JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

DESIGN OF BLDC MOTOR FOR AUTOMATIC GATE

Prof. Suhas Rewatkar, Assistant Professor, Dept.Of Mechanical Engineering, JD College Of Engineering And Management, Nagpur, Maharashtra, India

Palak Petkar[2], **Chetan Yuwnati**[3], **Kishan Lokhande** [4], **Rakshan Hedaoo** [5]

2,3,4,5 Students, Department of Mechanical Engineering, JD College of Engineering and Management, Nagpur, Maharashtra, India

Abstract

This research presents a detailed design and implementation of a Brushless DC (BLDC) motor drive system specifically engineered for automatic gate applications. The study addresses critical challenges in gate automation including high starting torque requirements, precise position control, energy efficiency, and long-term reliability. A comprehensive approach encompasses electromagnetic design optimization, advanced control system development, power electronics integration, and extensive experimental validation. The proposed system integrates a custom-designed three-phase BLDC motor rated at 750W with hall sensor feedback, intelligent electronic speed controller (ESC), ARM Cortex-M4 based control unit, and comprehensive safety systems. Rigorous testing demonstrates superior performance with efficiency improvements of 16.7% over brushed DC motors and 8.7% over AC induction motors. The system successfully operates gates weighing up to 500kg with positioning accuracy of ±1.5°, response time under 0.18 seconds, and operational lifespan exceeding 15 years with minimal maintenance requirements.

Keywords: BLDC motor design, automatic gate systems, hall sensor control, power electronics, electromagnetic optimization, gate automation, motor control algorithms

I. INTRODUCTION

A. Background and Motivation

The rapid advancement in home and commercial automation has significantly increased the demand for reliable, efficient, and intelligent gate automation systems. Traditional gate automation solutions predominantly utilize brushed DC motors or AC induction motors, each presenting inherent limitations that compromise long-term performance and operational efficiency. Brushed DC motors, while offering excellent starting torque characteristics, suffer from brush wear, regular maintenance requirements, electromagnetic interference generation, and limited operational lifespan typically ranging from 3-5 years under continuous operation.

AC induction motors, though more robust than brushed DC counterparts, present challenges in precise speed control, starting torque limitations, and relatively lower efficiency in variable speed applications common in gate automation. These limitations become particularly pronounced in residential and commercial gate applications where reliability, energy efficiency, and minimal maintenance are paramount requirements.

The emergence of Brushless DC (BLDC) motor technology presents compelling advantages for gate automation applications. BLDC motors eliminate mechanical commutation through electronic switching, resulting in superior efficiency, extended operational lifespan, reduced electromagnetic interference, and precise speed control capabilities. However, the successful implementation of BLDC motors in gate automation requires comprehensive understanding of application-specific requirements and careful optimization of motor design, control algorithms, and system integration.

B. Research Objectives

This research aims to address the following primary objectives:

1. **Design Optimization:** Develop a comprehensive electromagnetic design methodology for BLDC motors specifically tailored to automatic gate applications
2. **Control System Development:** Implement advanced control algorithms ensuring smooth operation, precise positioning, and robust performance under varying load conditions
3. **System Integration:** Create a complete drive system incorporating motor, power electronics, sensors, and safety systems
4. **Performance Validation:** Conduct extensive experimental testing to validate design objectives and demonstrate superior performance compared to conventional motor technologies
5. **Economic Analysis:** Evaluate total cost of ownership and return on investment for BLDC motor implementation in gate automation

C. Novel Contributions

This research makes several significant contributions to the field of gate automation:

- **Application-Specific Motor Design:** Development of BLDC motor design methodology optimized for gate automation requirements
- **Advanced Control Algorithms:** Implementation of intelligent control strategies addressing unique challenges in gate applications
- **Comprehensive Safety Integration:** Development of integrated safety systems ensuring reliable operation in residential and commercial environments
- **Performance Benchmarking:** Extensive comparative analysis with conventional motor technologies under realistic operating conditions
- **Economic Viability Analysis:** Detailed cost-benefit analysis demonstrating long-term economic advantages

II. LITERATURE REVIEW AND THEORETICAL BACKGROUND

A. Evolution of Gate Automation Technologies

Gate automation technology has evolved significantly over the past three decades. Early systems primarily utilized simple AC motors with basic on-off control, providing limited functionality and poor energy efficiency. The introduction of brushed DC motors in the 1990s improved starting torque characteristics and enabled better speed control, leading to smoother gate operation.

Recent developments have focused on incorporating advanced control systems, sensor integration, and improved safety features. However, motor technology has remained relatively stagnant, with most commercial systems still relying on conventional brushed DC or AC induction motors. This research gap motivated the current investigation into BLDC motor implementation for gate automation.

B. BLDC Motor Technology in Automation Applications

BLDC motors have gained significant adoption in various automation applications including robotics, HVAC systems, and industrial machinery. The elimination of mechanical brushes provides several advantages:

Efficiency Improvements: BLDC motors typically achieve efficiency ratings of 85-95% compared to 75-85% for brushed DC motors and 80-90% for AC induction motors.

Operational Lifespan: Without brush wear, BLDC motors can operate for 10,000+ hours with minimal maintenance, significantly exceeding the 2,000-5,000 hour lifespan of brushed DC motors.

Speed Control Precision: Electronic commutation enables precise speed control across wide speed ranges, essential for smooth gate operation.

Electromagnetic Compatibility: Reduced electromagnetic interference improves compatibility with gate safety systems and wireless communication devices.

C. Gate Application Requirements Analysis

Automatic gate systems present unique operational requirements that influence motor selection and design:

Torque Characteristics:

- High starting torque (6-10 Nm) for overcoming gate inertia and friction
- Constant torque delivery across operational speed range
- Overload capability for handling wind loads and mechanical resistance

Speed Control Requirements:

- Wide speed range operation (50-2000 RPM)
- Smooth acceleration and deceleration profiles
- Precise positioning for soft-start and soft-stop operation

Environmental Considerations:

- Outdoor installation exposure to temperature extremes (-30°C to +70°C)
- Moisture and dust resistance (IP65 rating minimum)
- Vibration resistance for reliable operation

Safety and Reliability:

- Fail-safe operation modes
- Obstacle detection integration
- Emergency stop functionality
- Position feedback for safety verification

III. SYSTEM DESIGN METHODOLOGY

A. Motor Design Specifications

The BLDC motor design is based on comprehensive analysis of gate automation requirements and market survey of existing systems. The following specifications were established:

Electrical Specifications:

- Rated Power: 750W
- Rated Voltage: 24V DC
- Rated Current: 35A
- Rated Speed: 1500 RPM
- Maximum Speed: 2000 RPM
- Power Factor: 0.95

Mechanical Specifications:

- Rated Torque: 4.8 Nm

- Starting Torque: 8.2 Nm
- Maximum Torque: 12 Nm
- Gate Weight Capacity: 500 kg
- Operational Speed Range: 50-1500 RPM

Environmental Specifications:

- Operating Temperature: -25°C to +65°C
- Storage Temperature: -40°C to +80°C
- Humidity: 0-95% non-condensing
- Protection Rating: IP65
- Vibration Resistance: 5G peak acceleration

B. Electromagnetic Design Optimization

1. Stator Design

The stator design optimization focused on achieving high torque density while minimizing torque ripple and cogging torque. A comprehensive finite element analysis was conducted to evaluate different slot configurations.

Slot Configuration Analysis:

- **9-slot configuration:** Lower material cost but higher torque ripple (8.5%)
- **12-slot configuration:** Optimal balance with moderate torque ripple (4.2%)
- **15-slot configuration:** Lowest torque ripple (2.8%) but higher manufacturing complexity

The 12-slot configuration was selected based on optimal balance between performance and manufacturing cost.

Winding Configuration:
Star-connected concentrated windings were chosen for the following advantages:

- Reduced copper usage (15% reduction compared to distributed windings)
- Improved fault tolerance
- Simplified manufacturing process
- Better thermal management

Slot Dimensions:

- Slot depth: 28 mm
- Slot width: 12 mm
- Tooth width: 8 mm
- Slot fill factor: 0.65
- Wire gauge: AWG 14 (2.08 mm diameter)

2. Rotor Design

The rotor design optimization focused on permanent magnet selection, pole configuration, and air gap optimization.

Permanent Magnet Selection:

Neodymium Iron Boron (NdFeB) Grade N42 magnets were selected based on:

Protection Features:

- Input overvoltage protection
- Output overcurrent protection
- Thermal shutdown protection
- Surge protection (6kV)
- Reverse polarity protection

2. Auxiliary Power Supplies

Control Circuit Supply:

- Input: 24V DC (main supply)
- Output: 5V DC, 3A
- Regulation: ±2%
- Ripple: <50mV peak-to-peak

Sensor Supply:

- Input: 5V DC (control supply)
- Output: 3.3V DC, 1A
- Regulation: ±1%
- Noise: <10mV RMS

IV. CONTROL ALGORITHMS AND IMPLEMENTATION

A. Six-Step Commutation Algorithm

The six-step commutation algorithm provides the foundation for BLDC motor control, implementing electronic switching based on hall sensor feedback.

1. Commutation Sequence

The commutation sequence follows a predetermined pattern based on hall sensor states:

Hall State	Phase A	Phase B	Phase C	Active Phases
001	0	-	+	B→C
011	-	0	+	A→C
010	-	+	0	A→B
110	0	+	-	B→A
100	+	0	-	C→A

Hall State	Phase A	Phase B	Phase C	Active Phases
101	+	-	0	C→B

Where: + = positive PWM, - = negative PWM, 0 = floating

2. PWM Implementation

Pulse Width Modulation (PWM) control implements variable speed operation:

PWM Parameters:

- Switching frequency: 20 kHz
- Resolution: 12-bit (4096 levels)
- Dead time: 2 μs
- PWM mode: Center-aligned

Speed Control:

Speed regulation is achieved through PWM duty cycle modulation:

- Duty cycle range: 0-95%
- Speed resolution: 0.4 RPM
- Response time: <200ms

3. Commutation Timing Optimization

Optimal commutation timing ensures maximum efficiency and minimum torque ripple:

Advance Angle Calculation:

$\theta\_advance = \arctan(\omega L/R)$

Where:

- ω = electrical angular velocity
- L = phase inductance
- R = phase resistance

Adaptive Timing:

The system implements adaptive commutation timing based on:

- Motor speed
- Load conditions
- Temperature compensation
- Battery voltage variations

B. Speed Control System

1. PI Controller Implementation

A Proportional-Integral (PI) controller maintains desired speed under varying load conditions:

Controller Parameters:

- Proportional gain (Kp): 0.8
- Integral gain (Ki): 45
- Sampling frequency: 1 kHz
- Saturation limits: ±95% PWM

Transfer Function:

G(s) = Kp + Ki/s = 0.8 + 45/s

2. Speed Feedback System

Speed feedback is derived from hall sensor timing measurements:

Speed Calculation:

RPM = 60 / (T_hall × P/2)

Where:

- T_hall = time between hall sensor transitions
- P = number of poles (8)

Filtering:
A first-order low-pass filter smooths speed measurements:

- Cutoff frequency: 10 Hz
- Time constant: 16 ms

C. Position Control System

1. Gate Position Monitoring

Gate position is monitored using incremental encoder feedback:

Encoder Specifications:

- Resolution: 1000 pulses per revolution
- Gear ratio: 50:1
- Effective resolution: 50,000 counts per gate revolution
- Position accuracy: ±0.0072° (±1.5 counts)

2. Positioning Algorithm

The positioning system implements trapezoidal motion profiles for smooth gate operation:

Profile Parameters:

- Maximum acceleration: 2000 RPM/s
- Maximum deceleration: 1500 RPM/s
- Maximum velocity: 1200 RPM
- Position tolerance: ±2 counts

Motion States:

Remote Monitoring System:

- Parameter logging: Speed, torque, current, temperature

- Sampling rate: 1 Hz continuous, 1 kHz during operation
- Data transmission: Wireless (4G/WiFi)
- Storage capacity: 1 year of operational data

Maintenance Monitoring:

- Bearing temperature monitoring
- Vibration analysis
- Electrical parameter trending
- Performance degradation tracking

VI. RESULTS AND ANALYSIS

A. Laboratory Test Results

1. Efficiency Performance

Comprehensive efficiency testing revealed superior performance compared to conventional motor technologies:

Peak Efficiency Results:

- Maximum efficiency: 91.8% at 1200 RPM, 75% load
- Average efficiency: 89.2% across operational range
- Efficiency at rated conditions: 89.8%
- Part-load efficiency: 87.4% at 25% load

Comparative Analysis:

Motor Type	Peak Efficiency	Average Efficiency	Part-Load Efficiency
BLDC (This Study)	91.8%	89.2%	87.4%
Brushed DC	84.2%	76.4%	68.9%
AC Induction	88.1%	82.1%	74.2%
Servo Motor	92.4%	88.7%	85.1%

2. Torque Characteristics

Starting Torque Performance:

- Measured starting torque: 8.2 Nm (102.5% of specification)
- Starting current: 38.5A (10% above rated current)
- Voltage sensitivity: ±0.8% torque variation per 1% voltage change
- Temperature coefficient: -0.3% per °C above 25°C

Torque Ripple Analysis:

- RMS torque ripple: 4.2% of rated torque

- Peak-to-peak torque ripple: 12.8% of rated torque
- Dominant harmonics: 6th and 12th order
- Cogging torque: 2.1% of rated torque

3. Speed Control Performance

Step Response Characteristics:

- Rise time (10%-90%): 0.18 seconds
- Settling time (2% band): 0.24 seconds
- Maximum overshoot: 3.2%
- Steady-state error: <0.5 RPM

Speed Regulation:

- Load regulation: ±0.8 RPM (0.05% at 1500 RPM)
- Line regulation: ±0.4 RPM for ±10% voltage variation
- Temperature stability: ±1.2 RPM over -10°C to +50°C range

B. Environmental Testing Results

1. Temperature Performance

Low Temperature Testing (-25°C):

- Starting capability: Successful down to -25°C
- Efficiency reduction: 3.2% compared to 25°C operation
- Torque reduction: 4.1% compared to rated conditions
- No mechanical binding or electrical faults observed

High Temperature Testing (65°C):

- Continuous operation: Stable performance up to 65°C
- Thermal derating: 15% above 50°C ambient
- Magnet strength reduction: 2.8% at 65°C (reversible)
- Salt air corrosion potential (coastal location)
- Temperature cycling (-5°C to +42°C)
- System performed within specifications throughout test period

3. Industrial Installation Performance

Site 3 Results (6-month evaluation):

- Total gate cycles: 54,000
- Average energy consumption: 0.15 kWh per cycle
- System availability: 98.9%
- Maintenance events: Two preventive maintenance checks
- Heavy-duty performance: Exceeded expectations

D. Comparative Performance Analysis

1. Energy Consumption Comparison

Annual Energy Consumption Analysis:

Application	BLDC System	Brushed DC	AC Induction	Annual Savings
Residential (20 cycles/day)	584 kWh	759 kWh	682 kWh	23.1% vs Brushed
Commercial (150 cycles/day)	6,570 kWh	8,544 kWh	7,665 kWh	23.1% vs Brushed
Industrial (250 cycles/day)	13,688 kWh	17,810 kWh	15,960 kWh	23.1% vs Brushed

2. Total Cost of Ownership Analysis

10-Year Cost Analysis (Commercial Application):

Cost Category	BLDC System	Brushed DC	AC Induction
Initial Cost	$2,800	$1,200	$1,800
Energy Cost	$6,570	$8,544	$7,665
Maintenance	$300	$2,400	$1,200
Replacement	$0	$2,400	$1,800
Total	**$9,670**	**$14,544**	**$12,465**
Savings	**-**	**$4,874**	**$2,795**

Payback Period:

- vs Brushed DC: 3.2 years
- vs AC Induction: 4.8 years

The comprehensive approach encompassing electromagnetic design, advanced control algorithms, robust power electronics, and extensive testing validation has resulted in a system that significantly outperforms conventional motor technologies.

A. Key Achievements

Performance Excellence: The developed system achieves 89.2% average efficiency, representing 16.7% improvement over brushed DC motors and 8.7% improvement over AC induction motors. Superior torque characteristics and precise speed control ensure excellent gate operation under all conditions.

B. Practical Impact

The research demonstrates that BLDC motor technology represents a viable and superior alternative to conventional motor technologies for gate automation applications. The combination of improved efficiency, enhanced reliability, and reduced maintenance provides compelling value proposition for residential, commercial, and industrial applications.

The comprehensive testing validation across diverse environments and operating conditions confirms robust performance suitable for widespread deployment. The modular design approach enables customization for specific application requirements while maintaining core performance advantages.

C. Research Contributions

This research makes significant contributions to the field of gate automation and BLDC motor applications:

1. **Design Methodology:** Development of systematic design approach for BLDC motors in gate applications
2. **Performance Benchmarking:** Comprehensive comparative analysis with conventional motor technologies
3. **Control Algorithm Development:** Advanced control strategies addressing unique gate automation requirements
4. **Economic Analysis:** Detailed cost-benefit analysis demonstrating long-term economic advantages
5. **Field Validation:** Extensive field testing providing real-world performance validation

D. Future Research Directions

Several areas merit further investigation to advance BLDC motor technology in gate automation:

Sensorless Control Development: Research into robust sensorless control techniques specifically adapted to gate automation requirements could further reduce system cost and complexity.

Advanced Materials Research: Investigation of new permanent magnet materials and power semiconductor technologies could enable further performance improvements and cost reductions.

Artificial Intelligence Integration: Development of AI-based control systems could enable adaptive operation, predictive maintenance, and enhanced user experience.

System Integration Optimization: Research into integrated motor-controller designs and standardized interfaces could simplify installation and reduce overall system costs.

E. Final Remarks

The successful development and validation of this BLDC motor drive system represents a significant advancement in gate automation technology. The demonstrated performance advantages, combined with long-term economic benefits, position BLDC motors as the preferred technology for next-generation gate automation systems.

The comprehensive research approach, combining theoretical analysis, systematic design, and extensive experimental validation, provides a solid foundation for commercial implementation and further research development. The positive results across diverse operating conditions and applications confirm the robustness and versatility of the developed system.

This research contributes to the broader adoption of efficient, reliable, and intelligent automation systems, supporting the ongoing evolution toward smarter, more sustainable building and infrastructure management systems.

References:

[1] Krishnan, R. (2017). *Permanent Magnet Synchronous and Brushless DC Motor Drives*. CRC Press, Taylor & Francis Group, Boca Raton, FL, USA.

[2] Pillay, P., and Krishnan, R. (1989). "Modeling, simulation, and analysis of permanent-magnet motor drives, Part II: The brushless DC motor drive," *IEEE Transactions on Industry Applications*, vol. 25, no. 2, pp. 274-279.

[3] Jahns, T. M., and Soong, W. L. (1996). "Pulsating torque minimization techniques for permanent magnet AC motor drives—A review," *IEEE Transactions on Industrial Electronics*, vol. 43, no. 2, pp. 321-330.

[4] Hanselman, D. C. (2003). *Brushless Permanent Magnet Motor Design*, 2nd ed. The Writers' Collective, Cranston, RI, USA.

[5] Lee, W., and Sul, S. K. (2004). "A new starting method of BLDC motors without position sensor," *IEEE Transactions on Industry Applications*, vol. 42, no. 6, pp. 1532-1538.

[6] Gieras, J. F., and Wing, M. (2002). *Permanent Magnet Motor Technology: Design and Applications*, 2nd ed. Marcel Dekker Inc., New York, NY, USA.

[7] Acarnley, P. P., and Watson, J. F. (2006). "Review of position-sensorless operation of brushless permanent-magnet machines," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 2, pp. 352-362.

[8] Shao, J., Nolan, D., Teissier, M., and Swanson, D. (2003). "A novel microcontroller-based sensorless brushless DC (BLDC) motor drive for automotive fuel pumps," *IEEE Transactions on Industry Applications*, vol. 39, no. 6, pp. 1734-1740.

[9] Toliyat, H. A., and Kliman, G. B. (2004). *Handbook of Electric Motors*, 2nd ed. CRC Press, Marcel Dekker Inc., New York, NY, USA.

[10] Yedamale, P. (2003). "Brushless DC (BLDC) Motor Fundamentals," Microchip Technology Inc., Application Note AN885, Chandler, AZ, USA.