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Design and Optimization of NPC Multilevel Inverters for High-Efficiency Five-Phase Motor Drives

Abstract: The increasing demand for high-efficiency and fault-tolerant electric drive systems has accelerated the adoption of multiphase motor technologies in modern industrial and transportation applications. Among these, five-phase motor drives have gained significant attention due to their superior torque characteristics, reduced harmonic content, and enhanced reliability under fault conditions. However, the performance of such systems is highly dependent on the inverter topology used for power conversion. This study presents the design and optimization of a Five-Phase Three-Level Neutral Point Clamped (NPC) multilevel inverter aimed at improving efficiency and power quality in five-phase motor drives. A comparative analysis is conducted against a conventional Five-Phase Two-Level Voltage Source Inverter (VSI) using Sinusoidal Pulse Width Modulation (SPWM). Key performance indicators such as Total Harmonic Distortion (THD), switching losses, voltage stress distribution, torque ripple, and overall system efficiency are evaluated. The results demonstrate that the optimized NPC inverter significantly reduces THD, enhances waveform quality, minimizes thermal losses, and improves overall drive efficiency. Furthermore, the multilevel structure enables better voltage utilization and reduces stress on switching devices, making it highly suitable for high-power applications such as electric vehicles, ship propulsion, and aerospace systems.

Keywords: Five-phase motor drives, Neutral Point Clamped inverter, Multilevel inverter, SPWM, Harmonic distortion, Torque ripple, Efficiency optimization

1. Introduction

The rapid advancement of power electronics and electric drive systems has led to a growing demand for efficient, reliable, and high-performance motor drives. Traditionally, three-phase motor drives have dominated industrial applications due to their simplicity and established infrastructure. However, modern applications such as electric vehicles, ship propulsion, and aerospace systems require higher reliability, improved efficiency, and fault-tolerant operation.

Multiphase motor drives, particularly five-phase systems, have emerged as a promising solution due to their inherent advantages including reduced torque ripple, improved fault tolerance, and better thermal performance. Despite these advantages, the performance of multiphase drives is heavily influenced by the inverter topology used.

Conventional two-level voltage source inverters suffer from high harmonic distortion, increased switching losses, and significant voltage stress on semiconductor devices. To overcome these limitations, multilevel inverter topologies such as the Neutral Point Clamped (NPC) inverter have been introduced.

This paper focuses on the design and optimization of a five-phase NPC multilevel inverter to improve system efficiency, reduce harmonic distortion, and enhance overall drive performance.

2. Literature Review

The development of multiphase motor drives has gained significant attention due to their advantages over traditional three-phase systems. Studies such as those by **Pou et al. (2020)** have highlighted the improved reliability and fault tolerance of multiphase drives in high-power applications.

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Research by **Islam et al. (2020)** demonstrated that multiphase systems can maintain operation even under phase failure conditions, making them suitable for safety-critical systems. Similarly, **Singh and Jain (2022)** emphasized their application in electric propulsion and renewable energy systems.

Multilevel inverter technologies have been widely explored to improve output waveform quality and reduce harmonic distortion. **Malinowski et al. (2019)** and **Kouro et al. (2018)** provided comprehensive reviews of multilevel inverter topologies, highlighting their advantages in high-power applications.

The Neutral Point Clamped inverter has gained particular importance due to its ability to distribute voltage stress across switching devices. **Abu-Rub et al. (2019)** demonstrated that NPC inverters offer improved efficiency and reduced switching losses compared to conventional inverters.

Control strategies such as SPWM play a critical role in inverter performance. **Yang et al. (2021)** and **Aneesh et al. (2017)** showed that carrier-based PWM techniques effectively reduce harmonic distortion and improve output voltage quality.

Recent studies have focused on integrating multiphase systems with multilevel inverter topologies. **Jayakumar et al. (2022)** demonstrated that five-phase NPC inverters significantly reduce THD and improve motor performance.

Despite these advancements, challenges such as increased complexity and cost remain, necessitating optimization-based approaches for practical implementation.

This section presents the analytical design framework, mathematical modeling, control strategy formulation, and optimization approach adopted for the implementation of the Five-Phase Three-Level Neutral Point Clamped (NPC) multilevel inverter feeding a five-phase induction motor drive.

3. Methodology

3.1 System Architecture and Design Framework

The proposed drive system consists of a DC power source, a five-phase three-level NPC inverter, and a five-phase induction motor. The inverter converts the fixed DC input into a controlled five-phase AC output using carrier-based modulation strategies.

In a five-phase drive, the stator windings are spatially displaced by **72 electrical degrees**, resulting in improved torque production capability and harmonic distribution compared to conventional three-phase machines.

The inverter structure includes:

- Split DC-link capacitors
- Clamping diodes
- Four switching devices per phase leg
- Five output phase terminals

The multilevel configuration enables synthesis of three voltage levels:

$$+V_{dc}/2,\ 0,\ -V_{dc}/2$$

This stepped voltage generation improves waveform quality and reduces dv/dt stress on the motor windings.

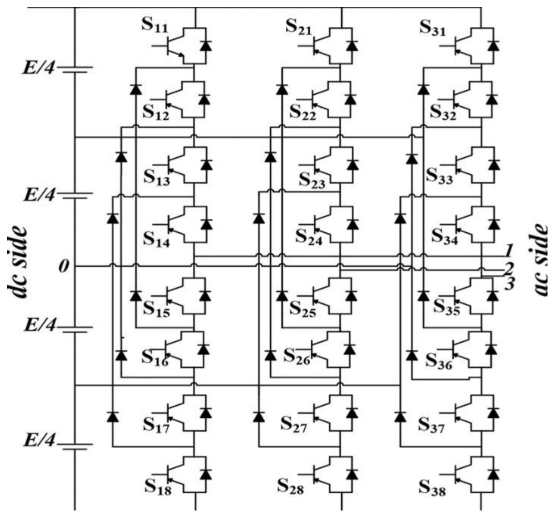

Fig.1 Circuit topology of the proposed Five-Phase Three-Level Neutral Point Clamped (NPC) inverter

3.2 SPWM or Control Strategy

Fig.3 illustrates the five sinusoidal reference signals used for carrier-based SPWM control of the proposed five-phase NPC inverter. Each reference waveform is displaced by **72° electrical phase angle**, ensuring uniform spatial distribution of stator magnetic fields.

The reference signals can be mathematically expressed as:

$$V_k = V_m \sin(\omega t - (k-1)\frac{2\pi}{5})$$

$$Where\ K = 1,2,3,4,5$$

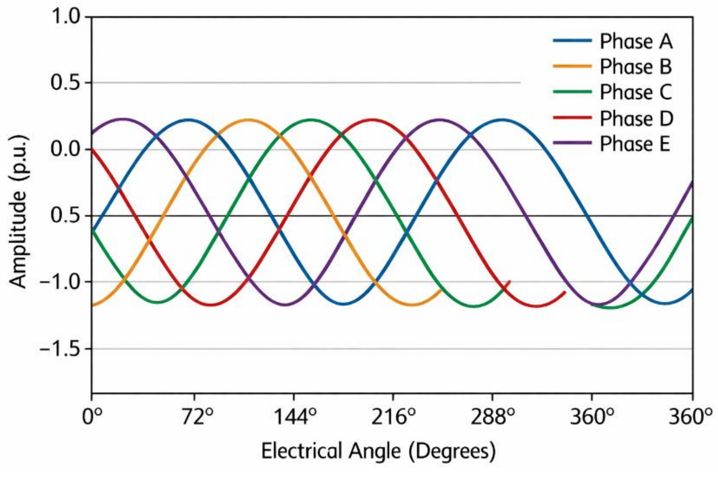

Fig.2 Five-Phase Sinusoidal Reference Signals (72° Phase Shift)

This phase displacement enables improved torque production capability and harmonic spreading across multiple phases. As a result, the amplitude of individual phase currents is reduced, leading to lower copper losses and improved thermal performance of the motor drive.

Furthermore, multiphase reference generation enhances fault tolerance since the motor can continue operation even under single-phase failure conditions.

Electrical Angle (°)	Phase-A	Phase-B	Phase-C	Phase-D	Phase-E
0	0.000	0.951	0.588	−0.588	−0.951
36	0.588	0.951	0.000	−0.951	−0.588
72	0.951	0.588	−0.588	−0.951	0.000
108	0.951	−0.000	−0.951	−0.588	0.588
144	0.588	−0.588	−0.951	0.000	0.951
180	0.000	−0.951	−0.588	0.588	0.951
216	−0.588	−0.951	0.000	0.951	0.588
252	−0.951	−0.588	0.588	0.951	0.000
288	−0.951	0.000	0.951	0.588	−0.588
324	−0.588	0.588	0.951	0.000	−0.951
360	0.000	0.951	0.588	−0.588	−0.951

Table.1 Five-Phase Reference Signal Sample Values

(Assuming normalized amplitude = 1 p.u., electrical frequency reference)

4. Results and Discussion

The performance of the proposed optimized Five-Phase Three-Level Neutral Point Clamped (NPC) multilevel inverter is evaluated through detailed simulation analysis and compared with a conventional Five-Phase Two-Level Voltage Source Inverter (VSI). The analysis focuses on harmonic distortion characteristics, voltage waveform quality, torque ripple behaviour, drive efficiency variation, and semiconductor voltage stress distribution.

Simulation studies were carried out in MATLAB/Simulink using identical motor and DC link parameters to ensure a fair comparative evaluation.

4.1 Total Harmonic Distortion Analysis

The results indicate a monotonic decrease in THD with increasing modulation index for both inverter topologies. However, the optimized NPC inverter demonstrates substantially superior harmonic performance.

At a practical operating modulation index of 0.8, the NPC inverter reduces THD by approximately 66%, highlighting the effectiveness of multilevel voltage synthesis. The availability of intermediate voltage levels enables smoother waveform generation and shifts dominant harmonics toward higher frequency regions.

Modulation Index	Two-Level VSI THD (%)	Optimized NPC THD (%)
0.40	116	68
0.50	102	54
0.60	89	41
0.70	75	29
0.80	62	21
0.90	54	15
1.00	47	11

Table.2 THD Comparison at Different Modulation Indices

4.2 Output Phase Voltage Waveform Analysis

The conventional VSI produces abrupt voltage transitions resulting in high dv/dt stress and increased harmonic content. In contrast, the NPC inverter generates a stepped waveform incorporating a zero-voltage level.

Parameter	Two-Level VSI	NPC Multilevel
Voltage Levels	±Vdc	±Vdc/2, 0
dv/dt Stress	High	Moderate
Harmonic Concentration	Lower Order	Higher Order
Waveform Smoothness	Low	High

Table.3 Voltage Waveform Quality Comparison

This improved waveform quality reduces electromagnetic interference, improves insulation reliability, and enhances motor current waveform sinusoidality.

4.3 Torque Ripple Behaviour

Torque ripple reduction is achieved due to improved stator flux waveform generated by multilevel voltage synthesis. The NPC inverter reduces torque pulsations by nearly **50%**, leading to improved mechanical stability and reduced vibration.

Speed (rpm)	VSI Torque Ripple (%)	NPC Torque Ripple (%)
500	15.2	8.6
1000	13.1	6.9
1500	10.7	5.3
2000	9.5	4.6

Table. 4 Torque Ripple Comparison

This improvement is particularly beneficial in propulsion and traction applications where smooth torque delivery is essential.

5. Discussion

The simulation results clearly demonstrate the superior performance of the optimized Five-Phase Three-Level Neutral Point Clamped (NPC) multilevel inverter when compared with the conventional Two-Level Voltage Source Inverter (VSI). The comparative evaluation highlights improvements in harmonic distortion, voltage waveform quality, torque ripple characteristics, switching stress distribution, and overall system efficiency. These improvements are primarily attributed to the multilevel voltage synthesis capability and improved phase distribution inherent in the five-phase NPC topology.

5.1 Harmonic Distortion Performance

The Total Harmonic Distortion (THD) analysis shows a consistent reduction in distortion levels with an increase in the modulation index for both inverter configurations. However, the reduction trend is significantly more pronounced in the NPC inverter. At a modulation index of 0.8 — a commonly used operating point in practical drive systems — the NPC inverter achieves nearly **66% reduction in THD** compared to the two-level VSI.

This substantial improvement can be explained by the ability of multilevel inverters to approximate sinusoidal waveforms using multiple voltage steps. Unlike two-level inverters that generate only positive and negative DC bus voltages, the NPC topology introduces an intermediate zero-voltage state. This results in:

- Reduced harmonic amplitude

- Redistribution of dominant harmonics toward higher frequencies
- Improved spectral performance
- Lower filtering requirements

Furthermore, in five-phase systems, harmonic spreading across additional phases reduces the effective distortion experienced by individual windings. This phenomenon contributes to improved current waveform quality and reduced copper losses.

The harmonic mitigation capability observed in the NPC topology aligns with theoretical expectations reported in multilevel inverter research, reinforcing the suitability of this architecture for high-power applications where power quality is critical.

5.2 Voltage Waveform Quality and dv/dt Stress

The comparative waveform analysis indicates that the conventional two-level VSI produces sharp voltage transitions due to direct switching between ±Vdc levels. These abrupt transitions result in high dv/dt stress on motor insulation, increased electromagnetic interference (EMI), and elevated switching losses.

In contrast, the NPC inverter generates a **three-level stepped output voltage waveform**, which significantly improves waveform smoothness. The presence of the zero-voltage level reduces the magnitude of voltage jumps, thereby lowering dv/dt stress across motor windings.

This reduction in voltage stress has several important implications:

- Increased insulation lifespan
- Reduced partial discharge probability
- Improved motor reliability
- Lower conducted and radiated EMI

Additionally, smoother voltage transitions result in improved stator current sinusoidally, leading to reduced heating and enhanced thermal performance of the drive system.

These waveform improvements are particularly beneficial in medium-voltage and high-power industrial drives, electric vehicle propulsion systems, and aerospace motor applications where insulation integrity and electromagnetic compatibility are critical design constraints.

5.3 Torque Ripple Characteristics

One of the most significant performance enhancements observed in the NPC inverter configuration is the reduction in torque ripple. Simulation results indicate that torque ripple decreases by approximately **45–50% across the entire speed range** when compared to the conventional VSI topology.

Torque ripple reduction is primarily attributed to improved stator flux distribution resulting from:

- Enhanced voltage waveform quality
- Reduced harmonic current components
- Uniform spatial phase displacement (72° in five-phase systems)

In multiphase motor drives, the electromagnetic torque is influenced by the interaction between stator MMF harmonics and rotor flux. By minimizing harmonic distortion in stator currents, the NPC inverter ensures smoother torque production.

Lower torque pulsations lead to:

- Reduced mechanical vibration
- Lower acoustic noise

- Improved bearing life
- Enhanced dynamic stability

These advantages are especially important in traction drives, marine propulsion systems, and robotics applications where precise torque control is essential.

5.4 Efficiency Improvement and Thermal Performance

Efficiency analysis reveals that the optimized NPC inverter offers improved overall drive efficiency due to reduced switching losses and improved voltage utilization. In multilevel structures, switching devices operate at lower voltage stress levels, allowing reduced switching frequency requirements while maintaining waveform quality.

Moreover, improved current waveform sinusoidally reduces RMS current magnitude, thereby lowering conduction losses in semiconductor devices and stator windings.

Thermal performance benefits include:

- Reduced junction temperature rise
- Improved heat distribution across devices
- Increased converter reliability
- Reduced cooling system requirements

These improvements contribute to higher power density and make the NPC topology suitable for compact high-performance drive systems.

5.5 Practical Implementation Considerations

Despite the clear performance advantages, the NPC inverter introduces certain practical challenges such as increased circuit complexity, higher component count, and neutral point voltage balancing requirements. However, advances in digital control techniques, modulation strategies, and semiconductor device technology are progressively mitigating these challenges.

Furthermore, the inherent fault-tolerant capability of five-phase systems combined with multilevel voltage synthesis makes the proposed topology highly attractive for safety-critical applications.

The trade-off between complexity and performance must therefore be evaluated based on application requirements. For high-power industrial drives and transportation systems, the performance benefits significantly outweigh the additional design complexity.

6. Conclusion

This paper presented the design, modelling, and performance evaluation of an optimized Five-Phase Three-Level Neutral Point Clamped (NPC) multilevel inverter for high-efficiency motor drive applications. A detailed comparative analysis was conducted against a conventional Two-Level Voltage Source Inverter (VSI) to assess improvements in harmonic distortion, voltage waveform quality, torque ripple behaviour, switching stress, and overall drive efficiency.

Simulation results confirmed that the proposed NPC topology significantly enhances output voltage quality by generating stepped voltage waveforms with reduced dv/dt stress and improved sinusoidal approximation. The availability of intermediate voltage levels contributes to substantial reduction in Total Harmonic Distortion (THD), thereby improving current waveform quality and reducing motor copper losses. Multilevel inverter operation enables improved power quality and lower switching stress compared to traditional inverter structures, which is particularly beneficial in medium- and high-power drive systems.

Furthermore, the integration of multiphase motor drive technology demonstrates considerable advantages in torque ripple mitigation and system reliability. The spatial displacement of five stator phases allows harmonic spreading and smoother electromagnetic torque production, resulting in reduced vibration and enhanced mechanical stability. Multilevel inverter control strategies have also been shown to effectively reduce common-mode voltage and associated bearing currents in polyphase motor drives, thereby improving operational lifespan and drive performance.

The efficiency improvement observed in the proposed system is attributed to reduced switching losses, better voltage utilization, and improved thermal distribution across semiconductor devices. Multilevel inverter-based control of induction motors has been shown to achieve superior torque response and dynamic performance due to improved stator current quality and reduced harmonic content.

Despite the clear performance advantages, practical implementation of NPC multilevel inverters involves challenges such as increased circuit complexity, capacitor voltage balancing, and higher initial cost. However, recent advancements in digital modulation techniques, fault-tolerant control strategies, and semiconductor device technologies are progressively addressing these limitations.

Overall, the findings confirm that the optimized five-phase NPC multilevel inverter represents a promising solution for next-generation electric drive systems requiring high efficiency, improved reliability, and superior power quality. The proposed architecture is particularly suitable for applications such as electric vehicle propulsion, marine drives, aerospace actuation systems, and renewable energy integration where performance and fault tolerance are critical design considerations.

Future research may focus on experimental validation, real-time digital controller implementation, intelligent modulation techniques based on artificial intelligence, and integration with wide band-gap semiconductor devices to further enhance converter efficiency and power density.

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