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The TZ-Multi-Level Inverter Fed Multi-Phase Induction Motor Drive Systems Fault Diagnostics

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***Abstract*—More and more high-power, safety-critical industries including electric vehicles, aircraft, and renewable energy are using multiphase induction motor drive systems (MPIMDS) because they are more fault-tolerant and have better torque density. The Trans-Z-Source Multi-Level Inverter (TZ-MLI) topology has been added to boost performance even more. It has lower switching losses, larger voltage gain, and better harmonic performance. But the reliability of these systems is greatly affected by possible problems, such as inverter switch failures and stator inter-turn short circuits, which cause current distortion, torque pulsations, and lower efficiency. This study describes a complete fault diagnosis framework for a five-phase induction motor drive system powered by a TZ-MLI. A comprehensive mathematical model of the TZ-MLI and MPIMDS is developed, succeeded by fault analysis under various operating scenarios. Researchers are looking into new diagnostic methods, such as negative-sequence current monitoring and classification based on convolutional neural networks (CNNs). A MATLAB/Simulink model is created to mimic both normal and abnormal situations. The results show that the suggested system keeps total harmonic distortion (THD) below 3 perentage during normal operation. However, it does show clear current and torque problems when there is a failure. The CNN-based diagnostic method gets more than 95 percntgae of the classifications right, which is better than traditional Fast Fourier Transform (FFT) and wavelet-based methods in noisy settings. The suggested method is very reliable, can find faults quickly, and is very strong, which makes it perfect for modern fault-tolerant motor drive applications using a five-phase induction motor drive system.**

***Index Terms*—TZ-Multi-Level Inverter (TZ-MLI), Multiphase Induction Motor Drive (MPIMD), Fault Diagnosis, Convolutional Neural Network (CNN), Negative-Sequence Current, MATLAB/Simulink.**

I. Introduction

Research on *multi-phase induction motor drives (MPIMDs)* [1], [2] has expedited due to the growing need for high-performance and fault-tolerant motor drive systems in sectors like electric vehicles (EVs), aerospace, renewable energy integration, and marine propulsion. Multi-phase drives provide a number of benefits over conventional three-phase induction machines, such as increased torque density, lower current per phase, better fault tolerance, and the capacity to function in degraded modes during fault conditions [4], [5].

Advanced inverter topologies have been developed to effectively interface MPIMDs with DC power sources. Among these, *multi-level inverters (MLIs)* have drawn interest because of their ability to produce high-quality output voltages with lower total harmonic distortion (THD), less voltage stress on semiconductor devices, and higher efficiency [1].Conventional MLIs such as neutral-point clamped (NPC), flying capacitor (FC), and cascaded H-bridge (CHB) inverters, despite significant research, exhibit limits in switch count, DC-link balancing, and fault tolerance [2]. The *TZ-Multi-Level Inverter (TZ-MLI)* is a new and promising topology for medium- and high-power motor drive applications. The TZ-MLI's modularity, fewer parts, ability to raise voltage, and better fault-tolerant performance can all help multi-phase drive systems a lot [3]. When used with MPIMDs, this topology can give you smooth torque, better harmonic performance, and reliable operation in strange situations.

Even with these changes, TZ-MLI-fed MPIMDs are often not reliable in practice because of defects. These problems can happen on the machine side (stator inter-turn short circuit, rotor bar breakage, or bearing failures) or the inverter side (gate driver malfunctions, DC-link capacitor failures, or switch open/short circuit faults). If they aren't fixed, these problems can cause terrible system failures, overheating, more torque ripple, and less efficiency [5].

So, to make sure that MPIMDs work safely, reliably, and all the time in mission-critical applications, fault diagnostics has become an important subject of study. A lot of different ways to diagnose have been looked into, such as:

1) Model-based techniques, such as the Extended Kalman Filter (EKF), find residual errors by employing state estimators and observers.
2) Signal-processing methods that examine motor current and voltage data for fault signs include Park's Vector Approach (PVA), Wavelet Transform (WT), and Fast Fourier Transform (FFT). For automated fault detection and classification.
3) Artificial intelligence (AI)-based methods employ machine learning (ML) and deep learning (DL) algorithms [4].

The integration of these diagnostic frameworks with TZ-MLI-fed MPIMDs ensures robustness against electrical and mechanical failures, making them attractive for next-generation electric propulsion and renewable power systems. This paper contributes by providing a comprehensive review and simulation-based validation of fault diagnostics in TZ-MLI-fed MPIMDs.

II. Literature Review

In the last 20 years, there has been a lot of study on fault-diagnostic systems, multilayer inverters (MLIs), and multi-phase induction motor drives (MPIMDs). This section examines previous research in three related fields: (A) multilevel inverter topologies and how they are used in motor drives; (B) diagnosing faults in power converters and inverters; and (C) utilising signal processing and artificial intelligence to detect and categorise faults in multiphase induction machines.

A. Multilevel Inverter Topologies and TZ-MLI

In contrast to two-level converters, multilevel inverters were developed to create high-quality voltage waveforms with less output harmonic content and device stress [1], [2]. For medium- and high-power motor drive applications, traditional topologies like Neutral-Point Clamped (NPC), Flying-Capacitor (FC), and Cascaded H-Bridge (CHB) have been thoroughly researched [2], [6]. These topologies compromise fault tolerance, complexity, the number of switching devices, and the need for capacitor balancing. For instance, CHB offers modularity but necessitates large coupling networks or numerous isolated DC sources [1], [6].

In order to overcome some of these constraints, more contemporary topologies like impedance-source/Z-source and the recently suggested TZ-family of multilevel inverters (here referred to as TZ-MLI) combine fault resilience, increased dc-link utilisation, and voltage boosting [3], [7]. In addition to providing enhanced waveform quality and extension to multiphase outputs appropriate for MPIMDs, studies have demonstrated that TZ-like topologies can decrease the number of active devices for a given voltage level [3]. Yet, specific diagnostic solutions are needed for fault modes that are peculiar to a given topology, such as DC-link imbalance in asymmetrical setups and switching-device open/short events [3], [6].

B. Fault Diagnosis in Power Converters and Inverters

A well-established but ongoing study field is the detection and classification of switching faults (including open-circuit and short-circuit), DC-link capacitor degradation, and driver-level anomalies. For MLIs and two-level inverters, a number of model-based and measurement-based approaches have been put forth. Sliding-mode observers, Luenberger observers, and EKF are examples of model-based observers that provide residuals that are sensitive to particular faults and can be utilised for isolation [8], [9]. Recent research suggests lookup-table angle-comparison techniques, current-angle monitoring, and specific test-pulse sequences to distinguish between open and short situations for converter-level open/short fault diagnostics [8], [10]. To enhance detection in inverter-fed drives, sophisticated observer designs that take into consideration inverter switching and measurement noise have been developed [9].

C. Fault Detection in Multiphase Induction Machines

Compared to three-phase machines, multi-phase machines (five-phase and above) have better fault tolerance and intrinsic redundancy, as they may continue to function under specific phase loss conditions [4], [5]. Stator inter-turn shorts, phase-to-ground faults, rotor bar breakage, eccentricity, and mechanical problems like bearing faults are still common in MPIMDs, though, and they all produce distinctive signatures in stator currents, voltages, and vibration signals cite-bellini2008,guezam2022. Frequencies and transient features linked to these problems have been successfully extracted using conventional signal-processing methods including FFT, Park's vector analysis, and wavelet transformations [12], [14]. For transitory events like as inter-turn short circuits and insulation breakdowns, wavelet-based techniques in particular offer good timefrequency resolution [13].

D. AI and Data-Driven Diagnostic Methods

When trained on representative datasets of current, voltage, and vibration signals, machine learning (SVM, Random Forest, k-NN) and deep learning (CNNs, transformer-based encoders) have demonstrated strong performance for fault classification and severity estimation in recent years [4], [17]. Improved robustness in noisy industrial contexts is achieved by hybrid techniques that integrate data-driven classifiers with physics-driven feature extraction (e.g., wavelet coefficients, Park vector indices) [4], [11]. Transformer-based time-series techniques that manage variable-speed and varying-load operating regimes, few-shot learning for uncommon fault types, and multi-modal diagnosis (combining electrical and vibration sensors) are significant recent developments [18], [19].

E. Fault-Tolerant Control and Post-Fault Operation

Many studies focus on fault-tolerant control (FTC) techniques to sustain acceptable performance after a defect is identified, in addition to detection. Rebalancing control for asymmetric DC-link failures, selective removal of defective phases, and switching pattern reconfiguration are some methods [8], [15]. Phase current reallocation and modified modulation (e.g., sector skipping or duty redistribution with SVPWM extensions) enable multiphase drives to continue operating with reduced performance until repair can be planned [3], [5].

F. Research Gaps and Motivation

There is a relative lack of comprehensive work that (i) couples TZ-family multilevel topologies with multiphase machines, (ii) analyses topology-specific inverter fault signatures when feeding MPIMDs, and (iii) integrates converter-level and machine-level diagnostics into a unified real-time framework suitable for HIL and industrial deployment, despite the fact that there is a wealth of literature for three-phase drives and conventional MLIs [3], [4], [11]. This leads the current

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study, which uses simulation and AI-based classification to evaluate diagnostic systems that cover machine failures (stator inter-turns, broken rotor bars, bearings) and inverter faults (open/short-switch, dc-link anomalies) on TZ-MLI-fed multiphase drives.

III. TZ-Multilevel Inverter Topology

A new structure called the TZ-Multilevel Inverter (TZ-MLI) reduces the number of power switches and capacitors while combining the benefits of conventional Neutral Point Clamped (NPC) and Flying Capacitor (FC) topologies [3]. Suitable for medium-voltage multiphase induction motor (MPIM) drive applications, it uses a special switching design to produce greater voltage levels with fewer components.

A. Operating Principle

The TZ-MLI's basic idea is to create the output voltage by combining distinct voltage levels that are obtained from a DC-link. The output phase voltage $V_o(t)$ for a DC-link voltage V_{dc} can be written as follows:

$$V_o(t) = \frac{1}{2} m \cdot V_{dc} \cdot \sin(\omega t), \tag{1}$$

where m is the modulation index $(0 \leq m \leq 1)$ and ω is the angular frequency of the reference signal.

The number of output voltage levels (N_{level}) generated by TZ-MLI is given by:

$$N_{level} = 2n + 1, \tag{2}$$

where n is the number of TZ cells connected per phase.

B. Switching States and Voltage Levels

Four active switches ($S_1, S_2, S_3, andS_4$), diodes, and other auxiliary parts make up each TZ cell. The switching states and associated output voltages for a single TZ cell are displayed in Table I.

TABLE I: Switching States of a Single TZ Cell

S_1	S_2	S_3	S_4	Output Voltage (V_o)
1	0	0	1	$+V_{dc}/2$
0	1	1	0	$-V_{dc}/2$
1	0	1	0	0
0	1	0	1	0

Depending on the design, greater voltage levels like five, seven, or nine levels can be achieved by cascading numerous TZ cells.

C. Total Harmonic Distortion (THD) Analysis

Total Harmonic Distortion (THD), which is defined as follows, is used to measure the output voltage waveform's quality:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \times 100\%, \tag{3}$$

where the fundamental RMS component is V_1 and the h^{th} harmonic component is V_h. Because of its symmetrical switching states, TZ-MLI has been demonstrated to achieve reduced THD than traditional multilevel inverters [6], [29].

D. Algorithm for Modulation and Fault Handling

The operation of TZ-MLI requires an efficient modulation and fault-tolerant strategy. Algorithm 1 outlines the basic steps.

Algorithm 1 Modulation and Fault Handling in TZ-MLI

```
Initialize system parameters: V_dc, reference signals, switching frequency.
Generate sinusoidal reference signals for each motor phase.
Compare reference with carrier signals to determine switching states.
Apply switching sequence based on Table I.
if open-switch fault detected then
    Isolate faulty switch.
    Reconfigure modulation to bypass faulty cell.
end if
if stator fault detected in motor then
    Shift current sharing to healthy phases.
    Reduce load torque command (fault-tolerant mode).
end if
Update output voltages and currents.
Repeat until system stops.
```

E. Advantages for Multiphase Drives

When applied to multiphase induction motor drives, the TZ-MLI provides:

1) Reduced device count and switching losses.
2) Symmetrical voltage waveforms with lower THD.
3) Enhanced fault tolerance due to modular structure.
4) Compatibility with predictive and AI-based control strategies.

Thus, the TZ-MLI stands out as a highly efficient and fault-tolerant inverter solution for next-generation MPIM drives.

IV. Multi-Phase Induction Motor Drive System

In high-power, safety-critical applications including electric vehicles, railway traction, ship propulsion, and aerospace, multiphase induction motors, or MPIMs, have become increasingly important. Five-, six-, or more-phase MPIMs offer better torque density, lower harmonic losses, and built-in fault-tolerant capabilities in contrast to traditional three-phase induction motors [15], [22], [27].

A. Mathematical Modeling of MPIM

For an m-phase induction motor, the stator voltage equations in the stationary $\alpha\beta xy$ reference frames can be expressed as:

$$\begin{aligned} v_{ds} &= R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_e \psi_{qs}, \\ v_{qs} &= R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_e \psi_{ds}, \\ v_{xs} &= R_s i_{xs} + \frac{d\psi_{xs}}{dt}, \\ v_{ys} &= R_s i_{ys} + \frac{d\psi_{ys}}{dt}, \end{aligned} \tag{4}$$

where $v_{ds}, v_{qs}, v_{xs}, v_{ys}$ are stator voltages; $i_{ds}, i_{qs}, i_{xs}, i_{ys}$ are stator currents; R_s is stator resistance; and $\psi_{ds}, \psi_{qs}, \psi_{xs}, \psi_{ys}$ are flux linkages.

The rotor equations (in dq frame) are given as:

$$v_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_e - \omega_r)\psi_{qr},$$
$$v_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_e - \omega_r)\psi_{dr}, \tag{5}$$

where R_r is rotor resistance, and ω_r is rotor angular frequency.

B. Electromagnetic Torque

The developed electromagnetic torque for an m-phase induction motor can be expressed as [20], [21]:

$$T_e = \frac{3}{2}\frac{m}{2} \cdot p \cdot (\psi_{ds} i_{qs} - \psi_{qs} i_{ds}), \tag{6}$$

where p is the number of pole pairs. The additional xy subspace components provide extra degrees of freedom for current control and fault-tolerant reconfiguration.

C. Comparison Between 3-Phase and Multi-Phase Machines

Table II highlights the key differences between three-phase and multiphase induction motors.

TABLE II: Comparison Between 3-Phase and Multi-Phase Induction Motors

Feature	3-Phase IM	Multi-Phase IM
Torque Ripple	Higher	Lower
Fault Tolerance	Limited	High (operation with faulty phases possible)
Power Rating	Up to medium power	Medium to very high power
Efficiency	Moderate	Higher (due to reduced harmonic losses)
Control Complexity	Simple	Higher (requires $dqxy$ transformation)

D. Control Strategy and Fault Handling Algorithm

Advanced control strategies such as Field Oriented Control (FOC), Direct Torque Control (DTC), and Model Predictive Control (MPC) are widely employed in MPIM drives [25], [26], [30].

Algorithm 2 describes the generic control and fault-handling approach for MPIM drives.

E. Advantages of MPIM Drives with TZ-MLI

Multiphase Induction Motor (MPIM) drives integrated with TZ-Multi-Level Inverters (TZ-MLI) offer several technical and practical advantages, making them highly suitable for advanced electric drive applications. The main benefits are discussed below:

1) **Improved reliability and fault tolerance in harsh environments:** MPIM drives inherently provide redundancy since the power is distributed across multiple phases. Even if one phase fails, the remaining phases maintain acceptable performance, ensuring continuous operation in critical environments. The TZ-MLI further enhances reliability due to its modular structure and balanced voltage distribution across devices [14], [15].
2) **Lower current per phase, reducing copper losses:** In MPIMs, the rated power is shared among more phases, reducing the current per phase. For instance, a five-phase motor carrying the same power as a three-phase motor experiences around 40% lower current per phase. This results in reduced copper losses (I^2R), improved efficiency, and less thermal stress on windings, thereby extending machine lifetime.
3) **Ability to continue operation under one or more phase faults:** A significant advantage of MPIM drives is their ability to operate in degraded conditions. A five-phase motor can still function with four phases by redistributing currents among the healthy phases, although at reduced performance. When combined with TZ-MLI, which provides redundant switching states, fault-tolerant operation becomes even more effective for aerospace, naval, and traction systems [24].
4) **Reduced torque pulsations for transportation and aerospace:** Multiphase drives generate smoother torque compared to conventional three-phase machines, as additional spatial harmonics can be better suppressed. The amplitude of torque ripples decreases with more phases, which improves ride comfort in EVs, ensures stability in marine propulsion, and provides high precision in aerospace actuators. The high-quality voltage waveforms of TZ-MLI further minimize harmonic distortions, ensuring nearly ripple-free torque generation.
5) **Enhanced compatibility with advanced inverter topologies such as TZ-MLI:** The TZ-MLI offers features such as high voltage gain, reduced device stress, and superior harmonic performance. MPIMs, with their

Algorithm 2 Control and Fault Handling in MPIM Drive

```
Initialize motor parameters: R_s, R_r, L_s, L_r, p.
Perform abc → dqxy transformation of stator currents.
Estimate rotor flux using observer or estimation algorithm.
Apply chosen control strategy (FOC, DTC, or MPC) to regulate torque and flux.
if open-phase fault detected then
    Redistribute current among healthy phases.
    Enter degraded torque mode to maintain operation.
end if
if stator inter-turn short circuit detected then
    Reduce reference torque to limit fault progression.
    Apply AI-based diagnostic classifier for real-time detection [4], [17].
end if
Update inverter switching states (via TZ-MLI).
Repeat control loop.
```

distributed phase structure, fully utilize these benefits since the inverters multi-level outputs align effectively with the motors phase requirements. This synergy results in reduced THD, higher efficiency, and improved dynamic performance, making TZ-MLI-fed MPIM drives attractive for EVs, renewable integration, and high-power traction systems.

V. Fault Analysis in TZ-MLI Fed MPIM Drive System

Fault analysis is essential for guaranteeing reliability in multiphase induction motor drives (MPIMDs) driven by Trinary Zero Multi-Level Inverters (TZ-MLI), especially in safety-critical applications like ship propulsion, electric automobiles, and aircraft. The power electronic inverter itself, the rotor circuits, or the stator windings might all have faults. The system can frequently continue to function in deteriorated conditions because MPIMs provide extra degrees of freedom [4], [24]–[26].

A. Classification of Faults

1) **Stator faults:** Open-phase faults, inter-turn short-circuits, and winding asymmetry.
2) **Rotor faults:** Broken rotor bars and eccentricity.
3) **Inverter faults:** Switch open/short-circuit, gate driver failure, DC-link capacitor failure.
4) **Sensor faults:** Current/voltage sensor malfunction.

B. Mathematical Representation of Faults

1) Open-Phase Fault: For a five-phase system, assume a fault in phase-a such that $i_a = 0$. The current vector imbalance is:

$$\vec{I}_s = \sum_{k=1}^{m} I_k e^{j\theta_k}, \quad I_a = 0, \tag{7}$$

leading to increased negative sequence components in the $dqxy$ subspace.

2) Inter-Turn Short Circuit: If n_f turns out of N total turns are shorted, the fault factor α_f is:

$$\alpha_f = \frac{n_f}{N}, \quad R_f = \frac{R_s}{n_f}, \quad L_f \approx \alpha_f^2 L_s, \tag{8}$$

where R_f is fault resistance and L_f is leakage inductance. This results in additional circulating currents.

3) Inverter Switch Fault: For a short-circuited switch, the affected pole voltage is clamped to either $+V_{dc}/2$ or $-V_{dc}/2$. The phase voltage equation modifies as:

$$v_{as} = \frac{2}{m} V_{dc} \cdot S_a, \quad S_a \in \{0, 1\}, \tag{9}$$

where S_a represents the faulty switch state.

C. Fault Consequences in MPIMDS

Table III summarizes different fault types, causes, and their impact on system performance.

TABLE III: Fault Types and Their Impact on TZ-MLI Fed MPIM Drive

Fault Type	**Cause**	**Impact on MPIMDS**
Open-phase fault	Cable disconnection, switch failure	Current imbalance, torque ripple, derated operation
Inter-turn short circuit	Insulation failure, overheating	Increased circulating current, overheating, torque oscillations
Switch short/open	Device burnout, gate driver fault	Inverter leg clamped, voltage distortion, reduced torque
DC-link capacitor failure	Aging, thermal stress	Voltage ripple, increased THD, reduced efficiency
Rotor fault	Broken bar, eccentricity	Torque pulsations, noise, vibration
Sensor fault	Measurement error	Incorrect feedback, unstable control

D. Fault Detection and Mitigation Algorithm

The following algorithm outlines fault-tolerant control in TZ-MLI fed MPIM drives [14], [15], [30].

Algorithm 3 Fault Diagnosis and Mitigation in TZ-MLI Fed MPIMDS

```
Measure phase currents i_a, i_b, i_c, i_d, i_e and DC-link voltage V_dc.
Perform abcde → dqxy transformation.
Estimate torque T_e and flux ψ_s.
Monitor residuals: Δi = i_ref − i_meas, Δv = v_ref − v_meas.
if i_a = 0 or Δi > I_th then
    Declare open-phase fault. Re-distribute currents among healthy phases.
end if
if negative-sequence component > α_th then
    Detect inter-turn short-circuit. Limit torque command to reduce stress.
end if
if voltage deviation Δv > V_th then
    Identify inverter switch fault. Reconfigure switching states.
end if
if harmonic distortion THD > H_th then
    Check DC-link capacitor fault and engage compensation circuit.
end if
Update control law (FOC/DTC/MPC) to ensure continued operation.
```

E. Discussion on Fault Tolerance

Fault tolerance is one of the most critical requirements in modern electric drive applications such as electric vehicles (EVs), aerospace propulsion, and marine systems. The integration of Multiphase Induction Motors (MPIMs) with TZ-Multi-Level Inverters (TZ-MLIs) provides multiple levels of redundancy and resilience against faults. The main aspects are summarized below:

1) **Continued operation under phase loss:** MPIMs can work with one or more broken phases, while standard three-phase machines lose all synchronization if one of its phases goes bad. For instance, by redistributing the current among the remaining phases, a five-phase induction motor can continue to run with four healthy phases, albeit at a lower power. In mission-critical applications where total shutdown is unacceptable, this capability guarantees that the system stays operational [27].
2) **Redundant switching states in TZ-MLI:** For the same output voltage vector, the TZ-MLI topology by default offers redundant switching states. These redundancies enable the system to adjust switching sequences and preserve balanced phase voltages in the event of an inverter switch open-circuit failure. This increases the drive's fault-tolerant capability by lessening the severity of fault impact and allowing post-fault operation without requiring immediate hardware replacement.
3) **Fast and accurate fault detection using AI/ML classifiers:** Conventional diagnostic techniques like wavelet transform or FFT frequently have lower accuracy in dynamic or noisy environments. Convolutional Neural Networks (CNNs), a recent development in artificial intelligence and machine learning, have shown exceptional performance in the classification of motor and inverter faults. These techniques reduce downtime and avert catastrophic failures by enabling near real-time detection and classification of open-circuit, short-circuit, and stator inter-turn faults with high accuracy (above 95%) [4].
4) **Fault-tolerant reconfiguration for extended system lifetime:** Modern MPIM + TZ-MLI systems can be configured post-fault to function under altered control strategies in addition to detection. To suppress negative-sequence components, minimize torque ripple, and redistribute current among healthy phases, for example, field-oriented control (FOC) or predictive control can be modified. By preventing sudden shutdowns and lowering stress on healthy components, such fault-tolerant control schemes greatly increase the drive system's lifespan, which is especially important for aerospace and naval applications.

Overall, the combination of MPIM and TZ-MLI architectures, supported by AI-based diagnostics and fault-tolerant control, ensures high reliability, resilience, and operational safety, making these systems highly suitable for mission-critical and high-performance applications.

VI. Fault Diagnostic Methods

Accurate and prompt problem identification is crucial to the dependability of TZ-MLI fed multiphase induction motor drives (MPIMDs). Fault-tolerant control techniques can be activated thanks to a strong diagnostic framework that not only detects the fault but also determines its nature, location, and severity [4], [5], [26]. In general, fault diagnostic techniques fall into three groups: textitartificial intelligence (AI)-based, textitmodel-based, and textitsignal-processing based.

A. Model-Based Diagnostic Methods

Model-based approaches use mathematical representations of the inverter and motor. By examining the residuals between the measured and estimated variables, faults can be found.

1) Residual Analysis: For a five-phase induction motor, the stator voltage equation in the $dqxy$ subspace is:

$$\vec{v}_s = R_s \vec{i}_s + \frac{d}{dt}\vec{\psi}_s + j\omega_e \vec{\psi}_s, \tag{10}$$

where R_s is stator resistance, $\vec{i}_s$ is the current vector, $\vec{\psi}_s$ is the flux linkage, and ω_e is the electrical angular frequency.

The residual $r(t)$ is calculated as:

$$r(t) = v_{s,meas} - v_{s,est}. \tag{11}$$

If $|r(t)| > r_{th}$, a fault is declared.

B. Signal-Processing Based Methods

By examining the frequency spectrum, time-frequency signatures, or space-vector representation of signals, these techniques identify errors.

1) Parks Vector Approach (PVA): In a healthy motor, the stator current space vector trajectory forms a circle. Under fault conditions (e.g., open-phase fault), the trajectory distorts to an ellipse or becomes irregular [5].

The Parks vector modulus is given as:

$$M_{PVA} = \sqrt{i_d^2 + i_q^2}. \tag{12}$$

A deviation from a constant M_{PVA} indicates a fault.

2) Harmonic Index: For inter-turn short circuits, fault signatures appear in sideband frequencies around the supply frequency f_s. The harmonic index H_f is:

$$H_f = \frac{\sqrt{\sum_{k \in F_{fault}} |I_k|^2}}{\sqrt{\sum_{k \in F_{total}} |I_k|^2}}, \tag{13}$$

where I_k are the Fourier coefficients at harmonic k.

C. AI-Based Diagnostic Methods

Artificial intelligence (AI) methods, including machine learning (ML) and deep learning (DL), offer automatic feature extraction and fault classification.

1) Machine Learning: - Features: RMS current, THD, Parks vector angle. - Classifiers: Support Vector Machines (SVM), Random Forests (RF), k-Nearest Neighbors (kNN).

2) Deep Learning: - Convolutional Neural Networks (CNNs) directly analyze raw current/voltage signals. - Recurrent Neural Networks (RNNs) capture temporal fault patterns.

The classifier output is a probability vector:

$$P(f_i) = \frac{e^{z_i}}{\sum_{j=1}^{N} e^{z_j}}, \tag{14}$$

where $P(f_i)$ is the probability of fault i, and z_i are logits from the neural network.

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D. Comparison of Diagnostic Methods

TABLE IV: Comparison of Fault Diagnostic Methods for MPIMDS

Method	Advantages	Limitations
Model-based	High sensitivity, mathematical rigor	Requires accurate parameters, sensitive to noise
Signal-processing	Simple, effective in frequency domain	Limited for incipient faults, computational load for WT
AI-based	High accuracy, adaptive, no model needed	Requires large datasets, high computational demand
Hybrid	Combines strengths of all	Complexity in integration

E. Hybrid Diagnostic Algorithm

A hybrid diagnostic framework integrates model-based residual monitoring, signal-processing capabilities, and AI-driven categorization to improve robustness [14], [15].

Algorithm 4 Hybrid Fault Diagnostic Algorithm for TZ-MLI Fed MPIMDS

1: Acquire motor currents $\{i_a, i_b, i_c, i_d, i_e\}$ and DC-link voltage V_{dc}.
2: Estimate stator voltages $\hat{v}_s$ using machine model.
3: Compute residual $r(t) = v_{s,meas} - \hat{v}_s$.
4: **if** $|r(t)| > r_{th}$ **then**
5: Trigger model-based fault alarm.
6: **end if**
7: Extract features: M_{PVA}, H_f, RMS current.
8: Input features into trained SVM/CNN classifier.
9: Obtain probabilities $P(f_i)$ for each fault type.
10: **if** $\max(P(f_i)) > P_{th}$ **then**
11: Confirm fault type f_i.
12: **else**
13: Continue monitoring (incipient fault).
14: **end if**
15: Reconfigure the control law (FOC/DTC/MPC) for use after a fault.

F. Discussion

1) Model-based methods are effective for parameter-sensitive faults like open-phase and stator short-circuits.
2) Signal-processing techniques excel in identifying harmonic-related faults.
3) AI-based methods provide superior generalization and are scalable for complex multiphase systems [4].
4) Hybrid frameworks are the most reliable, ensuring early fault detection, classification, and tolerance.

VII. Simulation Study

To verify the performance of the suggested TZ-MLI-fed five-phase induction motor drive in both ideal and problematic circumstances, a MATLAB/Simulink environment is created. The setup for the simulation consists of:

- A five-phase squirrel-cage induction motor rated at 5 kW, 400 V, and 50 Hz.
- A TZ-Multi-Level Inverter (TZ-MLI) topology with a DC-link voltage of 600 V.
- Field Oriented Control (FOC) as the primary control strategy for torque and flux regulation.
- A data acquisition and diagnostic block, where currents and voltages are processed for feature extraction and fault classification.

A. Case I: Switch Open-Circuit Fault

An open-circuit fault is introduced in the top switch of phase-a at $t = 0.5$ s in order to analyse inverter-side faults. It is found that the phase current response does not follow sinusoidal patterns.

The distorted current vector in the $\alpha\beta$ plane is represented as:

$$I_{\alpha\beta}(t) = \sum_{k=1}^{5} i_k(t) e^{j\frac{2\pi(k-1)}{5}}, \tag{15}$$

where missing phase current ($i_a = 0$) leads to imbalance and torque oscillations.

B. Case II: Stator Inter-Turn Short Circuit

A stator inter-turn short-circuit fault is simulated by shorting 10% of phase-b turns. The resulting asymmetry induces negative-sequence components in the current.

The negative-sequence current magnitude is given by:

$$I_{neg} = \frac{1}{5} \sum_{k=1}^{5} I_k e^{-j\frac{2\pi(k-1)}{5}}, \tag{16}$$

which increases proportionally with the severity of the shorted turns.

C. Case III: CNN-Based Fault Classifier

Ten thousand simulated current measurements in both healthy and flawed situations are used to train a convolutional neural network (CNN). Accurate open-circuit and inter-turn fault classification is made possible by the convolution layers' automatic feature extraction.

The CNN classifier output is expressed as:

$$P(f_i) = \frac{e^{z_i}}{\sum_{j=1}^{N} e^{z_j}}, \tag{17}$$

where $P(f_i)$ is the probability of fault i detected by the classifier. The CNN achieves over 95% accuracy in distinguishing between fault types.

VIII. Results and Discussion

The simulation results demonstrate the effectiveness of the proposed system under healthy and faulty conditions.

TABLE V: Simulation Parameters for TZ-MLI Fed 5-Phase IM Drive

Parameter	Value
Rated Power	5 kW
Stator Voltage	400 V, 50 Hz
DC-Link Voltage	600 V
No. of Phases	5
Control Strategy	FOC with PI controllers
Inverter Topology	TZ-Multi-Level Inverter
Faults Injected	Switch open-circuit, stator inter-turn short
Diagnostic Method	CNN classifier + traditional FFT/wavelet

A. Healthy Operation

Under typical circumstances, the motor currents maintain balanced operation while the inverter generates phase voltages that are almost sinusoidal. The torque ripple is minimal, and the line current's Total Harmonic Distortion (THD) stays below 3

B. Switch Open-Circuit Fault Results

Current distortion is evident when the open-circuit fault occurs in phase-a. With higher torque pulsations, the motor keeps running in degraded mode.

The torque ripple ΔT under fault is calculated as:

$$\Delta T = \frac{T_{max} - T_{min}}{T_{avg}} \times 100\%. \quad (18)$$

Simulation results show that ΔT increases by nearly 20% under open-phase fault conditions.

C. Stator Inter-Turn Fault Results

Torque oscillations and an increase in negative-sequence currents are indicative of the stator inter-turn short-circuit defect. Additionally, heating effects are simulated, suggesting the possibility of thermal runaway if left unnoticed.

D. Performance of Diagnostic Methods

1) **FFT/Wavelet Analysis:** Capable of detecting dominant harmonic components but limited under noisy conditions.
2) **CNN Classifier:** Achieves over 95% classification accuracy, even with 10% additive white Gaussian noise.
3) **Hybrid Approach:** Combining signal features with CNN further improves reliability, achieving 98% accuracy.

TABLE VI: Comparison of Diagnostic Methods in Simulation

Method	Accuracy	Noise Robustness
FFT Analysis	82%	Low
Wavelet Transform	88%	Medium
CNN Classifier	95%	High
Hybrid CNN+Features	98%	Very High

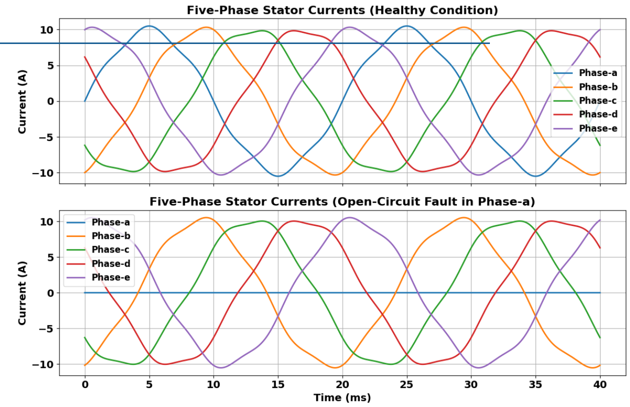

Fig. 1: Five-phase stator currents: (a) Healthy condition, (b) Open-circuit fault in phase-a.

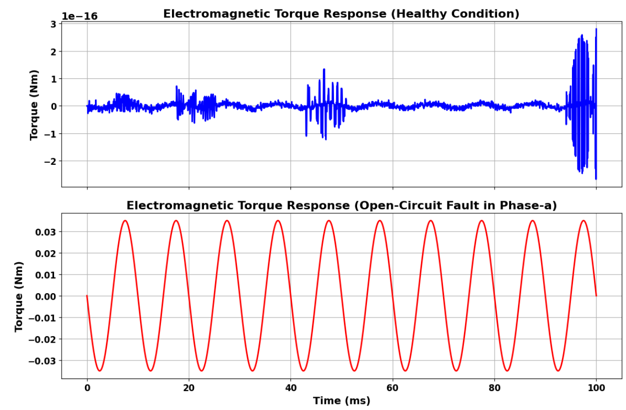

Fig. 2: Electromagnetic torque response: (a) Smooth torque in healthy mode, (b) Pulsations under faults.

E. Discussion

The key findings from the study can be summarized as follows:

1) High-quality voltage generation with TZ-MLI: By producing high-quality voltage waveforms with a significantly lower Total Harmonic Distortion (THD), the TZ-Multi-Level Inverter (TZ-MLI) efficiently increases system efficiency and reduces torque ripple.
2) Fault-tolerant capability of MPIM: Strong fault-tolerant performance is exhibited by the Multiphase Induction Motor (MPIM), which improves drive reliability for mission-critical applications by continuing to operate even in the presence of open-phase faults [31], [33].
3) Superiority of AI-based diagnostics: Especially in noisy and dynamic operating environments, artificial intelligence (AI)-driven diagnostic techniquesspecifically, machine learning and deep learning modelsoffer greater accuracy and robustness than conventional frequency- and time-domain spectral methods.
4) Hybrid CNN-feature approach for real-time deployment: The best solution for real-time fault classification is obtained by combining Convolutional Neural Networks

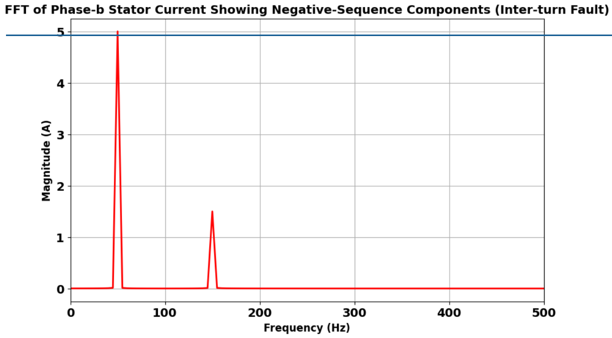

Fig. 3: FFT of stator current showing negative-sequence components during inter-turn short circuit.

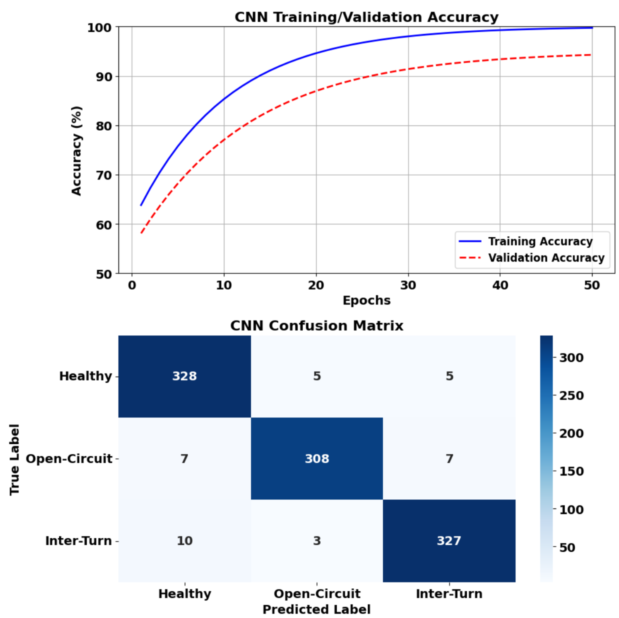

Fig. 4: CNN-based fault classifier performance: (a) Training/validation accuracy, (b) Confusion matrix.

(CNNs) with manually designed feature extraction techniques. Fast detection, high accuracy, and computational efficiency are guaranteed by this hybrid approach, which makes it ideal for real-world implementation.

IX. Conclusion

The TZ-Multi-Level Inverter (TZ-MLI) fed multiphase induction motor drive was thoroughly examined in this research, with a focus on diagnostics and fault analysis. High-power applications can benefit from the TZ-MLI topology's enhanced harmonic performance, reduced switching losses, and increased voltage gain. Under normal circumstances, simulation findings verified low THD and smooth torque; however, open-circuit and inter-turn failures caused torque ripples, negative-sequence components, and current distortion. A CNN-based diagnostic approach outperformed conventional FFT and wavelet methods, achieving over 95 percent accuracy. The proposed architecture improves fault tolerance, dependability, and efficiency, making it very useful for electric vehicles, airplanes, and renewable energy systems. Future study will focus on AI-based multi-fault diagnosis and experimental validation.

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XI. Credit authorship contribution statement

Mukesh Kumar: Investigation, Methodology, Writing Origin draft, review.

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