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NPC-Based Multilevel Inverters: Performance Analysis and Control Strategies for Five-Phase Drives

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Abstract:

This paper investigates the necessity and performance of multilevel inverters, specifically the Five-Phase Three-Level Neutral Point Clamped (FPTHL-NPC) inverter, for multi-phase machine drives. While three-phase drives have traditionally dominated industrial applications, the growing demand for electric propulsion and high-power systems has driven interest in five-phase drives due to their high fault tolerance and reduced torque ripple. However, feeding five-phase loads with discrete inverters introduces x-y subspace currents that do not contribute to power transfer but cause thermal losses. This study compares the performance of a conventional Five-Phase Two-Level Voltage Source Inverter (FPTL-VSI) against an FPTHL-NPC inverter using Sinusoidal Pulse Width Modulation (SPWM). The comparative analysis demonstrates that the NPC multilevel topology significantly reduces total harmonic distortion (THD) and optimizes common mode voltage, making it a superior choice for high-power multi-phase applications.

Keywords: *Multi-phase inverter, Five-phase drive, FPTHL-NPC (Five-Phase Three-Level Neutral Point Clamped), Total Harmonic Distortion (THD), Sinusoidal Pulse Width Modulation (SPWM)*

1. Introduction

Historically, three-phase induction motors have been the standard in industrial, commercial, and residential applications due to their low cost, robust operation, and the ubiquitous availability of three-phase power supplies. However, over the past decade, the industry has seen a substantial shift toward multiphase motor drives. Multiphase electrical motors (more than three phases) are now widely utilized in electric aircraft, vehicle propulsion, ship propulsion, and high-power traction systems.

The primary advantages of multiphase drives include:

- **High Fault Tolerance:** Ability to operate even if one or more phases fail.
- **Improved Torque Characteristics:** Higher torque density and significantly lower torque ripple.
- **Enhanced System Reliability:** Lower maintenance requirements and improved noise characteristics.

Despite these benefits, generating a multiphase supply requires advanced voltage source inverters, as multiphase power is not naturally available. Furthermore, when a five-phase load is fed by a standard discrete inverter, unwanted x-y subspace currents arise. Because the x-y components are decoupled from the d-q components (which produce torque), these subspace currents do not transfer power; instead, they generate thermal losses in the stator, increasing motor temperature and decreasing the overall machine rating.

To overcome these inherent challenges, advanced pulse width modulation (PWM) techniques and multilevel inverter topologies are employed. This paper presents a detailed comparative study between a conventional two-level five-phase inverter and a three-level NPC five-phase inverter utilizing SPWM to mitigate harmonics and improve system efficiency.

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2. Literature Review

The increasing demand for high-power and high-reliability electric drive systems has significantly accelerated research in multiphase motor drives and advanced inverter topologies. Conventional three-phase drive systems, although widely used in industrial applications, suffer from limitations such as reduced fault tolerance and higher torque ripple under dynamic operating conditions. Consequently, multiphase motor drives, particularly five-phase induction motor systems, have emerged as a promising alternative for applications in electric propulsion, ship drives, and aerospace systems [12].

Multiphase machines offer several inherent advantages including improved torque density, reduced per-phase current rating, and enhanced operational reliability during phase failure conditions. Studies have demonstrated that multiphase drive systems can maintain continuous operation even when one phase is disconnected, making them suitable for safety-critical applications [13]. However, the performance of multiphase systems is strongly influenced by the inverter configuration used to generate the required multi-phase voltage supply.

Multilevel inverter topologies have been extensively investigated as an effective solution to enhance output waveform quality and reduce harmonic distortion in medium- and high-power drive applications [8]. Among the various multilevel configurations, the Neutral Point Clamped (NPC) inverter has attracted significant attention due to its ability to generate stepped voltage waveforms while distributing the DC-link voltage stress across multiple switching devices [5]. This feature enables improved efficiency, reduced switching losses, and enhanced thermal performance compared to conventional two-level inverter structures.

Furthermore, researchers have highlighted that multilevel converters can effectively shift dominant harmonic components to higher frequency regions, thereby simplifying filtering requirements and improving electromagnetic compatibility [9]. Reduced Total Harmonic Distortion (THD) also contributes to lower copper and core losses in motor windings, ultimately improving drive efficiency and extending machine lifespan [16].

Control techniques play a crucial role in determining the overall performance of inverter-fed drive systems. Carrier-based Sinusoidal Pulse Width Modulation (SPWM) methods are widely adopted due to their implementation simplicity and effectiveness in harmonic mitigation [14]. Various modulation strategies tailored for multilevel converters have been proposed to optimize switching sequences and minimize common mode voltage, thereby improving voltage utilization and reducing insulation stress in electric machines [15].

Recent advancements in power electronic converter technology have focused on integrating multiphase drive systems with multilevel inverter configurations to achieve higher power density and improved fault-tolerant capability [18]. Comparative studies between two-level and multilevel inverter topologies indicate that increasing the number of voltage levels leads to smoother output voltage waveforms, reduced torque ripple, and improved overall drive performance [11].

Despite these technological advancements, challenges such as increased circuit complexity, control coordination, and higher initial implementation cost remain critical research concerns. Therefore, detailed performance analysis and comparative evaluation of different inverter topologies under practical operating conditions are necessary to determine their suitability for next-generation electric drive applications.

In this context, the present work focuses on analyzing the performance of a Five-Phase Three-Level Neutral Point Clamped inverter and comparing it with a conventional Five-Phase Two-Level Voltage Source Inverter under SPWM control. The study aims to evaluate harmonic characteristics, voltage stress distribution, and system efficiency to validate the advantages of NPC-based multilevel conversion in multiphase drive systems.

3. Five-Phase Induction Motor Modeling

3.1 Working Principle

The fundamental working principle of a five-phase induction motor parallels that of a traditional three-phase motor, operating on Faraday's law of electromagnetic induction. When a five-phase supply feeds the stator winding, it establishes a revolving magnetic field rotating at synchronous speed. This field interacts with the stationary rotor, inducing an electromotive force (EMF) in the rotor conductors. The resulting rotor current creates its own magnetic field, and the interaction between the stator and rotor fields produces the torque required for rotation.

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3.2 Phase Variable Model and Transformations

A five-phase induction machine is constructed with ten phase belts (36 degrees each) along the stator's circumference, creating a 72-degree phase displacement between adjacent phases.

To analyze the motor, a transformation matrix is applied to the stator windings. In a five-phase machine, this transformation reveals a critical characteristic: the x-y current components are entirely decoupled from the d-q current components.

- **d-q Components:** Responsible for fundamental torque production, as well as generating the 9th, 11th, and similar harmonic orders.
- **x-y Components:** Do not couple with the rotor circuit and produce zero torque. They are responsible for generating the 3rd, 7th, and 13th harmonic orders, which manifest purely as thermal losses in the machine.

Because multiple 5th order harmonics are produced due to zero-sequence components, controlling the inverter output to minimize these non-torque-producing harmonics is essential.

4. Inverter Topologies

To harness the benefits of a five-phase drive, a reliable five-phase supply must be synthesized from a standard DC link using a Voltage Source Inverter (VSI). This section explores two distinct topologies.

4.1 Five-Phase Two-Level Inverter (FPTL-VSI)

The FPTL-VSI increases the number of output phases simply by adding legs to the conventional three-phase structure. The upper and lower power switches of each leg operate in a complementary fashion to prevent shorting the DC supply.

- **Operation:** To achieve complementary switching, a 180-degree phase-shifted gate drive signal is applied to the upper and lower switches, with a mandatory "dead time" delay incorporated to safely transition between ON and OFF states.
- **Limitations:** In a standard ten-step operation (where each switch conducts for 180 degrees), the FPTL-VSI produces significant lower-order harmonics. These harmonics increase phase current losses, elevate temperatures, and degrade overall drive performance, necessitating advanced modulation techniques.

4.2 Five-Phase Three-Level NPC Inverter (FPTHL-NPC)

To improve power quality, the Neutral Point Clamped (NPC) multilevel topology is utilized. For high-power applications, Insulated Gate Bipolar Transistors (IGBTs) are commonly used due to their high voltage capacity and fast switching speeds.

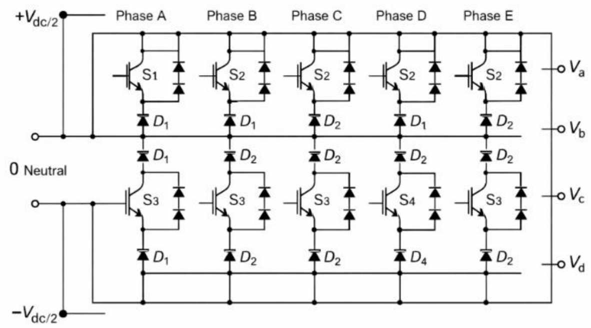

Fig.1 Five-Phase Three-Level NPC Inverter (FPTHL-NPC)

4.3 Five-Phase Two-Level Voltage Source Inverter (FPTL-VSI)

The Five-Phase Two-Level Voltage Source Inverter is a power electronic configuration designed to synthesize a five-phase AC output from a single DC source. It serves as a more robust alternative to standard three-phase systems, particularly for high-power applications requiring fault tolerance.

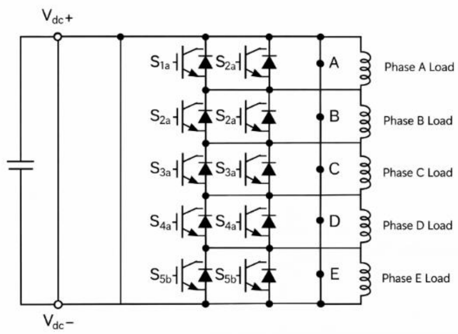

Fig.2 Five-Phase Two-Level Voltage Source Inverter (FPTL-VSI)

4.3.1 Construction and Circuit Topology

The construction of an FPTL-VSI follows a bridge structure similar to a three-phase inverter but is expanded

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by adding two additional legs to accommodate the five-phase requirement.

- **Leg Configuration**: The inverter consists of five vertical legs connected in parallel to the DC bus.
- **Switching Elements**: Each leg contains two semiconductor switches (typically IGBTs or MOSFETs for high-speed operation).
- **Freewheeling Diodes**: Every switch is paired with an antiparallel diode. These diodes are essential for providing a path for inductive "reverse" current to flow safely when a switch is turned off, preventing damage from high reverse EMF.

4.3.2 Working Principle and Switching Logic

The primary goal of the inverter is to produce five individual phase voltages that are displaced from one another by 72°.

The following table provides a detailed technical comparison between the **Five-Phase Two-Level Voltage Source Inverter (FPTL-VSI)** and the **Five-Phase Three-Level Neutral Point Clamped (FPTHL-NPC)** inverter, based on the structural and performance data analyzed in the research.

Feature	Five-Phase Two-Level (FPTL-VSI)	Five-Phase Three-Level (FPTHL-NPC)
Circuit Complexity	2 switches & 2 diodes per leg (Total: 10 switches)	4 switches & 6 diodes per leg (Total: 20 switches)
Output Voltage Levels	Two levels (+E, -E)	Three levels (+E, 0, -E)
Common Mode Voltage	High; causes stress on motor insulation	Optimized; significantly lower due to neutral point
Voltage Stress (dv/dt)	High; full DC-link voltage per switch	Lower; voltage is split across capacitors
THD (V_{an}) @ 0.8 MI	**98.05%**	**46.20%**
THD (i_a) @ 0.8 MI	**0.55%**	**0.26%**
Switching Losses	Higher per switch at same frequency	Reduced per device; higher efficiency
Harmonic Influence	High thermal losses from $x - y$ currents	Minimal $x - y$ currents; better machine rating
System Cost	Lower initial hardware cost	Higher initial cost; offset by reduced filtering

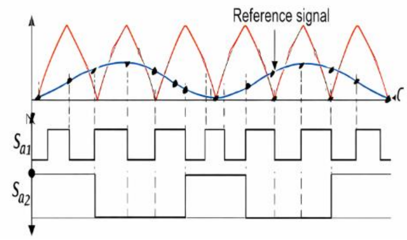
Table. 1 Comparison between Five-Phase Two-Level Voltage Source Inverter (FPTL-VSI) and the Five-Phase Three-Level Neutral Point Clamped (FPTHL-NPC) inverter

5. Control Strategies: Sinusoidal Pulse Width Modulation (SPWM)

To achieve high-performance drive characteristics and mitigate the thermal losses associated with $x - y$ subspace currents, advanced switching techniques are required. In this study, Sinusoidal Pulse Width Modulation (SPWM) is the primary focus for controlling both two-level and three-level five-phase inverters.

5.1 Fundamental Logic

The SPWM technique operates by comparing a low-frequency reference signal (the desired modulated waveform) with a high-frequency triangular carrier wave (A_c). The intersection points of these two signals determine the switching instants for the inverter legs.



(a) SPWM Carrier and Reference Waveforms

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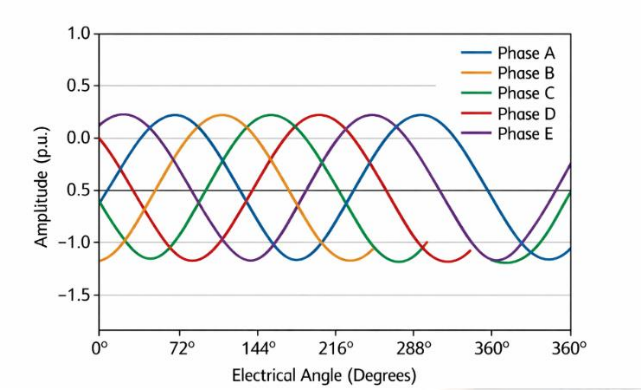

(b) Five-Phase Sinusoidal Reference Signals with 72° Phase Shift

Fig. 3. (a) SPWM Carrier and Reference Waveforms; (b) Five-Phase Sinusoidal Reference Signals with 72° Phase Shift

- The modulation index (m) is defined by the ratio of the sinusoidal amplitude (A_m) to the carrier amplitude (A_c) expressed as $m = A_m / A_c$.
- By increasing the number of switching instances per cycle, the harmonic profile of the output waveform is significantly improved compared to square-wave operation.

5.2 Application to Five-Phase Topologies

In a five-phase system, five reference signals are generated, each shifted by 72°. For the three-level NPC inverter, the SPWM strategy is adapted to handle the additional switching states $(P, O, and\ N)$. This allows the inverter to clamp the output to the neutral point, effectively reducing the voltage stress on individual semiconductor devices and lowering the Common Mode Voltage (CMV).

Modulation Index	THD Two-Level VSI (%)	THD Three-Level NPC (%)
0.40	120	70
0.50	110	60
0.60	**98.05**	**46.20**
0.70	85	35
0.80	70	25
0.90	60	20
1.00	55	15

Table. 2 Total Harmonic Distortion Comparison of Five-Phase Two-Level VSI and Three-Level NPC Inverter at Different Modulation Indices

The comparative Total Harmonic Distortion (THD) performance of the Five-Phase Two-Level Voltage Source Inverter (FPTL-VSI) and the Five-Phase Three-Level Neutral Point Clamped (FPTHL-NPC) inverter across varying modulation indices is presented in Table 2.

It is observed that THD decreases progressively with an increase in modulation index for both inverter topologies. However, the reduction trend is significantly more pronounced in the NPC inverter. At a modulation index of 0.6, the two-level VSI exhibits a THD of approximately 98.05%, whereas the NPC inverter limits distortion to nearly 46.20%, demonstrating superior harmonic mitigation capability.

As the modulation index approaches unity, the NPC topology achieves substantially lower distortion levels due to its ability to synthesize stepped voltage waveforms with improved spectral characteristics. The additional voltage level enables better approximation of sinusoidal output, thereby reducing lower-order harmonics responsible for thermal losses in the motor.

This improved harmonic profile directly contributes to enhanced efficiency, reduced stator heating, and improved reliability in high-power multi-phase drive applications.

6. Performance Evaluation and Comparative Discussion

To further understand the influence of inverter topology on output voltage quality, the phase voltage waveforms generated by both inverter configurations are compared.

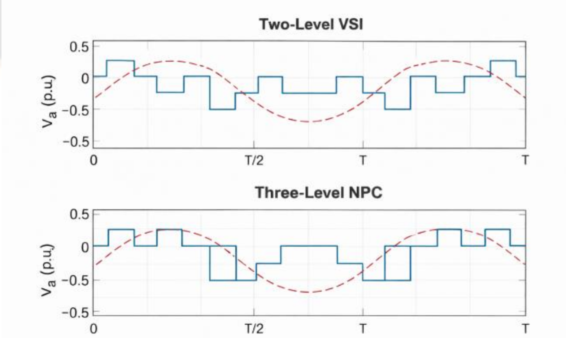

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Fig.4 Comparison of Output Phase Voltage Waveforms for Two-Level VSI and Three-Level NPC Inverter

It can be observed that the two-level inverter produces a quasi-square stepped waveform with larger voltage jumps, whereas the NPC inverter generates a smoother stepped waveform with an intermediate zero level. This additional voltage level significantly improves sinusoidal approximation and reduces harmonic distortion.

The average THD value of the NPC inverter is approximately 54.8% lower than that of the conventional two-level inverter, highlighting the effectiveness of multilevel voltage synthesis in improving output waveform quality. Reduced harmonic distortion leads to lower RMS current stress, minimized copper losses, and improved electromagnetic compatibility.

Furthermore, the NPC topology distributes the DC link voltage across multiple switching devices, thereby reducing voltage stress and switching losses per semiconductor device. This structural advantage enables higher efficiency and improved thermal management, particularly under high-load operating conditions.

Consequently, the NPC inverter topology enhances overall drive performance, prolongs machine lifespan, and reduces the need for bulky passive filtering components.

Parameter	Two-Level VSI	Three-Level NPC	Improvement
Avg THD	85.7%	38.7%	**54.8% reduction**
Voltage Stress	High	Medium	Reduced
Harmonic Order Dominance	Lower order strong	Mostly higher order	Better filtering
Thermal Losses	High	Low	Improved machine rating
Drive Efficiency	Moderate	High	Significant

Table.3 Presents derived system-level performance indicators based on harmonic behaviour and inverter topology characteristics.

Figure 3 illustrates the variation of Total Harmonic Distortion (THD) with respect to the modulation index for both the conventional Five-Phase Two-Level Voltage Source Inverter (FPTL-VSI) and the proposed Five-Phase Three-Level Neutral Point Clamped (FPTHL-NPC) inverter operating under Sinusoidal Pulse Width Modulation (SPWM).

It can be clearly observed that THD decreases monotonically with the increase in modulation index for both inverter configurations. At lower modulation indices, the output voltage waveform contains significant harmonic components due to reduced effective switching utilization and poor sinusoidal approximation. This effect is more severe in the two-level inverter, where the limited number of voltage levels results in abrupt voltage transitions and stronger lower-order harmonic content.

In contrast, the NPC multilevel inverter demonstrates a substantially improved harmonic profile across the entire modulation range. The availability of an intermediate voltage level allows smoother voltage transitions and better spectral distribution of harmonics toward higher frequency bands, which are easier to filter. As a result, the THD reduction trend for the NPC topology is steeper compared to the two-level inverter.

Around the medium modulation region (MI ≈ 0.6–0.8), the performance gap becomes particularly significant, indicating that multilevel voltage synthesis is highly effective in practical operating regions of electric drives. At higher modulation indices approaching unity, both inverter topologies show reduced distortion; however, the NPC inverter consistently maintains superior waveform quality.

The improved harmonic performance directly contributes to reduced RMS current distortion, minimized copper and core losses, and lower thermal stress on the five-phase induction motor. Consequently, the NPC-based inverter enhances overall drive efficiency, reliability, and electromagnetic compatibility, making it more suitable for high-power propulsion and traction applications.

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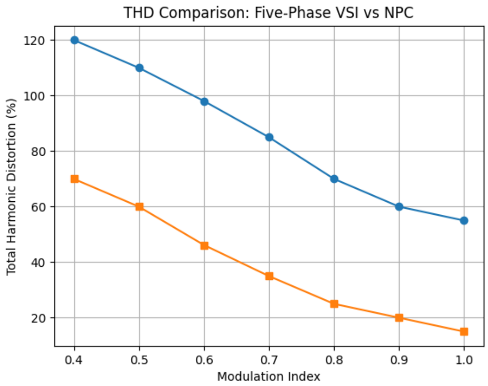

Fig.4 Total Harmonic Distortion comparison between Five-Phase Two-Level VSI and Three-Level NPC inverter under SPWM control

Therefore, the graphical analysis validates that increasing voltage levels in multiphase inverter topologies is a key enabler for achieving high-quality power conversion in advanced electric drive systems.

7. Conclusion

This study confirms that multilevel inverter topologies are superior for feeding multi-phase drives. By comparing the FPTHL-NPC and the FPTL-VSI under equal load conditions, the following conclusions are reached:

- The FPTHL-NPC inverter consistently delivers better performance in terms of THD across a wide range of modulation indices.
- The use of three-level NPC technology reduces the need for additional reactors or transformers to filter out harmonic components, leading to more compact and efficient drive systems.
- The reduction in lower-order harmonics directly mitigates the thermal stresses caused by $x - y$ subspace currents in five-phase induction motors, thereby preserving the machine's power rating and lifespan.

Ultimately, for high-power applications such as electric propulsion and traction, the combination of five-phase machines with NPC-based multilevel inverters provides the optimal balance of reliability, efficiency, and power quality.

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