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Advanced and intelligent field-oriented control for electric vehicles: a review of ai-based optimization, robust control, and real-time implementation

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ABSTRACT

Field-oriented control (FOC) is widely adopted in electric vehicle (EV) traction drives because it provides effective torque and speed regulation with high dynamic performance. Nevertheless, conventional FOC depends on accurately tuned proportional-integral controllers, reliable rotor-position information, and sufficiently precise motor parameters. These dependencies can limit performance under rapid load changes, parameter variations, sensor faults, and demanding operating conditions. This review examines recent developments in advanced and intelligent FOC, focusing on adaptive and sensorless control, artificial intelligence integration, model predictive control, robust regulation, and real-time implementation. Fuzzy logic, neural networks, and machine learning are discussed as approaches for improving controller adaptation, parameter estimation, and disturbance rejection. The combination of FOC and model predictive control is evaluated in terms of transient response, constraint handling, computational requirements, and implementation complexity. Furthermore, digital signal processors (DSP), field-programmable gate array (FPGA), and automotive microcontroller platforms are considered for practical deployment. The review identifies a transition from conventional fixed-parameter FOC toward intelligent, observer-assisted, and computationally optimized architectures. Future progress requires stronger experimental validation, functional safety assessment, and systematic evaluation under realistic EV driving conditions.

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1. INTRODUCTION

Electric vehicle performance depends strongly on the efficiency, reliability, and dynamic response of its electric traction drive. Permanent magnet synchronous motors (PMSMs) are widely used in EV applications because of their high-power density, efficiency, and favorable torque characteristics. Field-oriented control (FOC) is an established strategy for these machines because it regulates torque and magnetic flux through decoupled control channels. Its practical implementation, however, becomes increasingly challenging when vehicle operating conditions differ from the assumptions used during controller design [1], [2].

Conventional FOC generally employs proportional-integral (PI) controllers, current measurements, rotor-position feedback, and pulse-width modulation. Although this structure is mature and computationally manageable, its performance depends on controller tuning and the accuracy of motor parameters. Changes in temperature, magnetic saturation, load torque, and operating speed can degrade current decoupling and speed tracking. These limitations motivate the development of adaptive, intelligent, and robust FOC architectures [3], [4].

Recent research has explored artificial intelligence (AI), predictive control, advanced observers, and digital implementation to improve motor-drive performance. Nevertheless, these approaches introduce additional computational requirements, design complexity, and validation challenges. This review critically examines these developments and identifies how they can contribute to more efficient, reliable, and

responsive EV traction systems. The discussion progresses from conventional FOC limitations to intelligent control methods, robust operation, and real-time hardware implementation.

2. CONVENTIONAL FOC AND ITS LIMITATIONS

Conventional FOC transforms three-phase motor quantities into a rotating reference frame, allowing torque-producing and flux-producing current components to be regulated separately. The control structure typically includes an outer speed loop, inner current loops, coordinate transformations, and an inverter modulation stage. PI controllers remain popular because they are relatively simple to implement and can provide satisfactory steady-state performance when the motor model and operating conditions are well understood. This architecture has consequently become a fundamental reference for evaluating advanced PMSM drive controllers [1], [5].

Despite its advantages, conventional FOC has several important limitations. Fixed PI gains may produce excessive overshoot, slower recovery, or degraded tracking when motor parameters and load conditions change. Rotor-position sensors also introduce additional cost, wiring, mechanical installation requirements, and potential failure points. Furthermore, conventional control structures do not inherently optimize multiple constraints, such as current limits, voltage utilization, switching losses, and thermal operating boundaries, within a unified predictive framework [2], [6].

3. ADAPTIVE AND SENSORLESS FOC

3.1. Adaptive FOC

Adaptive FOC addresses operating-point variations by modifying controller parameters or control references according to changing system conditions. Adaptive PI tuning, gain scheduling, disturbance estimation, and online parameter identification are among the methods used to improve tracking performance. Fuzzy-based adaptive controllers can modify control actions without requiring an exact analytical representation of every operating condition. Experimental and simulation studies have demonstrated the potential of adaptive and fuzzy approaches to improve PMSM speed regulation under load variations [7]-[9].

Neural-network-based methods offer another approach to adaptive motor control. A neural network can approximate nonlinear relationships, estimate uncertain parameters, or adjust control actions using measured operating data. Recurrent neural networks and other learning structures have been investigated for robust predictive speed regulation and compensation of parameter mismatches. However, training-data coverage, computational cost, stability guarantees, and generalization to unseen operating conditions remain important concerns [10], [11].

3.2. Sensorless FOC

Sensorless FOC estimates rotor position and speed from electrical measurements rather than relying exclusively on mechanical sensors. Common approaches include model reference adaptive systems, sliding-mode observers, back-electromotive-force estimation, and flux observers. Removing mechanical sensors can reduce hardware complexity and improve tolerance to sensor failure, which is particularly relevant to traction-drive reliability. Nevertheless, estimation accuracy is strongly influenced by operating speed, inverter nonlinearity, parameter uncertainty, and measurement noise [12]-[14].

Low-speed operation remains a major challenge for many sensorless techniques because back electromotive force becomes weak and less informative. Sliding-mode observers can provide robustness against certain disturbances, but chattering and filtering delays may affect estimation quality. Model reference adaptive systems offer a structured alternative, although their performance depends on the reference model and adaptation law. Hybrid observers and intelligent estimation methods are therefore being investigated to improve position estimation across a wider operating range [13]-[16].

4. ARTIFICIAL INTELLIGENCE INTEGRATION IN FOC

4.1. Fuzzy logic control

Fuzzy logic can improve FOC by replacing fixed control rules with an inference mechanism that responds to speed error, error variation, and other measured operating variables. A fuzzy speed controller can adjust the control response under changing loads without requiring a complete mathematical model of the motor and vehicle. Fuzzy-PI structures combine the interpretability of conventional PI control with adaptive rule-based adjustment. Research on PMSM drives has reported improved dynamic response and robustness

using fuzzy-based controller structures, although performance depends on membership functions, rule design, and experimental conditions [7], [8], [17].

4.2. Neural networks and machine learning

Neural networks can support FOC through nonlinear compensation, speed estimation, parameter identification, and adaptive control. Their ability to approximate complex system behavior makes them attractive for motors operating under variable load and temperature conditions. Machine-learning observers have also been investigated to estimate rotor position and improve sensorless PMSM operation. Nevertheless, data quality, computational requirements, model transparency, and the possibility of unreliable predictions outside the training domain must be considered before automotive deployment [10], [18], [19].

4.3. Intelligent optimization

AI-based optimization can be applied to tune PI gains, fuzzy membership functions, neural-network parameters, and predictive-control weights. Optimization methods can reduce the dependence on manual tuning and improve performance across selected operating scenarios. However, an optimized controller is only as reliable as its objective function, constraints, and training or test conditions. Therefore, optimization should include efficiency, torque ripple, current limits, transient response, and robustness rather than focusing exclusively on speed-tracking error.

5. INTEGRATION OF MODEL PREDICTIVE CONTROL WITH FOC

Model predictive control (MPC) uses a mathematical model to predict future system behavior and select control actions that minimize a defined performance objective. When integrated with FOC, MPC can improve current regulation, optimize reference generation, or coordinate multiple operating constraints. Finite-control-set MPC evaluates available inverter switching states, whereas continuous-control-set MPC calculates a continuous voltage reference that is generally applied through modulation. Both approaches have been extensively investigated for PMSM drives because of their potential for rapid response and multi-objective control [20].

The integration of MPC and FOC can address limitations associated with fixed-gain current regulators. Predictive algorithms can account for current and voltage constraints, while the FOC structure retains a familiar framework for torque and flux regulation. However, prediction accuracy depends on the motor model and parameter estimates, while computational demand increases with prediction horizon, candidate switching states, and optimization complexity. Delay compensation, disturbance observers, simplified cost functions, and online parameter identification are therefore important techniques for practical implementation [20], [21].

6. ROBUST CONTROL UNDER LOAD AND PARAMETER VARIATIONS

Robust FOC aims to preserve acceptable motor performance despite disturbances, parameter uncertainty, and changes in operating conditions. Relevant uncertainties include stator resistance variation, inductance changes, magnetic saturation, load torque disturbances, and inverter nonidealities. Adaptive robust controllers combine online parameter estimation with feedback compensation to reduce the effect of these uncertainties. Experimental studies have demonstrated robust PMSM control strategies that explicitly address current constraints, external disturbances, and uncertain motor parameters [11], [22].

Disturbance observers and sliding-mode control can further improve the resilience of FOC-based drives. A disturbance observer estimates the combined effect of unmodeled dynamics and external disturbances, allowing the controller to compensate for their influence. Sliding-mode methods can provide strong disturbance rejection, although chattering and implementation sensitivity require careful design. Fault-tolerant FOC extends this concept by maintaining controlled operation under selected electrical faults, which is important for traction systems where unexpected loss of drive capability can affect vehicle safety [15], [23].

7. REAL-TIME IMPLEMENTATION PLATFORMS

7.1. Digital signal processors (DSP)

DSP platforms are widely used in motor-drive control because they support fast arithmetic operations, analog-to-digital conversion, PWM generation, and deterministic interrupt processing. Their architecture is suitable for implementing coordinate transformations, current regulators, observers, and speed-control algorithms within a fixed sampling period. DSP-based sensorless adaptive control has

demonstrated the feasibility of combining estimation and control functions on embedded hardware. However, the execution time of AI and predictive algorithms must be measured carefully to avoid missed sampling deadlines [24], [25].

7.2. Field-programmable gate arrays (FPGA)

FPGAs provide parallel processing and deterministic hardware execution, making them suitable for high-speed control functions and computationally intensive signal processing. Their parallel architecture can reduce latency in current acquisition, coordinate transformations, PWM generation, and observer calculations. Experimental motor-drive research has demonstrated FPGA-based control implementations with fast response and disturbance compensation. Nevertheless, development complexity, hardware resource utilization, verification effort, and integration with the vehicle control architecture remain significant considerations [26].

7.3. Automotive microcontrollers

Automotive microcontrollers provide an integrated platform for control, diagnostics, communication, and safety-related functions. They are attractive for production-oriented traction drives because they can support real-time motor control alongside communication with battery management and vehicle supervisory systems. Compared with general-purpose DSP or FPGA platforms, automotive microcontrollers may offer stronger integration with automotive development processes and safety mechanisms. Their suitability for advanced FOC depends on processor performance, peripheral availability, memory capacity, software architecture, and the computational demands of the selected algorithm [27].

Table 1 summarizes the main characteristics of the control strategies and hardware platforms discussed in this review. The comparison highlights that improved control performance is not determined by the algorithm alone, because computational capability, sensor configuration, and implementation complexity also influence the final result [28].

Table 1. Comparative assessment of advanced FOC strategies and implementation platforms

Method or platform	Main contribution	Principal limitation	Potential EV application
Conventional FOC	Mature torque and speed regulation	Fixed tuning and sensor dependence	Baseline traction control
Adaptive FOC	Adjusts control behavior to operating changes	Adaptation design and stability	Variable-load operation
Sensorless FOC	Reduces mechanical sensor dependence	Low-speed estimation challenges	Cost and reliability improvement
Fuzzy FOC	Rule-based nonlinear adaptation	Rule and membership-function design	Disturbance compensation
Neural-network FOC	Nonlinear estimation and compensation	Training and computational demands	Intelligent parameter adaptation
MPC-FOC	Predictive optimization and constraint handling	Model accuracy and execution time	High-performance traction drives
Robust FOC	Disturbance and uncertainty rejection	Design and validation complexity	Wide operating conditions
DSP	Fast embedded numerical processing	Limited resources for complex algorithms	Real-time motor control
FPGA	Parallel processing and deterministic execution	Development and verification complexity	High-speed control functions
Automotive MCU	Integrated control and vehicle communication	Processor and memory constraints	Production-oriented EV controllers

8. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite significant progress, several challenges remain before intelligent FOC can be adopted consistently across production EV platforms. Many published studies evaluate new algorithms through simulation or laboratory motor tests rather than complete vehicle operation. Comparisons are also difficult because different studies use different motor ratings, sampling frequencies, test conditions, and performance indicators. A more consistent evaluation framework should include efficiency maps, torque ripple, transient response, robustness, computational load, and fault behavior [29].

Future research should prioritize hybrid architectures that combine the strengths of conventional FOC, adaptive estimation, AI-based optimization, and predictive control. AI algorithms should support rather than replace safety-critical control functions unless their stability and failure behavior can be adequately demonstrated. Hardware-in-the-loop testing, processor-in-the-loop evaluation, and vehicle-level validation

are essential steps toward deployment. In addition, functional safety, cybersecurity, software verification, and thermal constraints should be considered from the beginning of the controller development process [30].

9. CONCLUSION

Advanced FOC is evolving from a conventional fixed-parameter control structure toward adaptive, sensorless, intelligent, and predictive motor-drive architectures. Fuzzy logic and neural networks offer opportunities for nonlinear compensation and adaptive parameter estimation, while MPC improves the ability to handle dynamic constraints and optimize control actions. Robust observers and adaptive controllers can reduce the effects of load disturbances, parameter variations, and selected sensor or electrical faults. DSPs, FPGAs, and automotive microcontrollers provide different pathways for implementing these methods under real-time constraints. The central challenge is to achieve a practical balance among control performance, computational complexity, reliability, and automotive safety. No single advanced strategy is universally superior because the most appropriate solution depends on motor characteristics, vehicle requirements, hardware resources, and validation conditions. Future EV traction systems will likely employ hybrid control architectures in which conventional FOC provides a dependable foundation and intelligent methods enhance adaptation, estimation, and optimization. Demonstrating these benefits through repeatable hardware and vehicle-level testing remains essential for translating research advances into reliable automotive products.

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