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Field-oriented control for electric vehicle traction drives: a review of control strategies, motor technologies, and performance optimization

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ABSTRACT

Field-oriented control (FOC) is a widely adopted strategy for regulating electric motor drives in electric vehicles (EVs), offering coordinated control of electromagnetic torque and magnetic flux. Its importance has increased with the demand for efficient traction systems capable of delivering rapid acceleration, smooth torque, and energy recovery during braking. This review examines the operating principles of FOC, including Clarke and Park transformations, and discusses its implementation in permanent magnet synchronous motors (PMSMs), brushless direct-current (BLDC) motors, and induction motors. The relationship between FOC, speed regulation, torque production, flux weakening, and maximum torque per ampere operation is evaluated. Its performance is also compared with direct torque control (DTC), particularly regarding dynamic response, torque ripple, computational requirements, and parameter sensitivity. Furthermore, the review considers regenerative braking and practical challenges associated with changing loads, temperature, motor parameters, and sensor reliability. The literature indicates that FOC provides a flexible foundation for high-performance EV traction, although its effectiveness depends on appropriate motor modeling, current regulation, and operating-point optimization. Future development should emphasize robust, adaptive, and computationally efficient control architectures.

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1. INTRODUCTION

Electric vehicle development depends not only on battery capacity but also on the efficiency and controllability of the electric traction drive. The traction motor must deliver high starting torque, operate over a wide speed range, respond rapidly to driver commands, and maintain acceptable efficiency under changing road conditions. These requirements place substantial demands on the inverter, motor, sensors, and embedded control system. Consequently, advanced motor-control strategies have become central to improving vehicle performance, driving range, and energy utilization [1]–[4].

Field-oriented control (FOC), also known as vector control, is an important approach for meeting these requirements. It transforms three-phase motor quantities into a rotating reference frame in which torque-producing and flux-producing current components can be regulated separately. This decoupled control structure provides characteristics similar to those of separately excited DC motors while retaining the

advantages of AC machines. Its application has been investigated extensively in permanent magnet synchronous motors (PMSMs) and induction motor drives, including traction systems for electric vehicles [5]–[8].

Despite its advantages, conventional FOC is not free from practical limitations. Its performance depends on accurate motor parameters, rotor-position information, current measurements, and properly tuned control loops. Temperature variation, magnetic saturation, inverter nonlinearity, and sudden load changes can introduce deviations between the mathematical model and the actual motor. This review therefore examines FOC principles, motor-specific implementation, comparisons with DTC, and performance optimization, with particular attention to the challenges that remain in EV traction applications.

2. OPERATING PRINCIPLES OF FIELD-ORIENTED CONTROL

FOC achieves independent regulation of motor torque and magnetic flux through coordinate transformations. The Clarke transformation converts measured three-phase currents into two orthogonal components in a stationary reference frame, commonly identified as the alpha-beta frame. The Park transformation then converts these components into direct-axis and quadrature-axis quantities in a rotating reference frame synchronized with the rotor magnetic field. This transformation makes the current-control problem easier to manage because the resulting direct and quadrature components can be assigned different control objectives [5], [9].

The direct-axis current is primarily associated with flux regulation, whereas the quadrature-axis current is primarily responsible for torque production. In a surface-mounted PMSM, the direct-axis current reference is commonly maintained near zero below base speed, while the quadrature-axis reference follows the demanded torque. Interior PMSM drives can also exploit reluctance torque by adjusting the direct-axis current. For induction motors, the corresponding vector-control structure regulates rotor flux and torque through appropriately oriented current components [6], [10], [11].

A typical FOC architecture contains a speed controller, current controllers, coordinate transformations, a pulse-width modulation stage, and a voltage-source inverter. The speed controller generates a torque-related current reference from the difference between commanded and measured speed. Inner current-control loops regulate the direct- and quadrature-axis currents, while decoupling compensation improves their dynamic behavior. Space-vector pulse-width modulation is frequently used to translate the voltage references into inverter switching signals [5], [12].

3. FOC IMPLEMENTATION IN DIFFERENT TRACTION MOTORS

The suitability of FOC depends partly on the electromagnetic characteristics of the selected traction motor. PMSMs are widely used in EVs because of their high torque density, efficiency, and favorable power-to-weight ratio. Their permanent magnets provide rotor excitation without requiring continuous magnetizing current, although magnet temperature and demagnetization limits must be considered. FOC is particularly suitable for PMSM traction because it supports precise torque regulation and a wide operating speed range [1], [2], [8].

BLDC motors are another option for electric propulsion, particularly in compact vehicles and applications where simple construction and high efficiency are attractive. Conventional BLDC operation commonly uses six-step commutation and trapezoidal back electromotive force, whereas FOC applies vector-based current regulation. The FOC approach can improve current waveform quality and torque smoothness, although its implementation requires suitable rotor-position information and motor modeling. Research on BLDC electric motorcycles and vehicle-related systems demonstrates the applicability of this approach beyond conventional PMSM drives [13], [14].

Induction motors remain relevant to EV traction because of their robust construction, absence of permanent magnets, and established industrial technology. Their FOC implementation generally uses indirect or direct rotor-flux orientation, with rotor-flux estimation playing an important role in the control structure. Accurate rotor resistance estimation is particularly important because resistance changes with temperature and can affect flux orientation. Studies of EV traction systems have evaluated induction-motor vector control under different driving cycles and operating conditions [6], [7], [15].

Table 1 compares the principal motor technologies from the perspective of FOC implementation. The comparison shows that PMSMs offer attractive efficiency and torque-density characteristics, while induction motors provide robustness and avoid dependence on permanent magnets. BLDC motors can be suitable for compact traction applications, although torque smoothness and commutation strategy influence their control design. Motor selection must therefore consider vehicle requirements rather than relying on a single performance indicator [1]–[4], [13].

Table 1. Comparison of motor technologies for FOC-based EV traction

Motor technology	FOC characteristics	Main advantages	Main challenges
PMSM	Independent d–q current regulation	High efficiency, torque density, precise control	Magnet temperature, parameter variation, field weakening
BLDC	Vector current control with rotor-position synchronization	Compact construction, smooth torque potential	Position estimation, implementation complexity
Induction motor	Rotor-flux-oriented current regulation	Robustness, no permanent magnets	Rotor resistance variation, flux estimation, magnetizing losses

4. TORQUE, SPEED, AND FLUX OPTIMIZATION

FOC performance is strongly influenced by the strategy used to generate current references. Below base speed, maximum torque per ampere (MTPA) control aims to produce the required torque with minimum stator current. This reduces copper losses and can improve the efficiency of the traction system. MTPA is particularly important for interior PMSMs because both permanent-magnet torque and reluctance torque contribute to the total electromagnetic torque [16], [17].

At high speed, the voltage limit of the inverter and DC battery bus restricts the available operating range. Field weakening addresses this limitation by adjusting the direct-axis current to reduce the effective air-gap flux and back electromotive force. This allows the motor to operate above its base speed, although the available torque generally decreases as speed increases. Recent reviews of PMSM field-weakening methods identify current-reference calculation, voltage feedback, and predictive approaches as important alternatives.

The speed-control loop must also maintain stable operation during acceleration, cruising, hill climbing, and sudden changes in road load.

Conventional proportional-integral controllers are widely used because of their simple implementation and manageable computational requirements. However, fixed controller gains may not provide optimal behavior across the full operating range, particularly when motor parameters and load conditions vary. Adaptive, fuzzy, and predictive approaches have therefore been investigated to improve transient response and robustness [8].

5. COMPARISON BETWEEN FOC AND DIRECT TORQUE CONTROL

Direct torque control (DTC) provides an alternative to FOC by regulating electromagnetic torque and stator flux more directly. Conventional DTC estimates torque and flux from motor quantities and selects inverter switching states according to control errors and switching tables. Its structure can provide a rapid torque response without requiring the same cascaded current-control architecture used in conventional FOC. However, hysteresis-based DTC may produce higher torque and flux ripple, while its switching frequency can vary with operating conditions [18].

FOC generally offers more structured current regulation and predictable switching behavior when combined with an appropriate PWM strategy. Its performance, however, depends on coordinate transformations, current-loop tuning, rotor-position information, and parameter accuracy. Comparative studies of induction motor drives for EVs have shown that the relative performance of FOC and DTC depends on the selected speed controller and operating conditions.

Therefore, neither strategy should be considered universally superior without specifying the motor, inverter, control implementation, and evaluation criteria [18]–[20]. Table 2 is general comparison of FOC and DTC for EV traction drives.

Table 2. General comparison of FOC and DTC for EV traction drives

Evaluation criterion	FOC	Conventional DTC
Torque response	Fast, dependent on current-loop tuning	Typically very fast
Torque ripple	Generally low with suitable PWM	Can be relatively high
Current regulation	Direct regulation in d–q axes	Indirect in basic switching-table DTC
Switching frequency	Usually controlled by PWM	May vary with hysteresis control
Parameter sensitivity	Sensitive to motor parameters and position estimation	Sensitive to flux and torque estimation
Implementation	More coordinate transformations and control loops	Simpler basic switching structure
Typical strength	Smooth and precise drive operation	Rapid torque response

Table 2 summarizes the principal differences between the two strategies. FOC is attractive where smooth torque production, current regulation, and controlled switching are priorities. DTC can be advantageous where rapid torque response and a simpler switching-selection structure are important.

Advanced DTC methods using space-vector modulation can reduce some conventional limitations, while predictive and adaptive FOC methods can improve the robustness of vector control [19].

6. REGENERATIVE BRAKING AND ENERGY EFFICIENCY

Regenerative braking allows an electric traction motor to operate as a generator during vehicle deceleration. In an FOC-based drive, the torque reference is adjusted to produce negative electromagnetic torque while maintaining current and voltage constraints. The generated electrical energy is transferred through the inverter and DC-link system toward the battery or an additional energy-storage device. This process can improve overall energy utilization, particularly during urban driving with frequent deceleration [20]–[22].

The amount of recoverable energy depends on vehicle speed, braking demand, motor efficiency, battery state of charge, and power-electronic limitations. Regenerative torque must also be coordinated with mechanical braking to preserve vehicle stability and satisfy the required deceleration. At low speeds, limited back electromotive force can reduce the effectiveness of energy recovery, making friction braking necessary. Therefore, FOC contributes to regenerative braking, but the achievable energy recovery is determined by the complete vehicle-level braking and energy-management system [20], [21].

7. PRACTICAL CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Several implementation challenges remain before FOC can deliver consistent performance under all EV operating conditions. Rotor-position sensors and current sensors increase system cost and may introduce reliability concerns, particularly in harsh automotive environments. Sensorless estimation can reduce hardware requirements, but accurate estimation at low speed and during rapid transients remains difficult. Research on sensorless PMSM vector control and sensor-reduced induction motor drives illustrates the continuing importance of reliable state estimation [18], [23].

Motor parameter variation is another important limitation. Winding resistance changes with temperature, while magnetic saturation and cross-coupling can affect inductance and flux estimates. These effects may degrade current decoupling, torque accuracy, and stability if the controller relies on fixed nominal parameters. Online parameter identification, adaptive control, robust observers, and data-driven compensation are promising directions for improving performance [17], [18], [23].

The growing use of wide-bandgap semiconductor devices also creates opportunities for improving traction-drive performance. Silicon-carbide inverters can support higher switching frequencies and reduced power losses, although their faster switching behavior introduces additional electromagnetic compatibility and thermal-design considerations. Future FOC research should therefore consider the motor, inverter, sensors, battery, and vehicle dynamics as an integrated system. Validation using standardized driving cycles and hardware-in-the-loop or vehicle-level experiments is also necessary to establish the practical value of proposed control improvements [24].

8. CONCLUSION

FOC provides a flexible and effective control framework for EV traction drives by separating torque-producing and flux-producing current components through Clarke and Park transformations. Its implementation in permanent magnet synchronous motors, BLDC, and induction motors demonstrates its adaptability to different traction technologies and vehicle requirements. MTPA and field-weakening strategies extend its usefulness across low- and high-speed operating regions, while coordinated negative-torque control enables regenerative braking.

Compared with conventional DTC, FOC generally offers structured current regulation and low-ripple operation, although it requires accurate motor information and appropriate controller tuning. The review identifies parameter variation, sensor reliability, computational requirements, and changing vehicle operating conditions as persistent challenges. Further progress will depend on adaptive control, reliable sensorless estimation, improved inverter technology, and integrated energy management. Equally important is the need for experimental validation under realistic driving cycles rather than relying exclusively on isolated motor simulations. These developments can strengthen the role of FOC in efficient, responsive, and reliable electric vehicle propulsion.

REFERENCES

[1] W. Cai, X. Wu, M. Zhou, Y. Liang, and Y. Wang, "Review and development of electric motor systems and electric powertrains for new energy vehicles," *Automotive Innovation*, vol. 4, no. 1, pp. 3–22, 2021, doi: 10.1007/s42154-021-00139-z.

[2] S. Krishnamoorthy and P. P. K. Panikkar, "A comprehensive review of different electric motors for electric vehicles application," *International Journal of Power Electronics and Drive Systems*, vol. 15, no. 1, pp. 74–90, 2024, doi: 10.11591/ijpeds.v15.i1.pp74-90.

[3] A. Eldho Aliasand and F. T. Josh, "Selection of motor foran electric vehicle: a review," *Materials Today: Proceedings*, vol. 24, no. 3, pp. 1804–1815, 2020, doi: 10.1016/j.matpr.2020.03.605.

[4] M. H. Basappa and P. Viswanathan, "Various control methods of permanent magnet synchronous motor drives in electric vehicle: a technical review," *Telkomnika (Telecommunication Computing Electronics and Control)*, vol. 20, no. 6, pp. 1225–1229, 2022, doi: 10.12928/TELKOMNIKA.v20i6.24236.

[5] M. Aktas, K. Awaili, M. Ehsani, and A. Arisoy, "Direct torque control versus indirect field-oriented control of induction motors for electric vehicle applications," *Engineering Science and Technology, an International Journal*, vol. 23, no. 5, pp. 1134–1143, 2020, doi: 10.1016/j.jestch.2020.04.002.

[6] N. Ibrahim, M. Abdelaziz, M. Ghoneima, and S. Hammad, "Implementation of vector control on electric vehicle traction system," *Bulletin of the National Research Centre*, vol. 44, no. 1, 2020, doi: 10.1186/s42269-019-0258-8.

[7] Ľ. Struharňanský, J. Vittek, P. Makyš, and J. Ilončiak, "Vector control techniques for traction drive with induction machines - comparison," *Procedia Engineering*, vol. 192, pp. 851–856, 2017, doi: 10.1016/j.proeng.2017.06.147.

[8] M. Monadi, M. Nabipour, F. Akbari-Behbahani, and E. Pouresmaeil, "Speed control techniques for permanent magnet synchronous motors in electric vehicle applications toward sustainable energy mobility: a review," *IEEE Access*, vol. 12, pp. 119615–119632, 2024, doi: 10.1109/ACCESS.2024.3450199.

[9] C. Miguel-Espinar, D. Heredero-Peris, R. Villafafila-Robles, and D. Montesinos-Miracle, "Review of flux-weakening algorithms to extend the speed range in electric vehicle applications with permanent magnet synchronous machines," *IEEE Access*, vol. 11, pp. 22961–22981, 2023, doi: 10.1109/ACCESS.2023.3252360.

[10] R. Jing, G. Wang, G. Zhang, and D. Xu, "Review of field weakening control strategies of permanent magnet synchronous motors," *CES Transactions on Electrical Machines and Systems*, vol. 8, no. 3, pp. 319–331, 2024, doi: 10.30941/CESTEMS.2024.00043.

[11] Q. Wang, S. Wang, and C. Chen, "Review of sensorless control techniques for PMSM drives," *IEEJ Transactions on Electrical and Electronic Engineering*, vol. 14, no. 10, pp. 1543–1552, 2019, doi: 10.1002/tee.22974.

[12] Y. Zbede and J. Apsley, "Field weakening control of a PM vehicle drive," *The Journal of Engineering*, vol. 2019, no. 17, pp. 3510–3515, 2019, doi: 10.1049/joe.2018.5347.

[13] Z. Amalia, A. Khabib, E. Yudaningtyas, T. Machfuroh, F. A. Nadhifatul Aini, and S. D. Nasiqiati Rosady, "Field-oriented control for speed regulation of BLDC motors in electric motorcycles," *Jurnal Elektronika dan Otomasi Industri*, vol. 10, no. 1, pp. 1–8, 2023, doi: 10.33795/elkolind.v10i1.1977.

[14] M. Hichem, B. Tahar, D. Djalel, B. Khouloud, and O. Brahim, "Control of a BLDC motor of an electric vehicle powered by a photovoltaic system based on fuzzy logic MPPT (FLC-MPPT)," *WSEAS Transactions on Circuits and Systems*, vol. 23, pp. 184–191, 2024, doi: 10.37394/23201.2024.23.19.

[15] V. R. Nippatla and S. Mandava, "Comparative vector control study on speed of PMSM drive using sensorless and machine learning techniques: review," *Journal of Intelligent and Fuzzy Systems*, vol. 46, no. 2, pp. 4381–4395, 2024, doi: 10.3233/JIFS-222164.

[16] H. Wang, C. Li, G. Zhang, Q. Geng, and T. Shi, "Maximum torque per ampere (MTPA) control of IPMSM systems based on controller parameters self-modification," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 3, pp. 2613–2620, 2020, doi: 10.1109/TVT.2020.2968133.

[17] J. Zhou, X. Xiao, Z. Wang, H. Lu, J. Chai, and M. Zhang, "Accurate MTPA strategy of PMSM considering cross saturation effect based on full-flux-linkage model," 2022, doi: 10.1109/ECCE50734.2022.9947768.

[18] O. E. Özçiflikçi and M. Koç, "Investigations of hysteresis based direct torque controlled and field oriented controlled IPM drives for electric vehicle applications," *Journal of the Institute of Science and Technology*, vol. 12, no. 3, pp. 1477–1488, 2022, doi: 10.21597/jist.1132197.

[19] M. G. Simon and D. Fodor, "Comparative analysis of field oriented control and direct torque control through simulation in MATLAB simulink for an automotive drive motor †," *Engineering Proceedings*, vol. 79, no. 1, p. 33, 2024, doi: 10.3390/engproc2024079033.

[20] D. Lu, M. Ouyang, J. Gu, and J. Li, "Instantaneous optimal regenerative braking control for a permanent-magnet synchronous motor in a four-wheel-drive electric vehicle," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 228, no. 8, pp. 894–908, 2014, doi: 10.1177/0954407014521173.

[21] I. Azizi and H. Radjeai, "Motor and regenerative braking operations for an electric vehicle using field oriented control," in *2022 19th IEEE International Multi-Conference on Systems, Signals and Devices, SSD 2022*, 2022, pp. 2145–2150, doi: 10.1109/SSD54932.2022.9955671.

[22] Z. Kangkang, L. Jianqiu, O. Minggao, G. Jing, and M. Yan, "Electric braking performance analysis of PMSM for electric vehicle applications," in *Proceedings of 2011 International Conference on Electronic and Mechanical Engineering and Information Technology, EMEIT 2011*, 2011, vol. 5, pp. 2596–2599, doi: 10.1109/EMEIT.2011.6023629.

[23] M. E. Elsayed, M. S. Hamad, and H. A. Ashour, "Modeling and analysis of PMSM under regenerative braking operations with fault-tolerant for EV/HEV applications," in *31st International Conference on Computer Theory and Applications, ICCTA 2021 - Proceedings*, 2021, pp. 112–119, doi: 10.1109/ICCTA54562.2021.9916631.

[24] M. Kumar, P. Deosarkar, S. Inamdar, and R. N. Mahanty, "Field oriented control of traction PMSM drive using WBG devices for EV application," 2023, doi: 10.1109/RESEM57584.2023.10236344.

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