ISSN Number: 2454-2024(Online)

International Journal of Technical Research & Science

# A REVIEW OF ADVANCED CONTROL STRATEGIES FOR PMSM DRIVES IN ELECTRIC VEHICLE APPLICATIONS

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**Abstract-** Electric vehicle (EV) propulsion systems rely heavily on Permanent Magnet Synchronous Motors (PMSMs) because of their exceptional torque performance, compact size, and great efficiency. Choosing the best control method for PMSM drives has become crucial as EV needs continue to rise. Field-Oriented Control (FOC), Direct Torque Control (DTC), Model Predictive Control (MPC), Sliding Mode Control (SMC), and intelligent control techniques like Fuzzy Logic Control (FLC) and Artificial Neural Networks (ANN) are just a few of the advanced control strategies that are applied to PMSM drives in this paper. The functioning principles, benefits, drawbacks, and applicability for EVs of each technique are examined. A comparison of performance metrics is provided, including robustness, torque ripple, dynamic responsiveness, and computing needs. The paper's conclusion offers perspectives on the state of PMSM drive control systems for electric mobility, including current trends and potential future directions.

**Keywords:** Permanent Magnet Synchronous Motor (PMSM), Electric Vehicle (EV), Field-Oriented Control (FOC), Direct Torque Control (DTC), Model Predictive Control (MPC), Sliding Mode Control (SMC), Fuzzy Logic Control (FLC), Artificial Neural Network (ANN), Torque Ripple, Sensorless Control.

## 1. INTRODUCTION

Electric vehicles (EVs) are currently at the forefront of international energy and environmental plans due to the swift transition to environmentally friendly transportation. In EVs, drive dynamics, power density, and energy efficiency are all directly impacted by the motor selection.[1] Permanent Magnet Synchronous Motors (PMSMs) are one of the many motor types that have become widely used because of their excellent torque characteristics, small size, high efficiency, and regenerative braking capacity.[2] Because of these characteristics, PMSMs are especially well-suited for vehicle propulsion, where energy efficiency and rapid reaction are essential.

A PMSM's dynamic performance and efficiency are influenced by both its physical design and the control approach employed. Under various driving circumstances, accurate torque, speed, and flux management is ensured by proper control. [3] Additionally, it is essential for lowering energy losses, prolonging battery life, and improving riding pleasure. PMSMs may experience torque ripple, ineffective operation, or even instability under varying loads and speeds if they are not properly controlled.[4] Therefore, a key component of high-performance EV drive systems is the application of improved motor control.

The lack of precision and poor dynamic performance of contemporary EVs make traditional motor control schemes like scalar control (e.g., V/f control) inadequate. Advanced techniques like Direct Torque Control (DTC), Field-Oriented Control (FOC), and complex algorithms based on artificial intelligence or predictive models have become more popular in the sector.[5] These cutting-edge methods are ideal for meeting the requirements of EV applications because they provide quick transient response, enhanced stability, and the capacity to manage nonlinearities and disturbances.

The purpose of this research is to examine and assess the several sophisticated control schemes created for PMSM drives in applications involving electric vehicles. It offers a thorough analysis of every technique, going over its theoretical foundations, practical application issues, and results in real-world situations. Engineers and researchers can select suitable control methods for various EV configurations with the aid of the comparative analysis provided in the next section. Current research trends and possible future paths in PMSM drive control are discussed in the paper's conclusion.

## 2. DYNAMIC MODELING AND INVERTER INTERFACE OF PMSM DRIVES IN ELECTRIC VEHICLE APPLICATIONS

In order to create and apply efficient control strategies, Permanent Magnet Synchronous Motors (PMSMs) must be accurately modeled. [4] Because PMSM drives are time-varying and intrinsically nonlinear, particularly in the dynamic environment of electric vehicle (EV) operation, control performance is highly dependent on the accuracy of the motor model used in controller design and simulation.

**DOI Number: https://doi.org/10.30780/IJTRS.V11.I05.001**

### 2.1 PMSM Structure and Operating Principle

The two major parts of a Permanent Magnet Synchronous Motor (PMSM) are : a Rotor, which is surface-mounted or embedded with high-energy permanent magnets (usually Neodymium-Iron-Boron or Samarium-Cobalt), and a stator, which carries the three-phase windings like an induction motor.

To create a synchronized electromagnetic torque, the stator's spinning magnetic field—which is produced by three-phase AC currents—interacts with the rotor's permanent magnetic field. Since PMSMs don't need rotor currents like induction motors do, they are more effective and don't have rotor losses.

Depending on the placement of magnets, PMSMs are classified into: Based on the positioning of permanent magnets in the rotor, there are primarily two types of motors: SPMS and IPMS motors.

#### 2.1.1 Surface-Mounted PMSM (SPMSM)

The magnets are attached to the rotor's surface. This arrangement creates a nearly sinusoidal back-EMF and maintains a consistent air gap. However, SPMSMs have a lesser torque per ampere and a restricted capacity to weaken fields.

#### 2.1.2 Interior PMSM (IPMSM)

Usually in a V-shape or other hidden arrangements, the magnets are integrated inside the rotor core. Higher-speed operation, better field weakening, and increased reluctance torque are all made possible by this design.

IPMSMs have gained widespread use in electric vehicle (EV) applications because of their increased torque density, improved high-speed capability, and field-weakening performance. They are better suited for high-performance traction systems because of their structure, which also provides greater mechanical integrity.

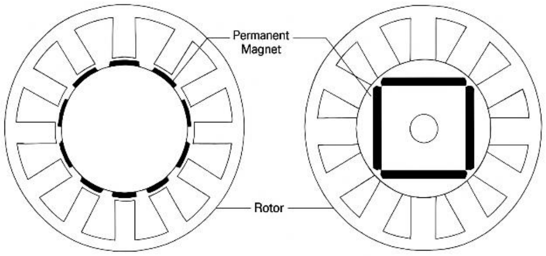

**Fig. 2.1 Construction of SPMSM and IPMSM**

### 2.2 Mathematical Modeling in the d-q Reference Frame

To simplify control implementation, the three-phase stator quantities are transformed into a two-axis rotating reference frame (d-q) using Park and Clarke transformations. The dynamic voltage equations of the PMSM in the d-q frame are given by:

$$V_d = R_s i_d + \frac{d\,\lambda d}{dt} - \omega_e \lambda_q \qquad (1)$$

$$V_q = R_s i_q + \frac{d\lambda_q}{dt} + \omega_e \lambda_d \qquad (2)$$

Where:

- Vd, Vq: d and q axis stator voltages,
- id, iq: d and q axis stator currents,
- λd, λq: d and q axis flux linkages,
- Rs : stator resistance,
- ωe: electrical angular speed.

The electromagnetic torque is expressed as:

$$T_e = \frac{3}{2} p[\lambda_d i_q - \lambda_q i_d]$$

For SPMSMs,

$\lambda d=Ldid+\lambda m\lambda d=Ldid+\lambda m$ ,

where λm is the permanent magnet flux

In contrast, for IPMSMs,
the inductance difference Ld ≠ Lq contributes to additional torque known as reluctance torque.

### 2.3 Inverter and Power Electronics Interface

The Permanent Magnet Synchronous Motor (PMSM), widely employed in electric vehicle (EV) propulsion systems is commonly driven by a three-phase Voltage Source Inverter (VSI). [6] The VSI serves as a critical interface between the DC power source (typically a battery pack) and the AC motor, enabling precise control of motor speed and torque. To achieve effective motor control, the VSI utilizes various Pulse Width Modulation (PWM) strategies that synthesize the required AC voltage waveform. The most prevalent PWM techniques in EV applications include:

- Sinusoidal PWM (SPWM)
- Space Vector PWM (SVPWM)
- Model Predictive PWM.

The inverter dynamics and switching strategy also influence current ripple, torque response, and total harmonic distortion (THD), which are crucial for overall system performance.

### 2.4 Relevance of PMSM Modeling to Control Strategy Design

The precision of the motor's mathematical model is crucial to the development and use of efficient control schemes for PMSM drives. For Electric Vehicle (EV) applications that require good performance under a variety of operating situations, simple linear control models are inadequate due to the nonlinear nature of PMSM dynamics, which include magnetic saturation, back EMF harmonics, and dependence on rotor position.

### 2.4.1 Dynamic and Nonlinear Characteristics

PMSMs show nonlinear electromagnetic behavior, particularly when the temperature, speed, and load are changed. The electrical position of the rotor is intrinsically linked to the torque produced and needs to be precisely tracked or estimated. More flexible and resilient approaches are required as a result of the difficulties these nonlinearities present for traditional linear controllers. [7]

### 2.4.2 Limitations of Simplified Control Models.

In real-world EV environments, proportional-integral (PI) controllers tuned under nominal conditions are unable to effectively manage issues including load disruptions, inverter nonlinearities, and parameter drift (e.g., owing to heating). This calls for control algorithms that have the ability to dynamically adjust for these fluctuations. [8]

### 2.4.3 Role of d-q Axis Modeling

The d-q transformation, also known as the Park transformation, is essential because it simplifies stator current control and permits independent torque and flux control by transforming the three-phase time-varying system into a two-axis rotating reference frame. The most sophisticated techniques, including Field-Oriented Control (FOC), Direct Torque Control (DTC), and Model Predictive Control (MPC), are mathematically based on this transformation.

### 2.4.4 Foundation for Advanced Strategies

Modern control strategies rely on this model to:

- Achieve decoupling of flux and torque-producing currents.
- Enhance disturbance rejection and robustness under uncertainties.
- Allow sensorless operation via observer or estimation techniques.
- Enable energy-efficient torque control in regenerative braking scenarios.

In summary, PMSM modeling is not just a preliminary step but a core enabler of advanced control development in electric vehicle drives. It directly influences the fidelity, adaptability, and safety of the entire EV propulsion system.[8]

## 3. OVERVIEW OF ADVANCED CONTROL STRATEGIES FOR PMSM DRIVES

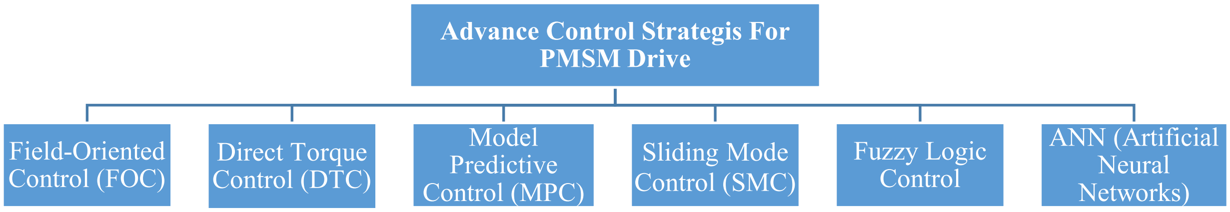

**Fig. 3.1 Advanced Control Strategies for PMSM Drives**

### 3.1 Field-Oriented Control (FOC)

Since field-oriented control, often referred to as vector control, can accomplish decoupled control of torque and flux, simulating the behaviour of a separately excited DC motor, it is the most commonly used technique in PMSM drives. The d-axis (flux) and q-axis (torque) currents can be independently controlled by FOC by utilising Clarke and Park transformations to convert the three-phase motor values into a rotating reference frame. The current and speed loops usually use PI controllers, and either sensed or calculated rotor position data is used. FOC's smooth torque output, great efficiency, and reliable performance over a broad speed range make it an excellent choice for electric vehicle applications. [9]

**Advantages:**

- FOC enables fine control of torque with minimal ripple, resulting in a smoother and quieter motor operation, especially important in electric vehicle (EV) drives. [9]
- It provides fast response to changes in speed and load conditions due to independent control of flux and torque components, making it suitable for dynamic driving conditions. [10]
- The method ensures efficient and stable performance across a broad speed range, including both low and high speeds, which is ideal for varied EV applications.

**Drawbacks:**

- Accurate rotor position (via sensors or estimators) is essential for proper transformation and control. Any error can degrade performance or cause instability. [11]
- Motor parameters like stator resistance and inductance may vary with temperature and load, affecting control accuracy unless compensated by advanced algorithms. [12]

**Suitability:** FOC is widely used in commercial EVs due to its mature development, balance between performance and complexity, and compatibility with sensorless estimation.

### 3.2 Direct Torque Control (DTC)

The goal of direct torque control is to produce quick torque response without requiring current controllers or coordinate transformation. [13] By choosing suitable inverter switching states using a lookup table and hysteresis control, it directly modifies the stator flux and torque. Compared to FOC, DTC has a simpler structure and a quicker response, but it has more torque and flux ripples. To get around these issues, more sophisticated variants such as predictive DTC and space vector-based DTC have been created. When torque dynamic performance is a top priority, DTC is still a good option despite its drawbacks. [13]

**Advantages:**

- Very fast torque response makes it perfect for applications requiring quick acceleration or deceleration, such as EV traction. [13]
- Simplified control architecture that reduces implementation complexity by doing away with the requirement for complicated coordinate transformations or existing controllers.

**Drawbacks:**

- High torque and flux ripple.[14]
- Requires flux and torque estimators.[14]

**Suitability:** Best suited for applications demanding fast transient response, such as in performance-oriented electric vehicles.

### 3.3 Model Predictive Control (MPC)

A dynamic model of the motor is used in the new control technique known as "Model Predictive Control" to forecast future outputs and identify the best course of action by minimising a cost function. MPC is capable of efficiently managing nonlinear dynamics, system limitations, and multivariable systems. [15] Despite requiring a lot of calculation, it provides superior transient and steady-state performance, less torque ripple, and increased energy efficiency. In PMSM drives, MPC predicts the motor behavior over a short horizon and selects optimal voltage vectors for inverter switching. [15] It is a viable solution for sophisticated EV systems with strong digital controllers because of its great precision and versatility.

**Advantages:**

- Optimal performance under constraints.
- Low torque ripple and high efficiency. [15]
- Good disturbance rejection. [15]

**Drawbacks:**

- High computational burden. [16]
- Requires accurate system modeling. [16]

**Suitability:** Promising for high-end EVs with powerful processors and complex driving conditions. [17]

### 3.4 Sliding Mode Control (SMC)

One nonlinear control method that is well-known for its resilience to changes in parameters and outside disruptions is sliding mode control. In order to move the system trajectory onto and retain it on a sliding surface defined in the state-space, control inputs are used. SMC has good robustness and quick dynamic responsiveness, however high-frequency switching may cause chattering. SMC works especially well in PMSM applications where there are variable load conditions or sensorless control systems. [18] Recent studies on SMC for PMSMs have increasingly focused on suppressing chattering without compromising system robustness, while also exploring integration with advanced control algorithms to enhance performance. [18]

**Advantages:**

- Robust to model uncertainties and disturbances.
- Good dynamic response.

**Drawbacks:**

- The occurrence of chattering, arising from high-frequency switching actions, remains a significant challenge in sliding mode control implementations

**Suitability:** Suitable for EVs under variable operating conditions or environments where disturbances are expected.

### 3.5 Fuzzy Logic Control

Fuzzy Logic Control (FLC) is a model-free, rule-based control method that uses fuzzy inference rules and linguistic variables to simulate human decision-making. For systems with high levels of nonlinearity, parameter uncertainty, and external disturbances—like the drives of electric vehicles' Permanent Magnet Synchronous Motors (PMSMs)—it works very well.

Unlike conventional PI controllers that rely on precise mathematical modeling, FLC handles imprecision and uncertainty through flexible rule sets, enabling smooth and adaptive control even under varying load, temperature, and speed conditions. [19] In PMSM applications, FLC is typically integrated with traditional control schemes like Field-Oriented Control (FOC) or Direct Torque Control (DTC), where it replaces or complements PI controllers in the speed or current loop to improve dynamic response and robustness. [20]

**Advantages:**

- No need for an accurate mathematical model.[21]
- It offers a flexible approach for handling nonlinearities without the need for an accurate mathematical model. [21]

**Drawbacks:**

- Requires expert-defined rule base.
- May lack generalization to all operating conditions.

**Suitability:** Used in hybrid control schemes (e.g., Fuzzy-FOC) for improved performance in adaptive or intelligent EV systems.

### 3.6 Artificial Neural Networks (ANN)

Computational models known as artificial neural networks (ANNs), which draw inspiration from the human brain, are capable of learning intricate nonlinear mappings between input and output signals during training. ANNs are very useful in PMSM drive systems for predicting control actions, estimating motor parameters, and taking the place of conventional controllers in intricate, time-varying settings where mathematical modelling is either too challenging or not good enough. [21]

ANN-based controllers are appealing for sensorless control, fault detection, and adaptive speed or torque control in electric vehicle (EV) applications since they don't need precise motor parameters. An ANN can improve system robustness by generalizing well to unknown operating situations after being trained with enough operational data. [22]

Key features of ANN-based control for PMSM drives include:

- High adaptability to nonlinearities, parameter variations, and disturbances. [22]
- Capability to approximate unknown system dynamics through supervised learning.
- Application in real-time control, observer design, and fault-tolerant systems.

ANN controllers are frequently used with traditional control techniques like FOC or DTC in contemporary EV traction systems to produce hybrid intelligent control architectures. When load and speed circumstances change quickly, this leads to higher performance than fixed-gain PI controllers. [23]

**Advantages:**

- High adaptability and learning ability.
- Suitable for fault-tolerant and sensorless control.[22]

**Drawbacks:**

- Requires large data sets and training.
- Black-box nature reduces interpretability.

**Suitability:** Future-ready method for autonomous and AI-integrated EV platforms.

## 4. COMPARATIVE ANALYSIS OF PMSM CONTROL STRATEGIES

A variety of control strategies have been developed for Permanent Magnet Synchronous Motor (PMSM) drives in electric vehicle (EV) applications. Each strategy offers trade-offs in terms of complexity, dynamic response, robustness, implementation cost, and computational burden. The table below summarizes the key aspects of the most prominent control methods.

**Table-4.1 Comparative Analysis of PMSM Control Strategies**

| Control Strategy | Torque Ripple | Dynamic Response | Computational Complexity | Robustness | Sensor less Ready | Practical Use in EVs | |
|---|---|---|---|---|---|---|---|
| FOC (Field-Oriented Control) | Low | High | Moderate | Moderate | Yes | Widely Used | [9][10] |
| DTC (Direct Torque Control) | Medium | Very High | Low | Moderate | Yes | Used in performance EVs | [13][14] |
| MPC (Model Predictive Control) | Very Low | Very High | High | High | Limited | Emerging | [15][16][17] |
| SMC (Sliding Mode Control) | Low | High | Medium | Very High | Yes | Research/Emerging | [18] |
| FLC (Fuzzy Logic Control) | Low | Medium | Medium | High | Yes | Hybrid systems | [20][21] |
| ANN (Artificial Neural Networks) | Low | Medium to High | High | High | Yes | AI-based EV control | [22][23] |

## CONCLUSION AND FUTURE SCOPE

Advanced control strategies significantly influence the performance, safety, and efficiency of PMSM drives in electric vehicles. While Field-Oriented Control (FOC) remains the dominant industrial choice due to its maturity and effectiveness, newer methods like Model Predictive Control (MPC) and Sliding Mode Control (SMC) offer higher robustness and dynamic performance suited for next-generation smart EVs.

Fuzzy and neural-based control strategies offer great promise in handling nonlinearity, uncertainty, and adaptive learning, especially in autonomous driving scenarios. However, challenges remain in terms of computational efficiency, chattering reduction (in SMC), and real-time implementation (in MPC and ANN).

Future trends are expected to move toward hybrid control architectures that combine the strengths of multiple strategies—for example, Fuzzy-MPC or ANN-FOC—integrated with IoT, AI, and vehicle-to-grid (V2G) capabilities for intelligent EV systems.

## ACKNOWLEDGMENT

I sincerely thank my guide Dr. Jai Kumar Maherchandani, for his continuous guidance and inspiration to write this research article.

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