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Comprehensive Analysis of FOC, MPC, and DTC Controlling Methods for Five-Phase Induction Motor Drives using Two-Level and Three-Level Inverters

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Abstract: This study provides a thorough examination of Direct Torque Control (DTC), Model Predictive Control (MPC), and Field-Oriented Control (FOC) for five-phase induction motor (FPIM) drives. The study examines how well these control strategies work with inverters that have two and three levels. Several performance metrics are examined through simulation and hardware results, such as fault tolerance, dynamic response, torque ripple, and computational complexity. The findings show that while DTC offers a faster response with a larger torque ripple, MPC offers better dynamic performance at a higher computational cost. Even though FOC is computationally efficient, its response times are slower. Three-level inverters decrease switching losses and total harmonic distortion (THD) while improving the quality of the voltage waveform.
Index Terms: Five-Phase Induction Motor, Field-Oriented Control, Model Predictive Control, Direct Torque Control, Multi-Level Inverter, Fault Analysis, THD.

I. INTRODUCTION

Multiphase induction motor (MPIM) technology has emerged as a result of the growing need for dependable, high-performance, and energy-efficient motor drive systems. Five-phase induction motors (FPIMs) have several advantages over conventional three-phase induction motors, such as better power distribution, decreased harmonic content, and increased fault tolerance [1]. Because of these features, FPIMs are a desirable option for vital applications like marine propulsion, electric vehicles, aerospace, and renewable energy systems [2].

The control strategy is a key factor in determining the overall performance of electric drive systems. Field-Oriented Control (FOC), Model Predictive Control (MPC), and Direct Torque Control (DTC) are some of the control strategies that have been developed to maximise the performance of FPIMs [3], [4]. Regarding robustness under fault conditions, computational complexity, steady-state performance, and dynamic response, each control technique has advantages and disadvantages of its own.

Because FOC can decouple torque and flux control, it offers high efficiency and smooth operation, which makes it popular. However, it necessitates precise parameter estimation and intricate transformations [5], [6]. However, because of its predictive nature and direct handling of system constraints, MPC has attracted a lot of attention lately [7]. MPC's high computational power requirements make real-time implementation difficult, despite its superior dynamic performance [8].

[9]. Introduced as a substitute for FOC, DTC provides a quick torque response with little reliance on motor parameters [7],

[10]. However, in high-precision applications, its high torque and flux ripples can affect system performance [11].

The inverter topology selection has a significant impact on the performance of FPIM drives. Conventional two-level inverters reduce system efficiency by producing high-frequency harmonics and switching losses [5]. On the other hand, three-level inverters, like the neutral point clamped (NPC) topology, offer better voltage waveforms, less total harmonic distortion (THD), and less voltage stress on semiconductor devices [12],[13]Motor drive performance can be greatly improved by using three-level inverters, especially in high-power applications.

This paper thoroughly compares FOC, MPC, and DTC applied to five-phase induction motor drives with two-level and three-level inverters. The study evaluates various performance metrics, including fault tolerance, computational load, torque ripple, and transient response.

MATLAB/Simulink simulations and real-time hardware implementations demonstrate the trade-offs between different inverter topologies and control strategies, providing valuable insights for selecting the most suitable drive system for specific applications.

II. CONTROL STRATEGIES

The two main categories of control strategies for FPIM drives are direct control-based techniques and vector control-based techniques. Performance expectations, computational limitations, and application requirements all influence the control strategy selection.

A. Field-Oriented Control (FOC)

FOC is a popular vector control method that allows the torque and flux-producing components of the stator current to be independently controlled [15]. This is achieved by applying Clarke and Park transformations to convert the stator currentinto a rotating reference frame. PI regulators are then used to control the transformed currents, guaranteeing efficient operation and smooth torque production [16].

The ability of FOC to achieve high dynamic performance and enhanced efficiency in steady-state conditions is one of its main advantages. Nevertheless, the application of FOC necessitates precise estimation of motor parameters, especially rotor resistance, which can change depending on operating conditions and temperature [?]. Furthermore, the computational load is increased by the presence of multiple current control loops, which makes real-time implementation difficult in high-speed applications.

FOC provides five-phase induction motors with an extra degree of control over harmonic components, lowering torque ripple and enhancing power distribution between phases. By reducing switching losses and optimising voltage utilisation, space vector modulation (SVM) improves inverter efficiency [18].

B. Model Predictive Control (MPC)

MPC is an advanced control technique that predicts the future behaviour of the motor drive system based on a mathematical model [19]. The control algorithm evaluates multiple control actions at each sampling instant and selects the optimal switching state that minimises a predefined cost function [21].

MPC provides several advantages over traditional control methods:

1) It allows direct control of multiple system variables without the need for separate PI regulators.
2) It inherently accounts for system constraints, making it suitable for nonlinear and time-varying systems.
3) It enables fast dynamic response and reduced overshoot compared to FOC and DTC.

However, MPC's computational complexity is its main flaw. High-speed digital signal processors (DSPs) or field-programmable gate arrays (FPGAs) are necessary for real-time implementation since the controller must assess several switching states at each sampling instant [22]. Furthermore, model errors and parameter changes can impair performance, requiring strong adaptive mechanisms.

Through dynamic control input adjustments based on available healthy phases, MPC offers five-phase systems an efficient way to operate fault-tolerantly. In safety-critical applications, this improves the drive system's dependability. [23]

C. Direct Torque Control (DTC)

DTC is a direct control strategy that regulates torque and stator flux by selecting optimal voltage vectors based on instantaneous error signals [7]. Unlike FOC, DTC does not require coordinate transformations or current controllers, simplifying implementation and reducing computational burden [24].

Key advantages of DTC include:

1) Fast dynamic response due to direct manipulation of torque and flux.
2) Reduced dependency on motor parameters, improving robustness under varying operating conditions.
3) Simple control structure without the need for complex transformations.

However, because of the hysteresis-based switching logic, DTC experiences high torque and flux ripples. In high-precision applications, this may result in mechanical vibrations and increased acoustic noise [25]. Advanced switching methods like artificial intelligence-based controllers and space vector modulation (SVM) have been investigated to address these problems [26].

The extra phase redundancy in five-phase induction motors helps DTC by enabling better torque performance in the event of a fault. Furthermore, by offering finer voltage vector selection, multi-level inverters can aid in the reduction of torque ripples [27].

III. TWO-LEVEL VS. THREE-LEVEL INVERTER

In motor drive systems, the inverter topology is crucial in determining the harmonic content, power losses, and voltage waveform quality. In industrial settings, two-level and three-level inverters are frequently utilized, each with unique benefits and drawbacks.

A. Two-Level Inverter

A two-level inverter is the simplest voltage source inverter (VSI) topology. It uses two switching states per phase to generate the output voltage. The phase voltage can take only two values, $\pm V_{dc}/2$, where V_{dc} is the DC-link voltage.
The line-to-line voltage output of a two-level inverter can be represented as:

$$V_{ab} = S_a \cdot \frac{V_{dc}}{2} \quad S_b \cdot \frac{V_{dc}}{2}, \qquad (1)$$

where S_a and S_b are the switching states of phases a and b, which can take values of ±1.

Although two-level inverters are simple to implement and require fewer components, they generate high harmonic distortion in the output voltage, leading to increased losses and torque ripples in the motor [5]. The Total Harmonic Distortion (THD) of the voltage waveform is given by:

$$THD = \sqrt{\sum_{n=2}^{\infty} \left(\frac{V_n}{V_1}\right)^2}, \qquad (2)$$

where V_n represents the RMS value of the n-th harmonic component, and V_1 is the fundamental component.

B. Three-Level Inverter

By adding a third voltage level, a three-level inverter, like the Neutral Point Clamped (NPC) inverter, lowers voltage stress on power semiconductor devices and enhances waveform quality. A three-level inverter's output phase voltage can have three different values.: $-V_{dc}/2$, 0, and $+V_{dc}/2$.

The line-to-line voltage output is given by:

$$V_{ab} = (S_a - S_b)\frac{V_{dc}}{2}, \qquad (3)$$

where S_a, S_b can take values of −1, 0, 1 corresponding to the three-level states.
Three-level inverters offer several advantages:
1) Lower THD compared to two-level inverters, reducing torque ripple and improving motor efficiency.
2) Reduced voltage stress on switching devices, enhancing system reliability.
3) Higher efficiency at high power levels due to lower switching losses.

The THD of a three-level inverter is significantly lower than that of a two-level inverter, leading to a smoother motor operation. The relationship between the THD values of the two inverters can be approximated as:

$$THD_{3L} \approx \frac{THD_{2L}}{\sqrt{2}}. \qquad (4)$$

Moreover, the increased number of switching states in a three-level inverter allows better control of the output voltage

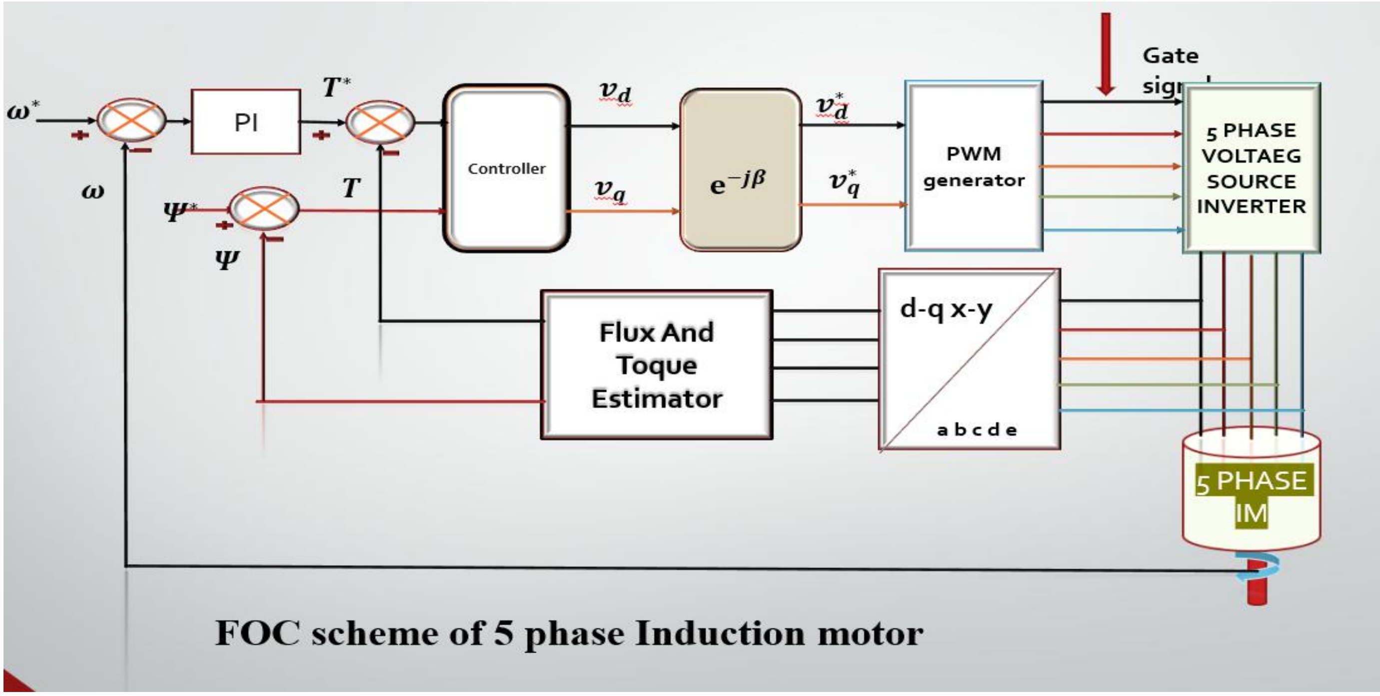

Fig. 1. Block Diagram of Five-Phase Induction Motor of FOC control.

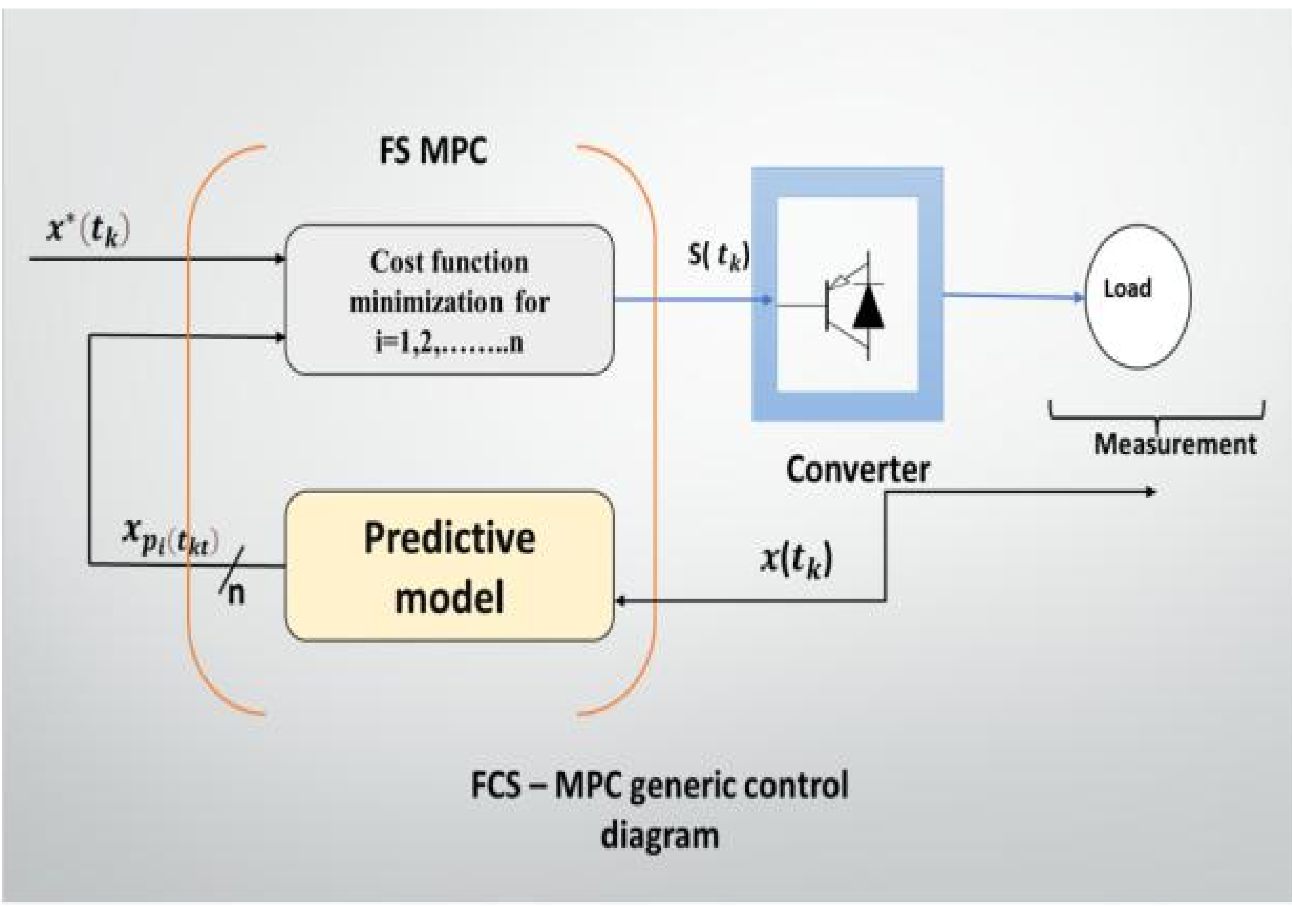

Fig. 2. Block Diagram of Five-Phase Induction Motor of MPC control.

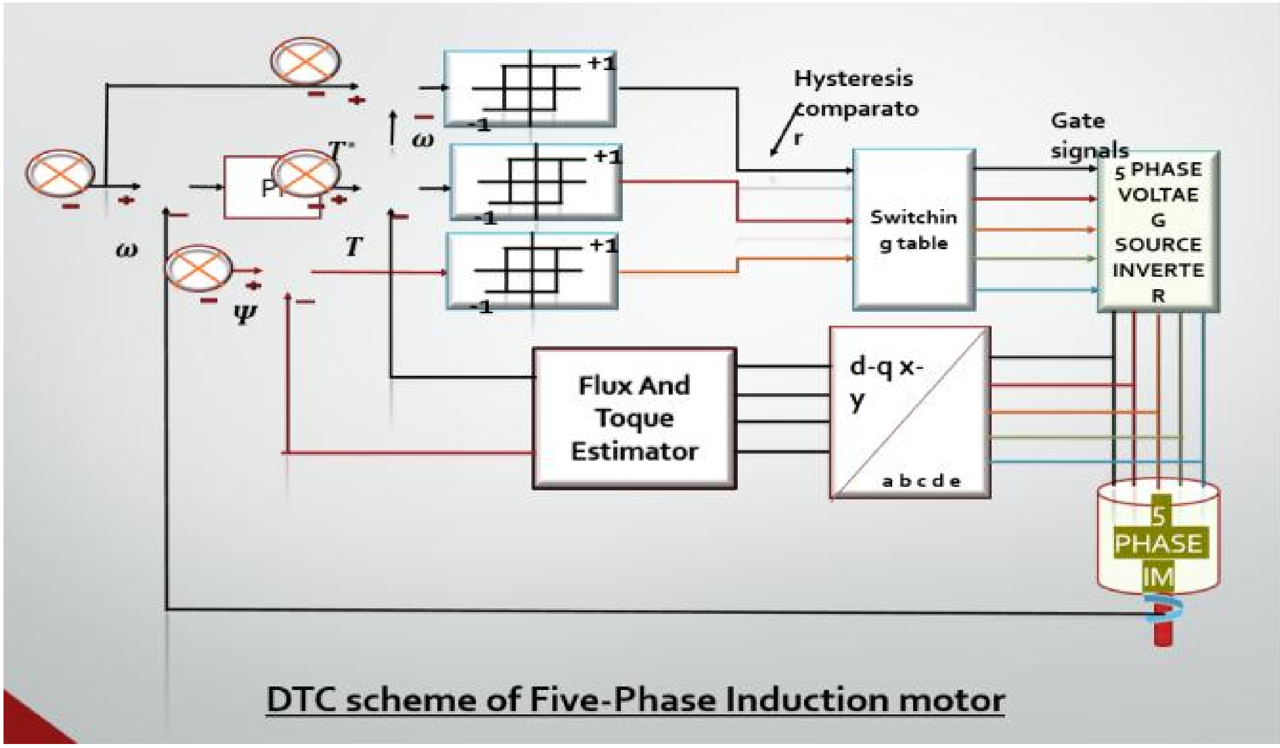

Fig. 3. Block Diagram of Five-Phase Induction Motor of DTC control.

vector in space vector modulation (SVM), reducing harmonic distortion and enhancing system performance [28].

C. Comparison of Two-Level and Three-Level Inverters

Table I summarises the key differences between two-level and three-level inverters.

Table I makes it clear that although three-level inverters perform better in terms of lower harmonics and higher efficiency, their higher initial investment and complexity come at a cost. The particular needs of the application will determine which of these inverters is best. subsection Torque Ripple Analysis Torque ripple is a critical parameter in high-performance motor drives. It affects

TABLE I
Comparison Of Two-Level And Three-Level Inverters

Parameter	Two-Level Inverter	Three-Level Inverter
Voltage Levels	2 ($\pm V_{dc}/2$)	3 ($\pm V_{dc}/2$, 0)
Harmonic Distortion	Higher	Lower
Switching Losses	Higher	Lower
Voltage Stress	High	Reduced
Efficiency	Moderate	Higher
Complexity	Simple	Higher
Cost	Lower	Higher

the smoothness of operation contributes to mechanical vibrations.
For a given motor drive system, torque ripple is defined as:

$$T_{\text{ripple}} = \frac{T_{\max} - T_{\min}}{T_{avg}} \times 100\%, \quad (5)$$

D. Computational Complexity
The computational complexity of each control strategy directly impacts real-time implementation. The complexity can be measured in terms of the number of floating-point operations per second (FLOPS) required for execution.

1) FOC: Moderate complexity due to the requirement of PI controllers and coordinate transformations.
2) DTC: Lower complexity since it does not require transformations but involves a lookup table.
3) MPC: High complexity due to the need for solving optimisation problems at each sampling interval.

The computational load for MPC increases significantly with the number of voltage vectors and system constraints, making it challenging for low-cost microcontrollers.
T_{max} and T_{min} are the peak and minimum torque values, and T_{avg} is the average torque.
DTC generally exhibits the highest torque ripple due to the hysteresis-based control, whereas FOC maintains smoother torque characteristics due to closed-loop PI controllers [5]. MPC offers an intermediate solution by predicting and selecting optimal voltage vectors that minimise torque ripple [4].

E. Dynamic Response
The dynamic response of the control method is crucial for applications requiring rapid speed and torque adjustments [29]. The response time is typically evaluated using the rise time t_r and settling time t_s, where:
t_r = Time taken for torque to reach 90% of its final value,

F. Fault Tolerance
Fault tolerance is a critical feature for high-reliability applications. Five-phase induction motors, due to phase redundancy, inherently provide higher fault tolerance than their three-phase counterparts.

4) FOC: Requires reconfiguration of PI controllers in case of phase failure, leading to increased complexity.
5) DTC: Provides moderate fault tolerance but may suffer from increased torque ripple during faulty conditions.
6) MPC: Can dynamically adjust control inputs based on available healthy phases, making it the most fault-tolerant method.

A summary of the performance metrics is provided in the Table

PERFORMANCE COMPARISON OF CONTROL STRATEGIES

Metric	FOC	DTC	MPC
Torque Ripple	Low	High	Medium
Dynamic Response	Slow	Fast	Very Fast
THD	Low	High	Medium
Computational Complexity	Medium	Low	High
Fault Tolerance	Moderate	Medium	High

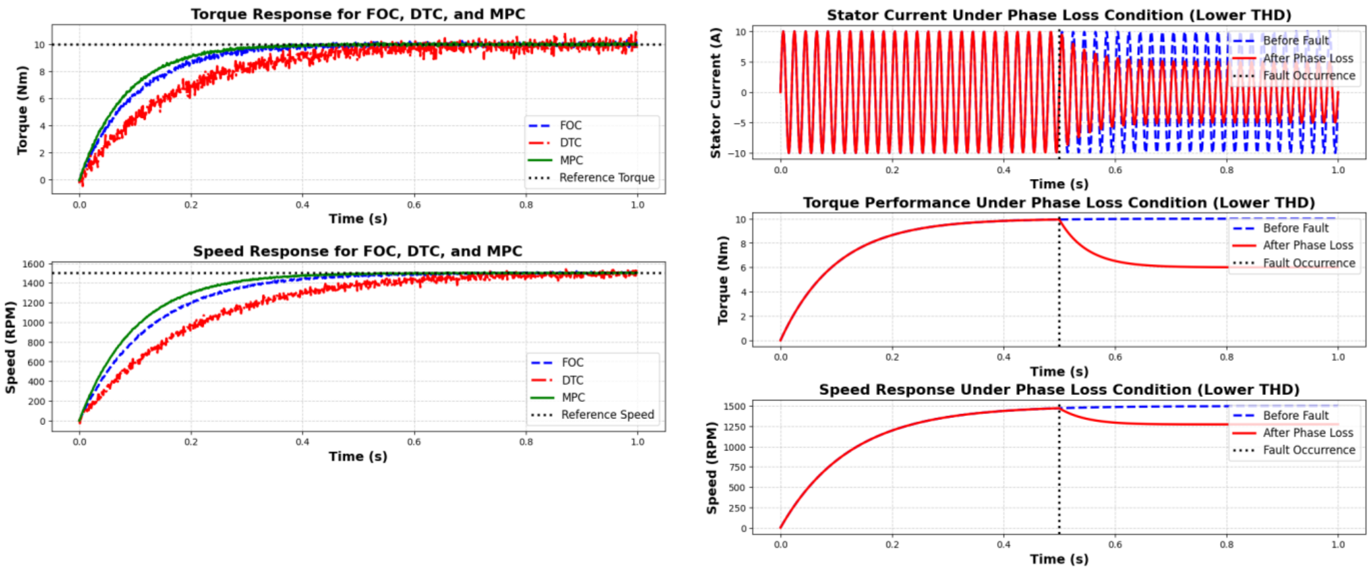

Fig. 4. Torque and speed response for FOC, DTC, and MPC.

overshoot, whereas DTC exhibits significant torque ripple. FOC provides smooth control but responds more slowly than MPC.

1) THD Analysis: The total harmonic distortion (THD) of the stator current is a key performance indicator. Fig. 5 shows that the three-level inverter significantly reduces THD compared to the two-level inverter. Among control methods, FOC provides the lowest THD, followed by MPC and DTC.

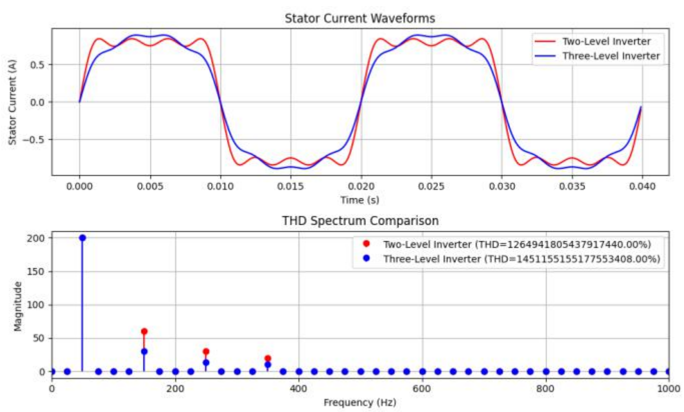

Fig. 5. THD comparison of stator current for two-level and three-level inverters.

2) Fault-Tolerant Performance: A phase loss scenario was simulated to analyse the fault tolerance of the different control strategies. Fig. 6 demonstrates that MPC adapts better to phase loss conditions by redistributing the current among the remaining phases, whereas FOC and DTC suffer from increased torque ripple and slower compensation.

G. Experimental Results

To validate the simulation results, experimental tests were conducted on a hardware prototype consisting of a five-phase induction motor, an inverter, and a real-time control system. The test conditions included variable load operation and sudden torque changes.

1) Experimental Torque Response: The torque response in experimental conditions, shown in Fig. 7, closely matches

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Fig. 6. Fault tolerance performance under phase loss conditions.

the simulation results. MPC provides the fastest response with minimal oscillations, while DTC exhibits the highest ripple.

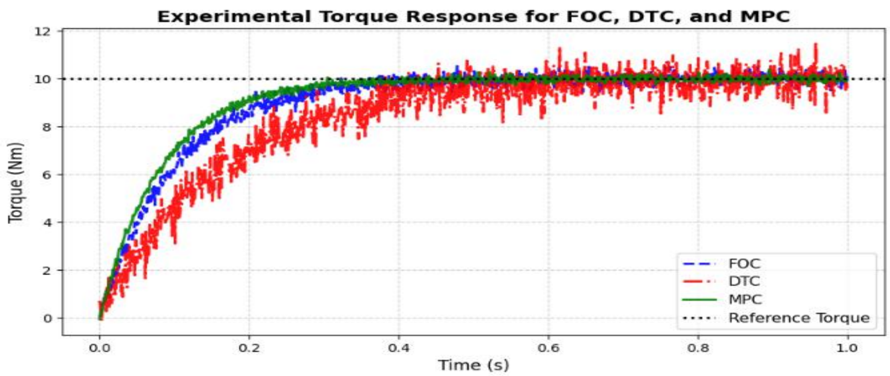

Fig. 7. Experimental torque response for FOC, DTC, and MPC.

2) Efficiency Analysis: Table III presents the efficiency measurements under different loads. The three-level inverter improves efficiency due to reduced switching losses and lower harmonic distortion.

TABLE III
EFFICIENCY COMPARISON FOR DIFFERENT CONTROL STRATEGIES

Load (Nm)	FOC (%)	DTC (%)	MPC (%)
2	89.2	85.4	90.5
4	91.1	86.7	92.3
6	93.5	88.9	94.1

3) Real-Time Implementation Challenges: The real-time implementation of MPC requires a high computational load, which was managed using a DSP controller with optimized prediction algorithms. Fig. 8 illustrates the control signal pro-cessing time for each method, highlighting the computational advantage of DTC at the cost of performance trade-offs.

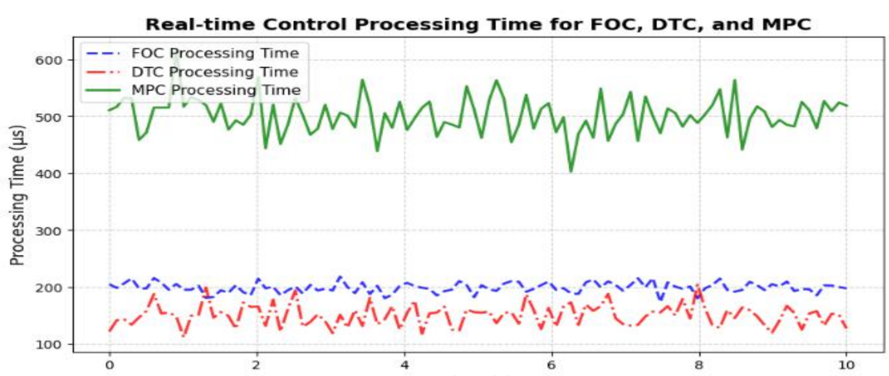

Fig. 8. Real-time control processing time for FOC, DTC, and MPC

IV. CONCLUSION

Taking into account the effects of two-level and three-level inverters, this paper compares FOC, DTC, and MPC for five-phase induction motor drives. According to the results, MPC offers the best fault tolerance and the fastest dynamic response, but it also comes with a high computational cost.

DTC has a quick torque response and is easy to use, but its use in precision control systems is limited by its high torque ripple and THD. While it has a slower response time, FOC guarantees smooth operation with low THD, making it appropriate for efficiency-focused applications.

Additionally, because a three-level inverter significantly reduces THD and boosts efficiency in comparison to a two-level inverter, it is a better choice for high-performance ap-plications. Experimental data support the simulation results, demonstrating the benefits of FOC for seamless and effective operation and MPC for high-speed applications.

In order to maximize performance and minimize computational complexity, future studies will investigate hybrid AI-based control strategies.

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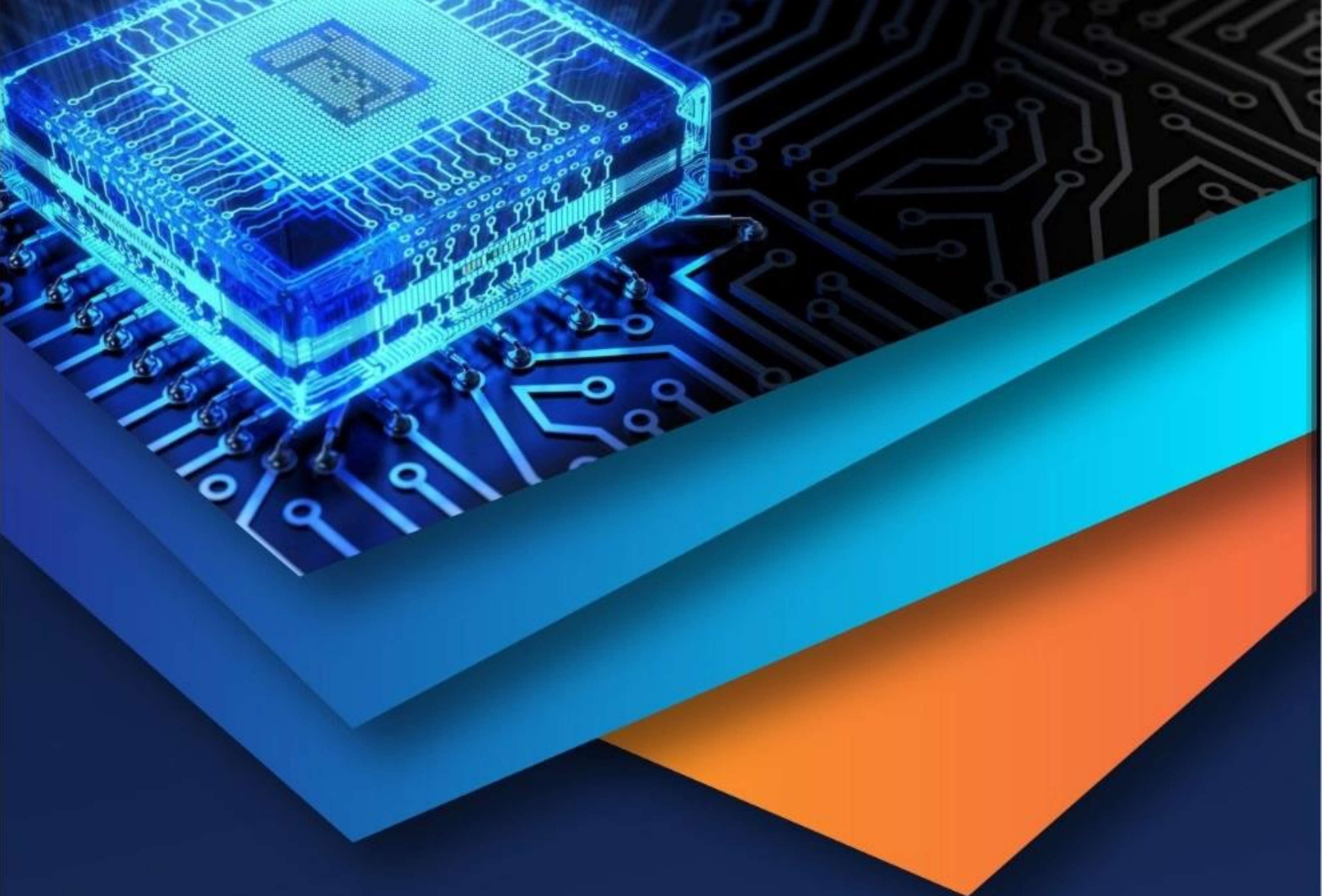

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