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PERFORMANCE EVALUATION OF TORQUE CONTROL STRATEGIES IN ELECTRIC VEHICLE IPMSM DRIVES

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ABSTRACT: *Interior Permanent Magnet Synchronous Motors (IPMSMs) are widely adopted in electric vehicle (EV) propulsion systems due to their high efficiency and torque density. However, torque ripple remains a significant challenge, particularly under dynamic load conditions affecting drivability, efficiency and component lifespan. This study presents a comparative analysis of two prominent control strategies—Field-Oriented Control (FOC) and Direct Torque Control (DTC)—in terms of their effectiveness in reducing torque ripple in IPMSM drives. A simulation framework was developed using Python to model the motor behaviour under identical speed and load conditions. The results indicate that FOC produces smoother torque output with minimal ripple, owing to its decoupled control of flux and torque through dq-axis currents. In contrast DTC despite offering faster dynamic response introduces higher torque ripple due to its hysteresis-based voltage vector switching. Quantitative comparisons based on torque ripple amplitude, current quality and speed regulation confirm the superiority of FOC for applications where smooth and efficient torque delivery is critical. This research reinforces FOC as the preferred control strategy for IPMSM-driven EVs, especially in scenarios demanding high precision and minimal mechanical stress*

***Keywords**: Interior Permanent Magnet Synchronous Motors (IPMSM), Field-Oriented Control (FOC) and Direct Torque Control (DTC)*

I.INTRODUCTION

The global shift toward electrified transportation has positioned electric vehicles (EVs) as a sustainable alternative to conventional internal combustion engine (ICE) vehicles. Unlike ICEs, EVs offer several advantages including zero tailpipe emissions, higher energy efficiency, lower maintenance costs, and quiet operation, making them increasingly attractive for both urban and highway applications. Furthermore, advancements in power electronics, battery technologies and control systems have significantly improved the range and performance of modern EVs [1].However, the transition from ICE to EV propulsion brings forth new engineering challenges, particularly in the domain of torque control. One of the critical concerns in EVs is torque ripple, which affects ride comfort, acoustic noise, drivetrain wear and energy efficiency. Torque ripple becomes especially prominent under dynamic load conditions such as acceleration, deceleration, or regenerative braking. These ripples when uncontrolled degrade the overall driving experience and introduce stress on mechanical components [2].

Interior Permanent Magnet Synchronous Motors (IPMSMs) are widely employed in EVs due to their high torque density and wide speed range capabilities. Nonetheless, their inherent magnetic saliency and switching behavior contribute to substantial torque ripple under varying operating conditions [3]. Therefore, precise torque control is essential to suppress these ripples and this has motivated extensive research into advanced control strategies like Field-Oriented Control (FOC) and Direct Torque Control (DTC). Each method exhibits unique strengths and trade-offs in terms of torque smoothness, dynamic response and implementation complexity [4][5].This study presents a simulation-based comparative analysis of FOC and DTC applied to IPMSM drives in the context of torque ripple mitigation. The goal is to identify the control strategy that best addresses ripple effects under realistic EV operating conditions.

1.1 General Block Diagram of Torque Control System for IPMSM

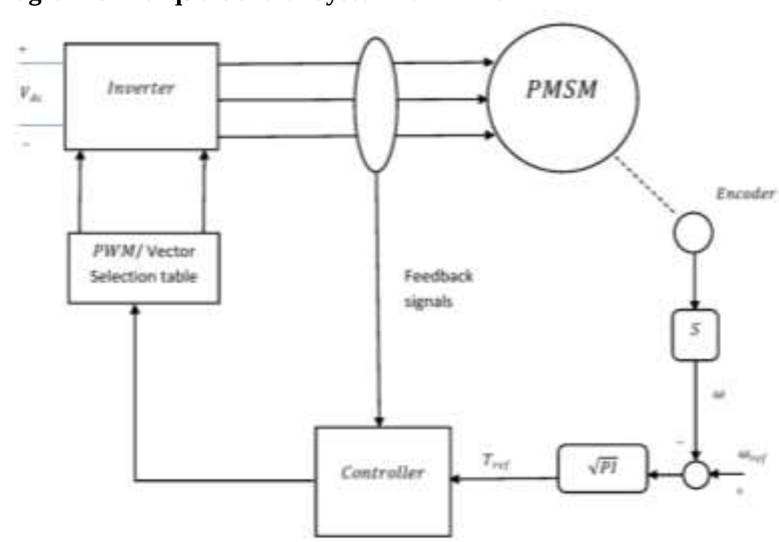

Figure.1: General Block Diagram of Torque Control System for IPMSM

The block diagram shown in Figure.1 represents a generalized control structure for torque regulation in an Interior Permanent Magnet Synchronous Motor (IPMSM) drive system commonly used in electric vehicles (EVs). The control system initiates with a speed reference input, which is processed through a Proportional-Integral (PI) controller to generate the desired torque reference. This reference is then managed by a torque controller that governs the inverter's output through either Field-Oriented Control (FOC) or Direct Torque Control (DTC) techniques. The inverter delivers appropriate voltage signals to the IPMSM, enabling precise electromagnetic torque generation. To maintain control accuracy, real-time feedback—such as stator current, rotor position and flux linkage—is continuously monitored. These signals are processed using observers or estimators to adapt the controller's response to dynamic operating conditions. This feedback loop is essential for mitigating torque ripple, enhancing system stability and ensuring smooth motor performance.

According to Qu et al. [1], torque ripple in IPMSM drives significantly affects drivability and acoustic comfort, particularly under variable loads. FOC offers precise decoupling of torque and flux through the transformation of stator currents into a synchronous reference frame, whereas DTC directly manipulates stator flux and torque via voltage vector selection [2],[3]. The block diagram encapsulates the core functional stages involved in both methods, providing a unified view of control flow and feedback integration.

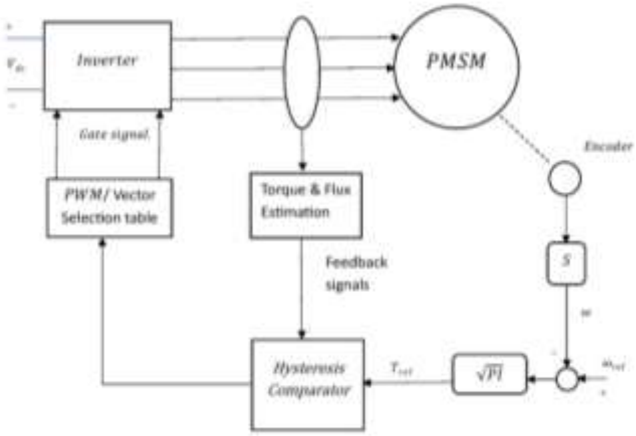

Figure.2 Block Diagram for DTC of IPMSM

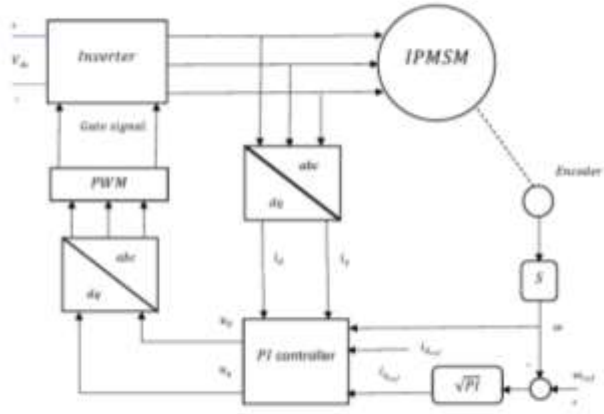

Figure.3 Block Diagram for DTC of IPMSM

II. DIRECT TORQUE CONTROL TO IPMSM

Direct Torque Control (DTC) is a dynamic, sensor-based control strategy widely used in AC motor drives, particularly for Permanent Magnet Synchronous Machines (PMSMs) and Interior PMSMs (IPMSMs). Unlike Field-Oriented Control (FOC), DTC eliminates the need for coordinate transformations or pulse width modulation. Instead, it directly regulates electromagnetic torque and stator flux linkage by selecting optimal voltage vectors through a predefined switching table.

The core working principle of DTC involves estimating electromagnetic torque (T_e) and stator flux (ψ_s) in the stationary α–β reference frame using real-time voltage and current measurements. These estimates are compared against reference values using hysteresis comparators, which monitor deviations within preset tolerance bands. Based on the comparator output, an appropriate voltage vector is selected from a vector selection table to adjust the inverter's switching state, as illustrated in Figure 2.

$$T_e = \frac{3}{2}P(\psi_d i_q - \psi_q i_d)$$

This equation governs torque estimation in DTC and is typically computed from the estimated stator quantities rather than measured flux components.

As depicted in Figure.2, the DTC control path includes key components such as torque and flux estimation, hysteresis comparators and a vector selection table. Feedback signals from the motor are continuously processed to maintain performance and response under varying loads.

DTC offers notable benefits, including rapid torque response, simple implementation, and elimination of modulation stages. However, it is associated with high torque ripple, variable switching frequency, and sensitivity to motor parameters, which can impact control quality under low-speed or high-precision applications.

III. FIELD ORIENTED CONTROL TO IPMSM

Field-Oriented Control (FOC), also referred to as vector control, is a widely adopted method for achieving high-performance torque and flux regulation in Permanent Magnet Synchronous Machines (PMSMs), especially Interior PMSMs (IPMSMs). The fundamental principle of FOC is the transformation of three-phase stator currents into a rotating dq reference frame, which allows for the independent control of torque-producing (i_q) and flux-producing (i_d) current components. This decoupling mimics the behavior of separately excited DC machines, enabling precise electromagnetic torque control.

The FOC process begins with Clarke and Park transformations of the stator currents to align them with the rotor's magnetic field. A pair of Proportional-Integral (PI) controllers then regulates i_d and i_q currents based on torque and flux demands. The computed voltages are transformed back to the stationary frame via inverse Park transformation and passed to a Pulse Width Modulation (PWM) or Space Vector PWM (SVPWM) block, which drives the voltage source inverter.

The torque produced is governed by:

$$T_e = \frac{3}{2}P\left[(\psi_m + L_d i_d)i_q + (L_d - L_q)i_d i_q\right]$$

As illustrated in Figure 3, the FOC block diagram highlights key stages including current regulation, frame transformations, and inverter control. Feedback from stator currents and rotor position is essential for maintaining performance offers low torque ripple, fixed switching frequency, and high dynamic efficiency, but is computationally intensive and sensitive to parameter and sensor inaccuracies.

IV.RESULTS AND DISCUSSION

Table.1: System specifications and control parameters for IPMSM Drive

Component	Symbol	Value
Motor Parameters		
Rated Mechanical Power	P_{mech}	1 kW
Rated Speed	n_{mech}	3000rpm
Number of Pole Pairs	P	2
Stator Resistance	R_s	0.18 Ω
d-axis Inductance	L_d	0.8 mH
q-axis inductance	L_q	1.2 mH
Permanent Magnet Flux Linkage	ψ_m	0.15 Wb
Inverter Specification		
Inverter Type	2-level VSI	
DC Link Voltage	V_{dc}	300 V

The simulation analysis was conducted using a 1kW Interior Permanent Magnet Synchronous Motor (IPMSM) whose parameters are listed in Table 1. The key parameters include a rated speed of 3000 rpm, stator resistance of 0.18 Ω, $L_d = 0.8$ mH, $L_q = 1.2$ mH and a flux linkage of 0.15Wb. A two-level voltage source inverter (VSI) was used supplied with a DC-link voltage of 300V. Both FOC and DTC control schemes were implemented with identical initial and operating conditions for fair comparison.

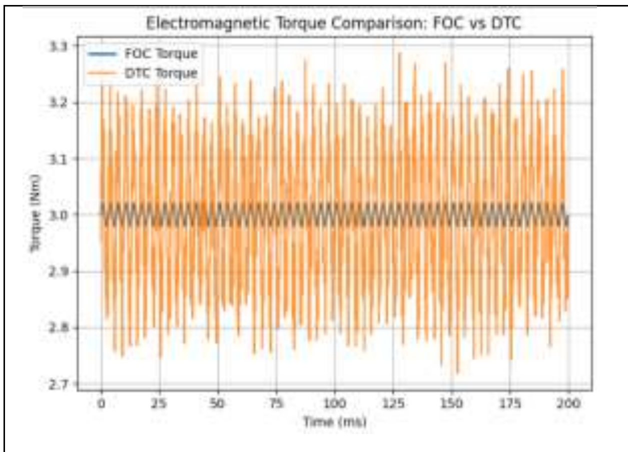

Figure.4 Electromagnetic torque comparison for FOC and DTC

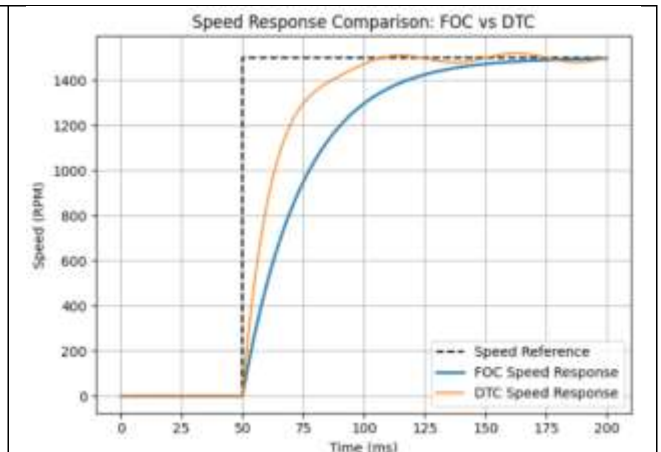

Figure.5 Speed Response comparison for FOC and DTC

As shown in Figure.4, the torque response under Field-Oriented Control (FOC) remains smooth and exhibits minimal ripple. In contrast, Direct Torque Control (DTC) produces visibly higher ripple content in the electromagnetic torque. The higher ripple in DTC results from the abrupt switching of voltage vectors based on hysteresis logic, whereas FOC benefits from smooth modulation through SVPWM. The peak-to-peak ripple in DTC is significantly greater than in FOC, indicating that FOC is better suited for applications requiring torque smoothness and reduced vibration.The speed response curves, depicted in Figure.5, shows that DTC achieves a faster transient response and quicker settling time following a step change in speed. However, it also presents noticeable overshoot and oscillatory behavior, which can degrade performance in sensitive applications. FOC on the other hand provides a slightly slower but more stable response, with zero overshoot and better steady-state tracking.

V.CONCLUSION

This study presents a comparative analysis of Field-Oriented Control (FOC) and Direct Torque Control (DTC) for IPMSM drives. Simulation results reveal that FOC delivers significantly lower torque ripple, smoother speed response and reduced harmonic distortion making it ideal for precision applications. Although DTC offers faster dynamic response, it suffers from high torque ripple and speed overshoot. Overall, FOC is better suited for electric vehicle applications where smooth operation, stability and control accuracy are critical.

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