IAES Journal of Electrical and Electronics Engineering
Vol. 3, No. 1, June 2016, pp. 11~15
ISSN: 2338-7432, DOI: 10.11591/jeee.v3i1.pp11-15

Development of microcontroller-based BLDC motor speed control systems: from conventional approaches to intelligent control

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Article Info

Article history:

Received Oct 25, 2014
Revised May 31, 2015
Accepted Jul 30, 2015

Keywords:

BLDC motor
Fuzzy logic
Intelligent control
Microcontroller
PID controller
PWM
Sensorless control
Speed control

ABSTRACT

Brushless direct current (BLDC) motors have become increasingly important in modern electrical drive applications because of their high efficiency, compact construction, high torque density, and relatively low maintenance requirements. Despite these advantages, achieving accurate and stable speed regulation remains challenging, particularly when operating conditions involve changing mechanical loads, nonlinear motor characteristics, and limited controller resources. Microcontroller-based control systems provide a practical platform for integrating electronic commutation, pulse-width modulation (PWM), speed measurement, and advanced control algorithms. This review examines the development of BLDC motor speed control techniques, beginning with conventional Hall-sensor-based commutation and proportional-integral-derivative (PID) control, followed by fuzzy logic, adaptive fuzzy PID, and sensorless intelligent approaches. Particular attention is given to the relationship between control algorithms, rotor position detection, power electronic converters, and microcontroller implementation. Previous studies indicate that intelligent control techniques can improve dynamic performance and reduce sensitivity to conventional PID parameter tuning. Nevertheless, computational requirements, sensor accuracy, torque ripple, and low-speed operation remain important implementation challenges. This review identifies research opportunities for developing reliable, efficient, and computationally practical intelligent BLDC motor controllers.

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1. INTRODUCTION

Brushless direct current motors are widely used in electrical and electronic systems because of their favorable efficiency, compact dimensions, and high power-to-weight ratio. Their applications include electric vehicles, industrial automation, robotics, cooling systems, medical equipment, and household appliances. Unlike conventional brushed DC motors, BLDC motors use electronic commutation instead of mechanical brushes and commutators. This arrangement reduces mechanical wear and provides opportunities for more flexible electronic speed regulation [1].

However, the development of an effective BLDC speed controller involves several interconnected technical challenges. The controller must determine rotor position, synchronize the switching sequence, regulate motor current, and maintain the desired rotational speed under different load conditions. Conventional controllers can perform these functions, but their effectiveness may decrease when the motor experiences nonlinear behavior, parameter variations, or sudden mechanical disturbances. These limitations have encouraged researchers to investigate more adaptive and intelligent control strategies.

Microcontrollers provide an economical and programmable platform for implementing BLDC motor control systems. They can process Hall-effect sensor signals, generate PWM switching commands, measure motor speed, and execute control algorithms through software. The integration of these functions allows

conventional control hardware to be replaced or supplemented by flexible digital architectures. Nevertheless, the controller must possess adequate processing capability, timing accuracy, and peripheral resources to ensure reliable motor operation.

This review examines the development of microcontroller-based BLDC motor speed control from conventional approaches to intelligent control methods. It focuses on six-step electronic commutation, PWM, PID, fuzzy logic, adaptive fuzzy PID, and sensorless estimation techniques. The main objective is to evaluate their technical characteristics, implementation advantages, and limitations using literature published no later than 2015. The review also identifies research gaps that can guide the development of more reliable and computationally efficient motor controllers.

2. FUNDAMENTAL PRINCIPLES OF BLDC MOTOR SPEED CONTROL

Understanding the operating characteristics of BLDC motors is essential for selecting an appropriate speed-control strategy. A typical three-phase BLDC motor consists of permanent magnets mounted on the rotor and three-phase windings installed in the stator. Its operation depends on the synchronization between stator current excitation and rotor magnetic position. Consequently, accurate rotor position information is necessary to determine the appropriate electronic commutation sequence [1].

The conventional BLDC drive uses a three-phase voltage-source inverter to supply the motor windings. Six semiconductor switching states are commonly employed during one electrical cycle, with two phases conducting at a time in conventional six-step operation. Hall-effect sensors provide rotor position information, allowing the controller to determine the appropriate switching sequence. PWM is subsequently used to regulate the average voltage applied to the motor and adjust its rotational speed.

The speed-control process must consider both electrical and mechanical operating conditions. Increasing the PWM duty cycle generally increases the effective motor voltage and can increase rotational speed, provided that the supply and load conditions permit it. However, changes in mechanical loading can produce speed deviations even when the PWM command remains unchanged. Therefore, closed-loop control using measured speed feedback is important when accurate regulation is required.

3. CONVENTIONAL MICROCONTROLLER-BASED CONTROL APPROACHES

3.1. Hall-sensor-based electronic commutation

Hall-effect sensors represent one of the most established approaches for detecting rotor position in BLDC motor drives. Three sensors are generally installed with appropriate electrical displacement to produce digital position information during rotor rotation. The microcontroller interprets these signals and generates the corresponding six-step inverter switching sequence. This method is relatively simple and provides reliable commutation when the sensors and switching circuits operate correctly [1].

Iizuka *et al.* [2] demonstrated the early application of microcomputer-based control for sensorless brushless motors, establishing an important foundation for digitally controlled electronic commutation. Their work illustrated the potential of replacing conventional position detection arrangements with information derived from motor electrical characteristics. Later research expanded these approaches through improved sensing, estimation, and switching techniques. These developments established the technological basis for more flexible microcontroller-based BLDC drives.

3.2. PWM-based speed regulation

PWM is a fundamental technique for controlling BLDC motor speed through electronic switching. The microcontroller generates switching pulses with adjustable duty cycles, which regulate the effective voltage applied to the motor windings. This method is attractive because it can be implemented using standard digital timers and hardware PWM peripherals. It also provides a straightforward interface for integrating speed references, feedback measurements, and protection functions.

Wang [3] developed a BLDC motor drive and control system incorporating a switching driver, speed detection circuit, and closed-loop PID controller. The experimental results demonstrated stable operation under different loading conditions. The study is particularly relevant because it connects the electronic power stage with the digital control algorithm and practical speed measurement. It also demonstrates the importance of evaluating controller performance under mechanical disturbances rather than relying exclusively on unloaded operation.

3.3. Conventional PID control

PID control is widely used in motor speed regulation because of its relatively straightforward implementation and established control characteristics. The controller processes the difference between the

reference speed and measured motor speed to determine the required control action. Its proportional, integral, and derivative components contribute to the response speed, steady-state accuracy, and damping characteristics. A microcontroller can execute the PID algorithm and update the PWM duty cycle at regular sampling intervals.

Nevertheless, conventional PID performance depends strongly on appropriate parameter selection. Poor tuning may produce excessive overshoot, slow settling time, or oscillatory behavior when the motor experiences load variations. Kandiban and Arulmozhiyal [4] compared conventional PID, fuzzy PID, and adaptive fuzzy PID techniques for BLDC motor speed regulation. Their results indicated that adaptive fuzzy PID provided better control performance than the conventional and non-adaptive fuzzy approaches examined in their study.

4. DEVELOPMENT OF INTELLIGENT CONTROL TECHNIQUES

4.1. Fuzzy logic control

Fuzzy logic control represents an important transition from conventional fixed-parameter control toward intelligent control. Unlike conventional PID tuning, fuzzy logic uses linguistic rules and membership functions to determine the control response based on system conditions. Typical inputs include speed error and the change in speed error, while the output can be used to modify the PWM duty cycle. This approach is particularly attractive for nonlinear systems where obtaining an accurate mathematical model may be difficult.

In a microcontroller-based BLDC drive, the fuzzy inference process can be executed using programmed membership functions and a predefined rule base. The controller evaluates the input conditions and determines an appropriate control action through fuzzy inference and defuzzification. This arrangement allows the controller response to adapt to different operating conditions without requiring continuous manual adjustment of conventional PID parameters. However, the quality of the resulting performance depends on the design of membership functions, rule selection, and available processing resources.

4.2. Adaptive fuzzy PID control

Adaptive fuzzy PID combines the familiar structure of PID control with the flexibility of fuzzy logic. The fuzzy controller can adjust PID parameters according to the instantaneous control error and its rate of change. This arrangement is intended to improve the response under operating conditions where fixed PID parameters are insufficient. Consequently, adaptive fuzzy PID offers an intermediate approach between conventional feedback control and more complex intelligent algorithms.

Kandiban and Arulmozhiyal [4] investigated this approach through a comparative study of three controller configurations. Their reported results indicated that adaptive fuzzy PID achieved better control characteristics than conventional PID and fuzzy PID under the conditions examined. The findings suggest that combining adaptive parameter adjustment with conventional feedback control can improve BLDC speed regulation. However, the reported results should be interpreted within the experimental and simulation conditions of the original study rather than generalized to every motor configuration.

Yu *et al.* [5] also investigated adaptive fuzzy self-tuning PID control for high-speed sensorless BLDC motors. Their study demonstrated the potential of combining intelligent parameter adjustment with sensorless motor operation. The research is relevant because it connects two important developments in BLDC technology, namely adaptive speed regulation and rotor position estimation. Nevertheless, the implementation complexity and computational requirements must be considered when transferring such approaches to low-cost microcontrollers.

4.3. Sensorless and intelligent state estimation

Sensorless control is another significant development in BLDC motor technology because it reduces dependence on physical rotor position sensors. Conventional Hall sensors increase hardware cost and require appropriate mechanical installation within the motor assembly. Sensorless approaches estimate rotor position and speed from electrical measurements, particularly back electromotive force (back-EMF). This information can then be processed to determine the appropriate commutation sequence [1].

Gamazo-Real *et al.* [1] reviewed several sensorless techniques, including back-EMF detection, terminal voltage measurement, current-based estimation, and observer-based methods. Their review also discussed more advanced approaches involving sliding-mode observers, Kalman filters, and artificial neural networks. These techniques provide different compromises between estimation accuracy, computational complexity, and operating speed. Their findings demonstrate that sensorless operation is not a single control method but a broader category of estimation techniques.

Lv *et al.* [6] proposed an unscented Kalman filter approach for estimating BLDC motor speed and rotor position. Their method used measured terminal voltages and three-phase currents to estimate the

required motor states. Simulation results demonstrated the feasibility of the proposed estimation approach under the investigated conditions. This development indicates that nonlinear state estimation can provide an alternative to conventional physical position sensing, although computational requirements and low-speed estimation accuracy remain important concerns.

Chern *et al.* [7] also investigated sensorless BLDC speed control using six-step switching and rotor position detection. Their approach employed electrical signal processing to identify commutation information without relying on conventional Hall sensors. The experimental investigation demonstrated the feasibility of implementing a sensorless controller for an air-conditioning fan motor. This study illustrates the practical importance of reducing sensor dependence while maintaining reliable electronic commutation.

5. COMPARATIVE EVALUATION OF BLDC CONTROL TECHNIQUES

The development of BLDC motor speed control demonstrates a gradual transition from fixed switching arrangements toward adaptive and intelligent control architectures. Conventional Hall-sensor-based commutation provides a relatively straightforward solution, while PID control introduces closed-loop speed regulation. Fuzzy and adaptive fuzzy PID techniques provide additional flexibility when motor characteristics and load conditions vary. Sensorless estimation further extends the possibilities by reducing the requirement for physical rotor position sensors.

The main characteristics, advantages, and limitations of the reviewed approaches are summarized in Table 1. The comparison considers the control principle, hardware requirements, operational advantages, and implementation challenges. Particular attention is given to the differences between conventional feedback control, intelligent algorithms, and sensorless estimation. Table 1 provides a basis for identifying the suitability of each method for different BLDC motor applications.

Table 1. Comparison of BLDC motor speed control methods

Control method	Main technology	Advantages	Limitations
Hall-sensor commutation	Hall sensors and six-step inverter	Simple and reliable rotor position detection	Additional sensors and installation requirements
PWM control	Microcontroller and inverter	Simple speed adjustment and low implementation complexity	Open-loop operation is sensitive to load changes
PID control	Closed-loop speed feedback	Established control structure and straightforward implementation	Requires appropriate parameter tuning
Fuzzy logic	Fuzzy inference system	Adaptable to nonlinear operating conditions	Membership functions and rules require careful design
Adaptive fuzzy PID	Fuzzy parameter adjustment and PID	Improved adaptability and dynamic response	Greater algorithmic complexity
Sensorless control	Back-EMF detection and observers	Reduced sensor cost and improved integration flexibility	Difficult estimation at low speeds
Kalman-filter-based estimation	Nonlinear state estimation	Estimates rotor position and speed from electrical measurements	Higher computational requirements

The comparison indicates that the appropriate control strategy depends on the performance requirements and available hardware resources. Conventional PID remains attractive for applications requiring relatively simple and economical speed regulation. Adaptive fuzzy PID is more appropriate when improved response to changing operating conditions is required and sufficient processing resources are available. Sensorless estimation is particularly attractive when reducing sensor cost and improving mechanical integration are important design objectives.

6. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

Despite considerable progress, several challenges remain in the implementation of intelligent BLDC motor controllers. The first concerns computational limitations when advanced algorithms are implemented on low-cost microcontrollers. The second involves maintaining accurate rotor position estimation during low-speed operation, where back-EMF signals may be weak. The third relates to torque ripple, switching losses, and speed fluctuations under rapidly changing mechanical loads. These challenges indicate that intelligent control must be evaluated not only by its theoretical performance but also by its practical hardware requirements.

Future research should focus on combining efficient digital commutation with adaptive closed-loop speed regulation. Hybrid architectures that integrate conventional PID with fuzzy parameter adjustment may offer a practical balance between control performance and computational complexity. Improved sensorless

estimation methods could also reduce hardware requirements while maintaining reliable rotor synchronization. Experimental comparisons should evaluate overshoot, settling time, steady-state error, torque ripple, energy consumption, and performance under different mechanical loads.

Another important direction is the development of intelligent control algorithms suitable for embedded implementation. The effectiveness of an algorithm should be evaluated using the actual processing time, memory consumption, sampling frequency, and switching synchronization requirements. These considerations are particularly important when comparing conventional microcontrollers with more advanced digital signal controllers. A systematic assessment of both control performance and hardware complexity would provide a stronger basis for selecting suitable intelligent BLDC drive architectures.

7. CONCLUSION

This review has examined the development of microcontroller-based BLDC motor speed control systems, beginning with conventional electronic commutation and PWM regulation and progressing toward intelligent control techniques. The reviewed literature demonstrates that Hall-sensor-based commutation and PID control provide established solutions for basic motor speed regulation. Fuzzy logic and adaptive fuzzy PID introduce greater flexibility and can improve dynamic performance under the operating conditions investigated in previous studies. Sensorless techniques, including back-EMF detection and Kalman-filter-based estimation, provide additional opportunities to reduce hardware requirements and improve system integration.

The principal research gap concerns the practical integration of intelligent algorithms with computationally efficient microcontroller architectures. Although advanced estimation and adaptive control techniques demonstrate promising results, their implementation must consider processing capacity, low-speed operation, switching accuracy, and robustness under changing loads. Future research should prioritize experimentally validated hybrid control systems that combine reliable commutation, adaptive speed regulation, and efficient sensorless estimation. Ultimately, the development of an effective BLDC controller requires a balanced consideration of speed accuracy, dynamic response, torque stability, hardware complexity, and implementation cost.

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