IAES Journal of Electrical and Electronics Engineering
Vol. 5, No. 2, December 2018, pp. 42~46
ISSN: 2338-7432, DOI: 10.11591/jeee.v5i2.pp42-46

Servo motors: technologies, control architectures, applications, and performance challenges

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Article Info

Article history:

Received Jun 23, 2017
Revised Apr 7, 2018
Accepted Jun 8, 2018

Keywords:

Brushless DC motor
Field-oriented control
Industrial automation
Motion control
Permanent-magnet synchronous motor
Position control
Servo motor

ABSTRACT

Servo motors are electromechanical actuators designed to deliver controlled motion through a feedback-based drive system. They are central to industrial automation, robotics, machine tools, aerospace mechanisms, and precision positioning, where commands must be followed despite changing loads and operating conditions. This review examines servo motor technologies and control developments reported up to 2017, focusing on brushed direct-current motors, brushless DC motors, permanent-magnet synchronous motors (PMSMs), and induction-motor-based servo drives. It connects motor construction and drive electronics with feedback sensing, cascaded position–speed–current loops, field-oriented control (FOC), and advanced methods for disturbance rejection and trajectory tracking. The literature shows that brushed DC servos remain attractive for simple low-cost systems, whereas brushless and permanent-magnet machines offer improved power density, efficiency, and maintenance characteristics. Nevertheless, high-precision operation is constrained by parameter variation, load disturbances, friction, torque ripple, sensor limitations, thermal effects, and control bandwidth. Sensorless estimation and robust or adaptive controllers can reduce some limitations, although they introduce computational and implementation demands. The review concludes that servo selection should be application-driven and that dependable performance requires coordinated motor, drive, feedback, mechanical, control-system, and operational-safety design.

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1. INTRODUCTION

Servo motors are fundamental components in systems that require accurate control of angular or linear motion. They are widely used in industrial robots, CNC machine tools, automated production lines, packaging equipment, medical devices, and aerospace actuators. Unlike a conventional motor operated primarily to produce continuous rotation, a servo motor is generally integrated with a controller and feedback device to regulate position, speed, or torque. This closed-loop arrangement enables the actuator to follow a commanded motion profile while responding to external loads and disturbances.

The central engineering problem in servo applications is achieving accurate and stable motion under changing operating conditions. Load variation, friction, inertia mismatch, electrical parameter uncertainty, and mechanical resonance can cause tracking errors or unwanted oscillations. High acceleration and rapid settling are also required in many applications, but these objectives can conflict with current limits, thermal constraints, and mechanical durability. Consequently, servo performance depends not only on motor construction but also on drive electronics, feedback sensors, control algorithms, and the mechanical transmission system [1], [2].

This review examines servo motor technologies and control approaches documented up to 2017. It considers brushed DC, brushless DC (BLDC), permanent-magnet synchronous motor (PMSM), and induction-motor-based servo systems, with particular attention to feedback architectures and motion-control strategies. The discussion follows the relationship between motor selection, drive configuration, control

performance, and application requirements. It also identifies persistent research challenges that must be addressed to improve accuracy, robustness, efficiency, and reliability.

2. SERVO MOTOR TECHNOLOGIES

2.1. Brushed DC servo motors

Brushed DC motors represent an established solution for servo applications because their torque can be controlled through the armature current and their drive structures are comparatively straightforward. A typical DC servo system combines the motor with a power amplifier, position or speed sensor, and feedback controller. Its relatively simple electrical characteristics make it suitable for applications requiring moderate power and accessible control implementation. However, brushes and commutators introduce mechanical wear, electrical noise, maintenance requirements, and limitations at high rotational speeds [2].

The main advantage of brushed DC servo systems is their relatively direct relationship between the control input and motor torque. This characteristic simplifies controller design and can provide satisfactory performance in low-cost positioning equipment. Nevertheless, brush friction and commutation effects can influence low-speed operation and positioning accuracy. These limitations have encouraged the use of brushless motor technologies in applications where higher reliability, power density, and reduced maintenance are required.

2.2. Brushless DC servo motors

BLDC motors replace mechanical commutation with electronic switching, using rotor-position information to coordinate phase-current excitation. This architecture reduces brush-related wear and supports compact systems with favorable power-to-weight characteristics. Hall-effect sensors are commonly used to identify rotor position, while back-electromotive-force methods and observer-based algorithms can estimate rotor position without mechanical sensors. Gamazo-Real *et al.* [1] reviewed these sensorless techniques and discussed their implementation challenges in BLDC drives.

BLDC motors are attractive for robotics, automotive actuators, medical equipment, and compact automation systems. Their performance depends on commutation accuracy, current regulation, rotor-position estimation, and the characteristics of the inverter. Conventional six-step commutation is relatively simple, but it can produce torque ripple and acoustic noise under certain operating conditions. More advanced current-control and modulation strategies can improve smoothness, although they increase computational requirements and implementation complexity.

2.3. Permanent-magnet synchronous motor servo systems

PMSMs are widely used in high-performance servo applications because permanent magnets provide rotor excitation without requiring rotor current. Their high efficiency, power density, and rapid dynamic response make them suitable for precision positioning and demanding motion-control tasks. In many industrial systems, PMSM drives employ field-oriented control (FOC), which regulates torque-producing and flux-related current components through coordinated transformations and current controllers. This arrangement enables the motor to achieve precise torque regulation over a broad operating range [3], [4].

PMSM servo performance is influenced by electrical parameters, rotor position information, load inertia, friction, and external disturbances. Changes in these factors can reduce tracking accuracy or destabilize the control response if they are not adequately compensated. Mohamed demonstrated a robust current-control approach using an adaptive disturbance observer, while Mohamed, Li and Liu [2], [3] investigated adaptive speed control under variations in load inertia. These studies illustrate that high-performance PMSM operation requires more than nominal motor modeling and conventional proportional-integral control.

2.4. Induction-motor and linear servo systems

Induction motors can also be used in servo applications when combined with suitable vector-control and feedback systems. Their robust construction and absence of permanent magnets can make them attractive for industrial environments where durability and cost are important. However, accurate torque and speed regulation requires appropriate flux estimation and decoupling between torque and flux components. Compared with PMSM systems, induction-motor servo drives can involve more demanding parameter estimation because rotor resistance and magnetic conditions vary during operation.

Linear synchronous motors extend servo technology to direct linear motion without requiring a rotary motor and mechanical transmission. They are relevant to high-speed positioning platforms, semiconductor equipment, and precision manufacturing systems. Li *et al.* [5] proposed an integrated controller for a permanent-magnet linear synchronous motor servo system, combining feedforward control, disturbance observation, tracking compensation, and inertia variation compensation. Their work highlights

the importance of coordinating motor characteristics and motion-control algorithms when high positioning accuracy is required.

3. SERVO DRIVE AND FEEDBACK ARCHITECTURE

A servo drive converts the motion command into electrical signals that regulate the motor's torque, speed, and position. In a typical AC servo system, a power converter supplies controlled phase currents, while a digital controller processes feedback from current sensors and rotor-position devices. The control structure often consists of nested current, speed, and position loops, with the current loop operating at the highest bandwidth. This hierarchical arrangement allows the inner loop to regulate electromagnetic torque while the outer loops determine the required speed and position response [4], [6].

Feedback devices are essential because the controller must compare actual motor behavior with the reference command. Encoders and resolvers provide rotor-position information, while tachometers or estimated signals can be used for speed feedback. High-resolution encoders support precise positioning, but they increase system cost and may introduce installation or environmental constraints. Sensorless techniques can reduce hardware requirements, although estimation accuracy may deteriorate at low speed, during rapid acceleration, or under significant parameter variation [1], [7].

4. SERVO MOTOR CONTROL STRATEGIES

4.1. Conventional PID and field-oriented control

Proportional-integral-derivative (PID) control remains common in servo systems because it is relatively simple to implement and can provide effective regulation when the plant characteristics are adequately understood. In a cascaded architecture, the position controller generates a speed reference, the speed controller produces a torque or current reference, and the current controller regulates motor excitation. This structure is widely adopted because it separates the motion-control objectives into manageable control loops. However, fixed-gain PID controllers may show degraded performance when the load, inertia, friction, or motor parameters change substantially [3], [4].

FOC is a major control approach for AC servo motors, particularly PMSM drives. It transforms phase currents into a rotating reference frame so that torque and flux components can be regulated more independently. This decoupling simplifies torque control and supports smooth operation over a wide speed range. Nevertheless, FOC depends on accurate rotor-position information and suitable motor parameters, meaning that estimation errors and parameter drift can affect its performance [8], [9].

4.2. Robust, adaptive, and disturbance-rejection control

Advanced servo controllers have been developed to address disturbances and uncertainties that conventional control methods cannot adequately compensate. Sliding-mode control, backstepping, adaptive control, and disturbance-observer-based approaches are among the techniques investigated for PMSM servo systems. Zhang *et al.* [6] combined sliding-mode control with disturbance compensation to improve speed regulation under uncertain operating conditions. Yang *et al.* [9] subsequently reviewed disturbance and uncertainty estimation techniques in PMSM drives, emphasizing the complementary roles of disturbance observers, robust control, and adaptive methods.

Position tracking is another important objective in high-performance servo applications. Ha *et al.* [8] developed an internal-model-principle-based nonlinear controller to improve PMSM position tracking and reject load torque disturbances and position ripple. Linares-Flores *et al.* [10] investigated robust backstepping control for low-speed PMSM positioning, addressing tracking accuracy through a controller supported by disturbance estimation. These studies demonstrate that advanced control methods can improve robustness, although their effectiveness depends on model assumptions, sensor quality, computational capacity, and implementation details.

4.3. Predictive and time-optimal control

Predictive control methods use a model of the motor or servo system to anticipate future behavior and determine suitable control actions. Liu and Li [4] applied predictive functional control with an extended-state observer to the speed loop of a PMSM servo system, aiming to improve regulation under disturbances. This approach combines prediction with disturbance estimation, providing an alternative to conventional fixed-gain speed regulation. Its practical implementation, however, depends on model quality, sampling frequency, and the computational resources available in the drive controller.

Time-optimal control is relevant when a servo mechanism must reach a commanded position rapidly while maintaining acceptable settling behavior. Lu and Cheng [11] extended proximate time-optimal servo

control to a PMSM system and evaluated its tracking performance through simulation and experimental implementation. Their approach illustrates the potential of combining rapid acceleration or braking with smoother control near the target position. In practical applications, such methods must also respect current limits, voltage constraints, mechanical vibration, and actuator thermal capacity.

5. APPLICATIONS AND PERFORMANCE REQUIREMENTS

Servo motors support a broad range of applications, but the required performance varies considerably across sectors. Industrial robots require coordinated multi-axis motion, repeatable positioning, and rapid response to changing payloads. CNC machines emphasize contour accuracy, smooth feed motion, and resistance to cutting-force disturbances. Packaging and assembly systems often prioritize rapid cycling and reliable operation, whereas aerospace and medical mechanisms may place greater emphasis on compactness, safety, and fault tolerance.

The choice of servo technology should therefore reflect the operating environment and motion requirements. Brushed DC motors may be sufficient for simple and cost-sensitive positioning systems, while BLDC and PMSM technologies are often preferred where maintenance, efficiency, and power density are important. Linear servo motors are useful when direct linear actuation can reduce mechanical transmission complexity or improve positioning performance. The final system design must consider the motor, drive, feedback device, mechanical load, and controller as an integrated unit rather than selecting a motor solely on its rated power [1], [5], [12].

6. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite extensive development, servo systems continue to face challenges involving parameter uncertainty, friction, torque ripple, thermal effects, and mechanical resonance. These factors can produce tracking errors, limit achievable bandwidth, and reduce repeatability under changing loads. Sensorless control can reduce dependence on mechanical feedback devices, but reliable operation across the full speed range remains difficult. Zhang and Cheng [7] investigated extended Kalman filter parameter tuning for sensorless PMSM control, illustrating both the potential and complexity of observer-based estimation.

Future research should focus on control architectures that combine accuracy, robustness, computational efficiency, and practical implementability. Disturbance observers and adaptive methods can compensate for changing loads and uncertain parameters, but they must be designed to avoid excessive noise amplification and unstable interactions between control loops. Predictive and intelligent algorithms may improve motion performance, although their real-time computational requirements must be considered during hardware selection. Equally important, experimental validation should include realistic load variations, thermal conditions, sensor imperfections, and long-duration operation rather than relying exclusively on nominal simulations [9], [11].

7. CONCLUSION

Servo motors are essential actuators for applications requiring accurate position, speed, and torque regulation. Brushed DC motors remain useful in simple systems, while BLDC and PMSM technologies offer advantages in efficiency, power density, and reduced maintenance. High-performance servo operation depends on coordinated motor design, power conversion, feedback sensing, and control architecture. Conventional PID and FOC remain important foundations, while robust, adaptive, observer-based, and predictive approaches extend performance under disturbances and parameter uncertainty.

The reviewed literature shows that no single servo motor or control method is optimal for every application. Selection should be based on motion accuracy, dynamic response, load characteristics, maintenance requirements, energy efficiency, and implementation cost. Further progress requires stronger integration of motor modeling, real-time control, disturbance estimation, and practical validation. Ultimately, reliable servo performance is achieved through the coordinated design of the complete electromechanical system rather than through motor selection or controller optimization in isolation.

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