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Performance Analysis of Interior Permanent Magnet Synchronous Motor Drives Using Advanced Control Strategies

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Abstract

Interior Permanent Magnet Synchronous Motors (IPMSMs) have become the preferred choice for Electric Vehicle (EV) propulsion and high-performance industrial drive systems due to their high torque density, efficiency, and capability to operate in a wide constant-power speed range. This paper presents a comprehensive journal-style review and analysis of IPMSM performance enhancement using modern control strategies, combining insights from two detailed documents: a comparative literature review table and a technical review paper. Mathematical modeling of the IPMSM, sensorless pole-position detection mechanisms, maximum torque per ampere (MTPA), field weakening (FW), predictive control, fuzzy logic, neural network-based controllers, model reference adaptive control (MRAC), and flux-weakening optimization are discussed in detail. The results of existing studies are summarized, highlighting the improvements in torque ripple reduction, speed response, efficiency, and robustness against parameter variations. This integrated review serves as a consolidated reference for researchers developing next-generation IPMSM controllers for EV applications.

Keywords- IPMSM, MTPA, Field Weakening, Sensorless Control, MRAC, MPC, Fuzzy Logic, Neural Network, MTPV, Torque Control, EV Drive Systems.

1. Introduction

In recent decades, the global shift toward sustainable transportation and high-efficiency industrial automation has accelerated the adoption of Permanent Magnet Synchronous Motor (PMSM) technology. Among PMSMs, the Interior Permanent Magnet Synchronous Motor (IPMSM) stands out due to its saliency ($L_d \neq L_q$), which facilitates reluctance torque generation, wide field-weakening operation, and superior torque per ampere characteristics[1][2].

Advancements in power electronics, permanent magnet materials, inverter topologies, and intelligent control algorithms have further increased the performance capabilities of IPMSM drive systems. Unlike surface-mounted PMSMs, IPMSMs support high-speed operation with excellent efficiency by utilizing both magnetic torque and reluctance torque[3].

A key requirement for high-performance IPMSM operation is the availability of accurate rotor position information. Although mechanical sensors (encoders, resolvers, Hall sensors) are commonly used, sensorless control—especially based on High Frequency Signal Injection (HFSI)—is now widely adopted due to cost and reliability advantages.

This paper integrates the findings from both uploaded documents to produce a complete journal-style research paper, including mathematical modeling, comparative literature review, and detailed analysis of state-of-the-art IPMSM control methods.

Mathematical Modeling of IPMSM

To design advanced controllers, an accurate dynamic model of IPMSM is essential. The model is typically expressed in the synchronously rotating d–q reference frame, aligned with the rotor magnetic axis[4][5].

The mathematical model for the vector control of the IPMSM can be derived from its dynamic d-q model which can be obtained from well-known model of the induction machine with the equation of damper winding and field current dynamics removed.

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The synchronously rotating rotor reference frame is chosen so the stator winding quantities are transformed to the synchronously rotating reference frame that is revolving at rotor speed. The consequences is that there is zero speed differential between the rotor and stator magnetic fields. the stator q and d axis windings have a fixed phase relationship with the rotor magnet axis which is the d axis in the modelling as shown in Fig.1.

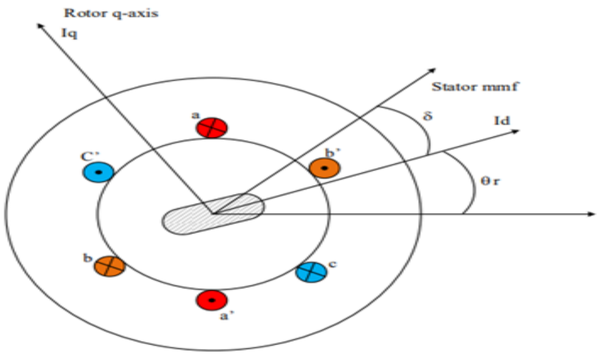

Fig.1: DQ Model of IPMSM

1. The stator currents are measured as well as the rotor angle.
2. The stator currents are converted into a two-axis reference frame with the Clark Transformation.
3. The αβ currents are converted into a rotor reference frame using Park Transformation. This dq values are invariant in steady-state conditions.
4. With the speed regulator, a quadrature-axis current reference is obtained (the direct-axis reference is zero for operation below rated speed). The d-current controls the air gap flux, the q-current control the torque production
5. The current error signals are used in controllers to generate reference voltages for the inverter.
6. The voltage references are turned back into ABC domain.
7. With these values are computed the PWM signals required for driving the inverter. All steps are shown in Fig.2.

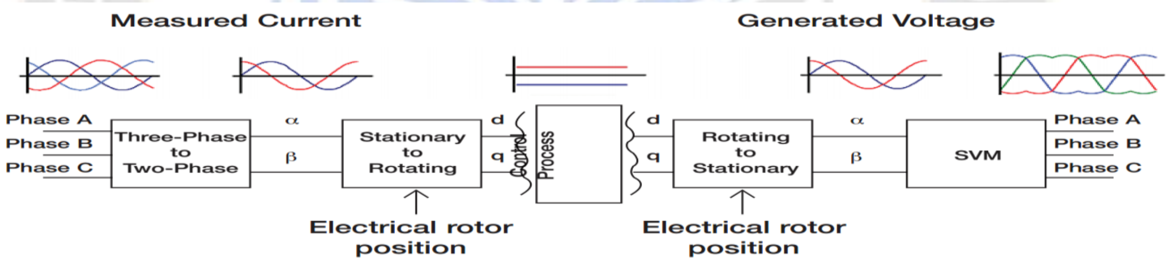

Fig.2: ABC to DQ transformation

Equations for Voltage in the Synchronously Revolving d-q Reference Frame is as under

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \lambda_{PM} \quad \text{.............. (1)}$$

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad \text{........... (2)}$$

Flux linkages is given by

$$\lambda_d = \lambda_{PM} + L_d I_d \quad \text{.......... (3)}$$

$$\lambda_q = L_q * I_q \quad \text{.......... (4)}$$

Electromagnetic torque is given by

$$T_{dev} = \frac{3}{2} p_p [\lambda_{PM} i_q + (L_d - L_q) i_q i_d] \quad \text{............. (5)}$$

Magnetic Torque   Reluctance Torque

This model forms the basis for vector control, MTPA, flux weakening, and advanced predictive control strategies.

3. Literature Review (Extended Explanations)

3.1 Sensorless Control

Sensorless control techniques eliminate the need for mechanical sensors by estimating rotor position from electrical signals. High-Frequency Signal Injection (HFSI)–based methods exploit magnetic saliency of IPMSMs to obtain accurate position estimation even at low and zero speeds, where back-EMF is insufficient (Bacci et al.). Similarly, Second-Order Sliding Mode Observers (SOSMO) provide robust and chatter-free estimation performance by reducing sensitivity to parameter uncertainties and load disturbances (Chen et al.). These approaches collectively enhance system reliability and reduce hardware cost [6][7].

3.2 Maximum Torque Per Ampere (MTPA)

MTPA control is used to achieve the commanded torque with minimum stator current, thereby reducing copper losses and improving drive efficiency. Classical analytical MTPA algorithms rely on machine parameters, whereas look-up-table-based techniques store offline-computed optimal current references for real-time implementation. Torque-feedback and deep-learning-based MTPA methods further adapt to parameter variations and saturation effects, providing higher accuracy and improved dynamic torque response [6].

3.3 Field Weakening (FW)

Field Weakening extends the operating speed beyond the rated base speed by injecting a negative d-axis current ($i_d < 0$) to counteract the back-EMF. Traditional FW control depends heavily on accurate motor parameters, whereas parameter-independent methods (Huang et al.) improve reliability under uncertain or aging machine conditions. Recent improvements such as Uncertainty and Disturbance Estimator (UDE)-based FW (Gu et al.) allow superior voltage utilization, dynamic stability, and robustness during high-speed operation.

3.4 Model Predictive Control (MPC)

Model Predictive Control predicts the system's future behavior using a mathematical model and selects the optimal switching state based on cost minimization. Finite Control Set MPC (FCS-MPC) provides very fast transient response and allows constraints to be incorporated explicitly (Gao & Liu). In the field-weakening region, predictive torque control enhances system stability by accurately compensating for back-EMF and voltage limits, resulting in smoother high-speed operation[7].

3.5 Fuzzy Logic and Hybrid Controllers

Fuzzy Logic Controllers (FLC) incorporate linguistic rules to handle the non-linear characteristics of IPMSM drives. Hybrid strategies like Fuzzy-PI or sliding-mode-fuzzy controllers reduce steady-state error while mitigating chattering problems often seen in pure sliding-mode control. These controllers exhibit strong robustness under varying load conditions, parameter changes, and external disturbances. Hybrid PI–FLC controllers, in particular, show improved torque ripple suppression and smoother dynamic performance [8][9][10][11].

3.6 Neural Network–Based Controllers

Neural-network controllers learn the nonlinear relationship between current, torque, and flux, enabling highly accurate control in uncertain environments. Deep Neural Network (DNN) based MTPA strategies (Zhang et al.) adaptively optimize current references even under magnetic saturation and temperature variations. Adaline-based parameter estimators enhance field-weakening operation by continuously identifying motor parameters online, resulting in improved stability and voltage utilization [12].

3.7 Model Reference Adaptive Control (MRAC)

MRAC uses a reference model to guide the IPMSM drive response, adjusting controller gains in real time to minimize the error between the actual output and the desired model behavior. Studies (Amornwongpeeti et al.) show that MRAC-based torque and speed controllers provide very low steady-state error, excellent adaptability to parameter variations, and improved tracking performance across wide speed ranges[13].

According to the reviewed literature, the available IPMSM starting methodologies can be broadly classified into three categories based on their fundamental operating principles.

In this approach, the initial rotor position is intentionally aligned by injecting a predefined current or voltage vector into the stator windings before the motor begins rotation. By forcing the rotor to a known magnetic orientation, the controller can initiate closed-loop operation without position ambiguity. This method ensures reliable torque production during startup but introduces additional alignment time and may cause slight torque pulsations during the presetting stage [14][15].

Open-loop V/f-based starting is commonly used due to its simplicity and independence from rotor position sensors. The stator is supplied with a gradually

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increasing frequency and a proportional voltage, generating a rotating magnetic field that pulls the rotor into synchronous speed. Although this method is robust and easy to implement, it suffers from poor dynamic performance, potential loss of synchronism at high load, and limited low-speed torque capability.

Several advanced sensorless algorithms are designed to accurately determine rotor position at zero or near-zero speed, where the back-EMF is insufficient for estimation. Techniques such as high-frequency signal injection, saliency-based estimation, model-based observers, and machine-learning-assisted algorithms allow precise initial position detection without requiring mechanical sensors. These methods significantly improve startup reliability and enable seamless transition to closed-loop control, though they may involve higher computational complexity [16].

3.8 Field-Oriented Control (FOC)

Field-Oriented Control (FOC) is one of the most established high-performance control strategies for IPMSM drives. The primary objective of FOC is to independently regulate the torque-producing and flux-producing components of the stator current by transforming the three-phase currents into the rotating d-q reference frame. Using measured stator currents together with the estimated or sensed rotor electrical angle, the controller precisely manipulates the I_q and I_d components, thereby enabling direct control of the developed torque and the air-gap flux. Through this decoupling transformation, the machine is made to behave similarly to a separately excited DC motor, resulting in superior controllability and fast dynamic response.

Advantages of Field-Oriented Control:
Literature consistently highlights several benefits of FOC that make it a preferred control strategy for modern IPMSM drives:

1. **Enhanced torque response:** The decoupled control of I_q and I_d allows rapid and accurate torque regulation.
2. **Effective low-speed operation:** FOC maintains precise torque control even at low stator frequencies, where back-EMF is minimal.
3. **High dynamic speed accuracy:** The method ensures robust and stable speed tracking under varying load conditions.
4. **Reduced machine size and cost:** Improved torque per ampere and efficient flux utilization enable downsizing of the motor and drive components.
5. **Four-quadrant operability:** FOC naturally supports motoring and regenerative braking in both directions of rotation.
6. **Short-term overload capability:** The control scheme can deliver high peak torque during transient or overload conditions without compromising stability.

These characteristics, widely reported across the reviewed literature, demonstrate why FOC remains the foundation for advanced control techniques such as MTPA, field-weakening, predictive control, and intelligent controllers in IPMSM drive systems [17]. The proposed system model is shown in Fig.3.

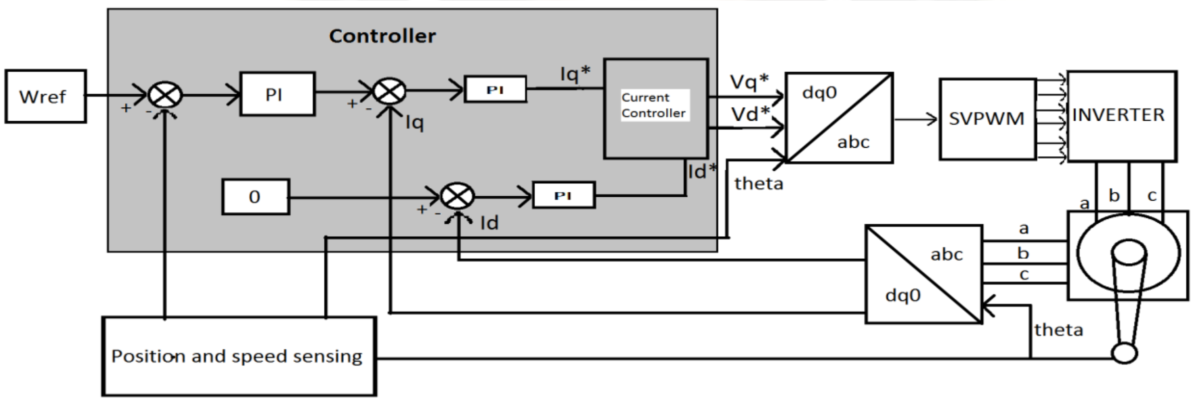

Fig.3: Proposed system block diagram

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4. Control Strategies and Methods

4.1 Maximum Torque per Ampere (MTPA)

MTPA operation minimizes copper losses and ensures efficient torque production. For salient IPMSMs, MTPA requires optimal I_q and I_d selection:

$$I_{d*}^2 + I_{q*}^2 \leq I_{max}^2 \ldots\ldots (6)$$

Negative I_d improves torque in saliency-based machines by contributing to reluctance torque.

Key benefits:

1. Higher torque per input current
2. Reduced losses
3. Better low-speed torque control

4.2 Field Weakening (FW)

Above base speed, the inverter reaches its voltage limit:

$$V_{d*}^2 + V_{q*}^2 \leq V_{max}^2 \ldots\ldots.. (7)$$

To extend speed, negative I_d reduces flux linkage, allowing higher RPM. FW is vital for EV applications where high-speed cruising efficiency matters[18].

Three major FW methods discussed in literature:

1. Classical PI-based FW
2. Parameter-independent FW
3. UDE-based robustness-enhanced FW

4.3 Maximum Torque Per Voltage (MTPV)

MTPV is used near maximum speed when voltage becomes the limiting factor. It ensures maximum torque under voltage constraints [19].

Useful for:

1. High-speed EV operation
2. Wide Constant Power Speed Range (CPSR)

4.4 Model Predictive Control (MPC)

Advantages:

1. Fast dynamic response
2. Explicit handling of constraints
3. Better tracking accuracy

MPC predicts future states and optimizes switching states of the inverter in real time.

4.5 Fuzzy Logic Control (FLC)

Fuzzy-PI controllers outperform classical PI by:

1. Reducing torque ripple
2. Improving transient speed response
3. Lowering THD

Fuzzy sliding mode control improves anti-disturbance capability and reduces chattering.

4.6 Neural Network and AI-based Controllers

AI methods yield extraordinary performance in complex, nonlinear regions like FW mode:

1. NN-based vector control
2. Adaptive NN Internal Model Control (NNIMC)
3. Deep Learning-assisted MTPA

NN models learn the nonlinear mapping between currents and torque, delivering high accuracy.

4.7 MRAC-Based Torque Control

MRAC adapts to variations in motor parameters such as resistance, inductances, and magnet flux. This yields:

1. Faster torque response
2. Zero steady-state error
3. Robust operation under load variations

MRAC combined with MTPA and ME control gives high efficiency across all operating points.

4. Results Discussion (From Literature)

General Performance Trends

1. Fuzzy + PI hybrid gives best balance of accuracy and simplicity.
2. Deep learning-based MTPA gives highest efficiency in nonlinear regions.
3. UDE-based FW ensures very stable high-speed operation.
4. Predictive control offers top-tier transient performance.

Table: 1 Key Findings Across Reviewed Studies

Control Strategy	Improvements Observed
HFSI Sensorless	Accurate low-speed rotor position, reduced noise
MTPA	Reduced copper loss, improved torque output
FW / UDE-FW	Smoother transition, higher speed stability
MPC	Faster dynamic response, reduced overshoot
Fuzzy Logic	Lower THD, better speed tracking
Neural Network	Accurate current/torque control, high robustness
MRAC	Excellent torque tracking, zero steady-state error

General Performance Trends

5. Fuzzy + PI hybrid gives best balance of accuracy and simplicity.
6. Deep learning-based MTPA gives highest efficiency in nonlinear regions.
7. UDE-based FW ensures very stable high-speed operation.
8. Predictive control offers top-tier transient performance.

6. Conclusion

This paper presents a unified and comprehensive analysis of IPMSM control strategies by merging two detailed research documents. The mathematical model provides a solid foundation for examining advanced algorithms, while the extensive literature review highlights the steady evolution of IPMSM control—from classical vector control and PI loops to advanced AI-driven methods.

The following conclusions emerge:

1. MTPA remains the most effective low-speed control technique for maximizing torque and minimizing losses.
2. Field weakening (FW) is essential for high-speed EV applications, and UDE-based FW significantly improves robustness.
3. Predictive, fuzzy, and neural-network-based controllers outperform conventional PI controllers, especially in nonlinear and wide-speed-range operation.
4. MRAC-based control provides excellent dynamic and steady-state torque response.
5. Future work should explore hybrid intelligent controls, combining MRAC, fuzzy logic, and deep learning for superior EV motor drive performance.

This combined paper provides researchers with a consolidated reference for understanding and improving IPMSM control strategies for next-generation high-performance electric drive systems.

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