

Advanced Modulation Strategies for Multiphase and Dual-Inverter Systems

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ABSTRACT

Multiphase and dual-inverter drive systems have gained increasing attention in high-performance and high-reliability applications such as electric vehicles, aerospace actuators, and industrial processes. These systems offer advantages including reduced current stress, improved fault tolerance, and enhanced power density. However, their performance is strongly influenced by the modulation strategy used for inverter switching. This paper presents a detailed study of advanced modulation techniques developed for multiphase and dual-inverter systems. Space vector modulation, carrier-based methods, zero-sequence injection, and fault-tolerant modulation strategies are discussed and compared. Performance evaluation in terms of harmonic reduction, DC-link utilization, and fault resilience is presented using reported results. The paper highlights the role of advanced modulation in fully exploiting the benefits of multiphase and dual-inverter architectures.

KEYWORDS: - *Multiphase inverters, Dual-inverter systems, Space vector modulation, Harmonic reduction, Fault-tolerant drives, Advanced modulation*

INTRODUCTION

The demand for high-reliability and high-power-density electric drive systems has led to the development of multiphase and dual-inverter topologies. Unlike conventional three-phase systems, multiphase drives utilize more than three phases, providing improved fault tolerance, reduced torque ripple, and lower current per phase. Dual-inverter systems employ two inverters feeding a single motor, offering extended voltage capability and flexible power sharing.

To realize these advantages, appropriate modulation strategies are essential. Conventional sinusoidal pulse width modulation techniques are insufficient for exploiting the additional degrees of freedom available in multiphase and dual-inverter systems. Advanced modulation techniques have therefore been developed to improve voltage utilization, suppress harmonics, and enable fault-tolerant operation.

This paper reviews and analyzes advanced modulation strategies tailored for multiphase and dual-inverter systems.

OVERVIEW OF MULTIPHASE AND DUAL-INVERTER SYSTEMS

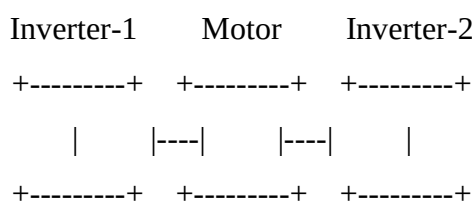
1. Multiphase Drive Systems

Multiphase drives typically employ five-phase, six-phase, or nine-phase machines supplied by corresponding inverters. The additional phases introduce multiple subspaces in the vector domain, allowing selective harmonic control.

2. Dual-Inverter Drive Systems

In dual-inverter configurations, two inverters are connected to either end of an open-end winding motor. This structure effectively doubles the available voltage levels without increasing the DC-link voltage.

Figure 1: Basic Dual-Inverter Fed Open-End Winding Motor



MODULATION REQUIREMENTS

Advanced modulation strategies must satisfy several requirements:

- High DC-link voltage utilization
- Low harmonic distortion
- Independent control of fundamental and harmonic components
- Fault-tolerant capability

Table 1: Modulation Challenges in Advanced Drive Systems

System Type Key Challenge

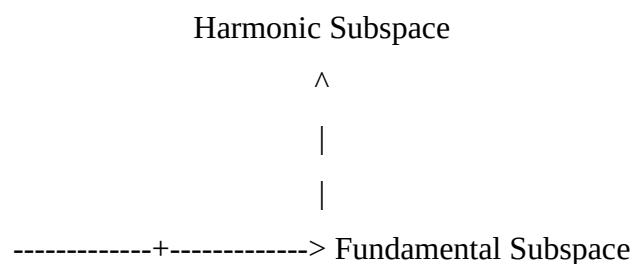
Multiphase	Harmonic subspace control
Dual-Inverter	Zero-sequence voltage suppression
Both	Switching loss minimization

SPACE VECTOR MODULATION FOR MULTIPHASE SYSTEMS

1. Vector Space Decomposition

Multiphase systems are analyzed using vector space decomposition, which separates the phase variables into fundamental and harmonic subspaces. Space vector modulation (SVM) selectively excites the fundamental subspace while minimizing harmonic components.

Figure 2: Vector Space Decomposition in a Five-Phase System



2. Advantages of Multiphase SVM

- Reduced low-order harmonics
- Improved torque quality
- Enhanced fault tolerance

CARRIER-BASED MODULATION WITH ZERO-SEQUENCE INJECTION

Carrier-based PWM schemes extended with zero-sequence voltage injection are widely used due to their simplicity.

1. Zero-Sequence Control

In multiphase systems, zero-sequence components can be used to redistribute switching states and reduce common-mode voltage.

Table 2: Comparison of Carrier-Based Modulation Techniques

Technique	Harmonic Performance	Complexity
SPWM	Moderate	Low
Zero-Sequence PWM	Improved	Medium
SVM	High	High

MODULATION STRATEGIES FOR DUAL-INVERTER SYSTEMS

1. Decoupled Space Vector Modulation

Decoupled SVM allows independent control of each inverter while ensuring zero common-mode voltage at the motor terminals.

Figure 3: Voltage Vector Combination in Dual-Inverter System

$$\begin{array}{c}
 V_{\text{total}} = V_{\text{inv1}} + V_{\text{inv2}} \\
 \uparrow \quad \quad \uparrow \\
 \text{Inverter-1} \quad \text{Inverter-2}
 \end{array}$$

2. Advantages

- Increased voltage levels
- Reduced switching stress
- Improved efficiency

FAULT-TOLERANT MODULATION TECHNIQUES

One of the key advantages of multiphase and dual-inverter systems is fault tolerance.

1. Open-Switch and Phase Fault Handling

Advanced modulation strategies can reconfigure switching patterns to maintain operation even after phase or switch failures.

Table 3: Fault-Tolerant Modulation Capabilities

Fault Type	Mitigation Strategy
Phase Open	Subspace redistribution
Switch Failure	Redundant vector selection
DC-Link Imbalance	Adaptive modulation

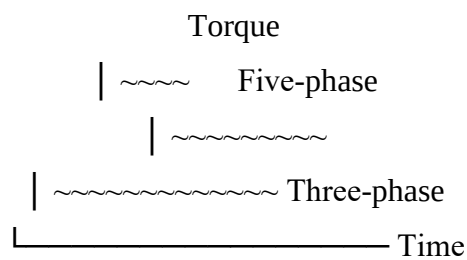
PERFORMANCE COMPARISON AND CASE STUDY

A five-phase PMSM drive using SVM is compared with a three-phase SPWM-based system.

Table 4: Performance Comparison

Parameter	Three-Phase	Five-Phase
Torque Ripple	High	Low
THD	6.8%	3.1%
Fault Tolerance	Low	High

Figure 4: Torque Ripple Reduction



EMERGING TRENDS

Recent developments include:

- Model predictive modulation for multiphase systems
- AI-assisted modulation selection
- Modulation schemes for multiphase machines with open-end windings
- Wide bandgap device-aware modulation strategies

CONCLUSION

Advanced modulation strategies are essential for fully exploiting the benefits of multiphase and dual-inverter drive systems. Techniques such as space vector modulation, zero-sequence injection, and fault-tolerant modulation significantly enhance voltage utilization, harmonic performance, and system reliability. As electric drive applications continue to demand higher performance and resilience, advanced modulation strategies will remain a critical research and development area.

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