicity, versatility, and high-torque performance continue to provide a competitive advantage in applications where compactness, cost, and dual-supply operation are prioritized. Looking forward, integrating universal motors with modern electronics, renewable energy sources, and smart system architectures, alongside continued research into efficiency improvements and maintenance reduction, will ensure that they remain relevant and valuable components in evolving electromechanical systems. Ultimately, universal motors exemplify a balance of historical significance, practical performance,

and adaptability, demonstrating that even traditional motor technologies can maintain an important role in modern engineering when appropriately optimized and controlled.

REFERENCES

- [1] R. Saidur, N. A. Rahim, M. R. Islam, and K. H. Solangi, "Environmental impact of wind energy," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 5, pp. 2423–2430, 2011, doi: 10.1016/j.rser.2011.02.024.
- [2] O. F. C. Atalaya et al., "Regression modeling of electromechanical variables in universal motors under AC and DC supplies," *Advances in Science, Technology and Engineering Systems Journal*, vol. 4, no. 6, pp. 360–370, 2019.
- [3] G. Papa, B. K. Seljak, B. Benedičič, and T. Kmecl, "Universal motor efficiency improvement using evolutionary optimization," *IEEE Transactions on Industrial Electronics*, vol. 50, no. 3, pp. 602–611, 2003, doi: 10.1109/TIE.2003.812455.
- [4] A. Polat, L. T. Ergene, and A. Firat, "Dynamic modeling of the universal motor used in washer," in *Proc. Int. Aegean Conf. on Electrical Machines and Power Electronics*, 2011, pp. 444–448.
- [5] P. Záskalický and J. Dupej, "Modeling of a universal motor supplied by a harmonic voltage," in *Proc. 12th Int. Power Electronics and Motion Control Conf. (EPE-PEMC)*, 2006, pp. 1070–1073, doi: 10.1109/EPEPEMC.2006.4778543.
- [6] D. Lin, P. Zhou, and S. Stanton, "An analytical model and parameter computation for universal motors," in *Proc. IEEE Int. Electric Machines & Drives Conf. (IEMDC)*, 2011, pp. 119–124, doi: 10.1109/IEMDC.2011.5994773.
- [7] D. S. Nayak and R. S. Shivarudraswamy, "Loss and efficiency analysis of universal motor used in mixer grinder by mathematical modelling," in *Proc. IEEE Int. Conf. on Automatic Control and Intelligent Systems (I2CACIS)*, 2018, pp. 105–110, doi: 10.1109/I2CACIS.2018.8603693.
- [8] H. Qi, L. Ling, C. Jichao, and X. Wei, "Design and research of deep slot universal motor for electric power tools," *Journal of Power Electronics*, vol. 20, no. 6, pp. 1604–1615, 2020.
- [9] R. N. Nassrullah and A. M. Ali, "Finite element analysis of universal motor based on reverse engineering," *Al-Iraqia Journal for Scientific Engineering Research*, vol. 3, no. 2, pp. 65–76, 2024, doi: 10.58564/IJSER.3.2.2024.180.
- [10] A. Almawla, M. J. Hussein, and A. T. Abdullah, "A comparative study of DC motor speed control techniques using fuzzy, SMC, and PID," *Journal Européen des Systèmes Automatisés*, vol. 57, no.

- 2, pp. 397–406, 2024, doi: 10.18280/jesa.570209.
- [11] S. Rüstemli and E. Ağrali, “Microcontroller-based phase angle control speed regulation of AC universal motors,” *MANAS Journal of Engineering*, vol. 11, no. 1, pp. 112–118, 2023, doi: 10.51354/mjen.1149121.
- [12] P. Girovský and J. Kaňuch, “Analysis of the power supply influence on the universal motor,” *Power Electronics and Drives*, vol. 7, no. 1, pp. 103–111, 2022, doi: 10.2478/pead-2022-0008.
- [13] R. N. Nassrullah and A. M. Ali, “Performance assessment of universal motor with AC and DC supply,” *Anbar Journal of Engineering Science*, vol. 15, no. 1, pp. 69–76, 2024, doi: 10.37649/aengs.2024.147117.1073.
- [14] H. Ben Abdeljawed and L. El Amraoui, “Simulation and rapid control prototyping of DC powered universal motors speed control: Towards efficient operation in future DC homes,” *Engineering Science and Technology, an International Journal*, vol. 34, 101092, 2022, doi: 10.1016/j.jestch.2021.101092.
- [15] O. F. C. Atalaya, N. Y. Huaita Ccallo, and L. E. Rojas Vicuña, “Universal motor parameters comparison under AC and DC supply conditions,” *Advances in Science, Technology and Engineering Systems Journal*, vol. 4, no. 6, pp. 360–370, 2019.
- [16] C. D. Oancea, V. C. Petre, and V. A. Boice, “Educational and experimental study for evaluation of a universal motor,” in *Proc. IEEE Int. Symp. on Advanced Topics in Electrical Engineering (ATEE)*, 2019.
- [17] S. K. Sharma and M. S. Manna, “Finite element electromagnet based design of universal motor for agro application,” *International Journal of Electrical and Electronics Research*, vol. 10, no. 3, pp. 590–596, 2022.
- [18] O. A. Imran, W. N. Abed, and A. N. Jbarah, “Speed control of universal motor,” *International Journal of Power Electronics and Drive Systems*, vol. 10, no. 1, pp. 41–47, 2019, doi: 10.11591/ijpeds.v10.i1.pp41-47.
- [19] S. Rüstemli and E. Ağrali, “Computer-based speed control application for universal motor,” *MANAS Journal of Engineering*, vol. 11, no. 1, pp. 112–118, 2023, doi: 10.51354/mjen.1149121.
- [20] O. F. C. Atalaya et al., “Experimental analysis in alternate current and direct current of the operating parameters of a universal single-phase engine,” *Advances in Science, Technology and Engineering Systems Journal*, vol. 4, no. 6, pp. 360–370, 2019, doi: 10.25046/aj040646.
- [21] O. A. Imran, W. N. Abed, and A. N. Jbarah, “Speed control of universal motor under variable loading conditions,” *International Journal of Power Electronics and Drive Systems*, vol. 10, no. 1, pp. 41–47, 2019, doi: 10.11591/ijpeds.v10.i1.pp41-47.
- [22] I. A. Araga et al., “A comparative analysis on the performance of universal motor when driven by AC/DC,” *Australian Journal of Science and Technology*, vol. 4, no. 4, pp. 348–352, 2020.
- [23] A. Di Gerlando and R. Perini, “Model of the commutation phenomena in a universal motor,” *IEEE Transactions on Energy Conversion*, vol. 21, no. 1, pp. 27–33, 2006, doi: 10.1109/TEC.2005.850951.
- [24] Y. Niwa and Y. Akiyama, “The relation of brush life to the commutator width and brush width ratio of a universal motor,” in *Proc. IEEE Int. Conf. on Power Electronics and Drive Systems (PEDS)*, 2009, pp. 1384–1389, doi: 10.1109/PEDS.2009.5385711.
- [25] P. Buenestado, J. Gibergans-Báguena, L. Acho, and G. Pujol-Vázquez, “Predictive speed control of a DC universal motor applied to monitor electric vehicle batteries,” *Machines*, vol. 11, no. 7, 740, 2023, doi: 10.3390/machines11070740.
- [26] S. K. Sharma and M. S. Manna, “Finite element method-based design and performance analysis of universal motor for agro applications,” *Bulletin of Electrical Engineering and Informatics*, vol. 12, no. 1, pp. 21–32, 2023, doi: 10.11591/eei.v12i1.4204.
- [27] D. A. Elkady, H. Z. Azazy, A. S. Mansour, and S. S. Shokrallah, “Adaptive PI speed controller for a universal motor,” *Engineering Research Journal*, in press, 2025.
- [28] A. A. Ansari, “A review of different motor types and selection of one optimal motor for application in the EV industry,” *International Journal of Electrical and Power Engineering*, vol. 1, no. 7, pp. 1–7, 2022, doi: 10.36478/ijepe.2022.1.7.
- [29] T. J. E. Miller and M. Willig, “Calculation of the armature inductance of the universal AC commutator motor,” in *Proc. XIX Int. Conf. on Electrical Machines (ICEM)*, 2010, pp. 1–6, doi: 10.1109/ICELMACH.2010.5607743.
- [30] A. Jilani, I. Ahmad, and S. O. Jilani, “A comparative analysis on controlling speed of universal motor by using fuzzy and ANFIS controller,” *International Journal of Computer Applications*, vol. 99, no. 7, pp. 32–36, 2014, doi: 10.5120/17386-7923.