

# Multilevel Converter-Based Power Conditioning for Motor Drives

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## Abstract

Motor drive systems used in industrial automation, electric transportation, process plants, and renewable-energy-integrated applications require high power quality, low harmonic distortion, smooth torque response, and reliable operation over a wide speed range. Conventional two-level converters, though widely used, often suffer from high switching stress, elevated total harmonic distortion (THD), significant common-mode voltage, and poor waveform quality in medium- and high-power applications. Multilevel converters have emerged as an effective solution to these limitations by synthesizing staircase voltage waveforms from multiple dc voltage levels, thereby improving output quality and reducing device stress. This paper presents an IEEE-style review and proposed framework for **multilevel converter-based power conditioning in motor drives**. It examines the role of multilevel topologies—specifically **Neutral Point Clamped (NPC)**, **Flying Capacitor (FC)**, **Cascaded H-Bridge (CHB)**, and **Modular Multilevel Converter (MMC)**—in harmonic mitigation, dc-link voltage regulation, reactive power support, current conditioning, and torque ripple reduction. A comparative analysis of modulation and control methods, including sinusoidal PWM, space vector PWM, selective harmonic elimination, and model predictive control, is also provided. A generalized multilevel power-conditioning architecture for motor drives is proposed, and its expected performance is discussed in terms of harmonic suppression, reduced switching losses, improved efficiency, and better dynamic response. The paper concludes that multilevel converter-based power conditioning offers a robust and scalable pathway for high-performance motor drives, particularly in medium-voltage industrial systems, electric vehicles, and smart manufacturing environments. Claims in this paper are aligned with recent reviews showing that multilevel converters outperform conventional two-level converters in harmonic quality, efficiency, and device voltage stress while introducing new challenges in capacitor balancing and control complexity.

**Keywords**— Multilevel converter, motor drives, power conditioning, total harmonic distortion, PWM, model predictive control, NPC inverter, cascaded H-bridge, modular multilevel converter.

## I. Introduction

Motor drives are a core component of modern electromechanical energy-conversion systems and are extensively used in conveyors, pumps, compressors, electric vehicles, robotic manipulators, and traction systems. The rapid increase in demand for **energy-efficient, high-power-density, low-harmonic, and highly controllable motor drives** has intensified research into advanced power electronic converter topologies. Traditional two-level voltage source inverters remain widely deployed because of their simple control and mature implementation. However, in medium- and high-power motor drive applications, these converters face critical limitations such as high dv/dt stress, increased switching losses, significant harmonic distortion, large common-mode voltage, and the need for bulky passive filters. These issues degrade motor insulation life, increase bearing current risk, and reduce the overall efficiency and power quality of the drive system. Recent review papers consistently position multilevel converters as a preferred alternative for medium-voltage and high-power drive systems because they can synthesize output voltages with lower harmonic distortion and lower device voltage stress than conventional two-level converters.

Multilevel converters (MLCs) overcome these limitations by dividing the dc-link voltage into several smaller voltage levels and generating a staircase approximation of the desired AC waveform. By increasing the number of levels, the output waveform becomes closer to sinusoidal, resulting in lower total harmonic distortion (THD), lower electromagnetic interference (EMI), and reduced filter requirements. In motor drive applications, these features translate into **smoother torque, lower current ripple, reduced motor heating, and better dynamic performance**. Beyond simple inversion, multilevel converters perform an essential **power-conditioning** role: they regulate voltage quality, suppress harmonics, stabilize dc-link voltages, reduce common-mode voltage, and support reactive power management. Reviews focused on multilevel inverter applications and topology evolution emphasize that these converters are especially attractive in medium-voltage industrial drives, traction systems, renewable-energy interfaces, and other high-power applications where power quality and scalability are decisive.

This paper presents an IEEE-style research review and conceptual framework for **multilevel converter-based power conditioning for motor drives**. The work aims to bridge the gap between multilevel converter topology research and practical drive-system power-conditioning requirements. The paper first reviews major multilevel topologies and their power-conditioning characteristics, then examines modulation and control methods, and finally proposes a generalized multilevel converter-based drive architecture. The paper also discusses performance expectations, practical challenges, and future directions, including capacitor voltage balancing and predictive control strategies, both of which are identified as major research themes in the recent literature.

## A. Motivation

The motivation for this work arises from the increasing use of medium-voltage and high-efficiency motor drives in industrial and transportation sectors. As these drives operate under stricter energy-efficiency and power-quality standards, the converter stage must do more than supply variable-frequency power; it must actively condition the electrical power delivered to the motor.

## B. Objectives

The main objectives of this paper are:

1. To review the role of multilevel converters in power conditioning for motor drives.
2. To compare major multilevel converter topologies with respect to drive performance and power-quality improvement.
3. To examine modulation and control strategies that enhance multilevel converter operation in motor drives.
4. To propose a generalized multilevel converter-based power-conditioning framework for industrial motor drives.
5. To identify challenges and future research directions for practical deployment.

## C. Organization of the Paper

The remainder of the paper is organized as follows. Section II reviews relevant literature on multilevel converters and motor drive conditioning. Section III presents the proposed methodology and generalized system model. Section IV discusses expected results and performance outcomes. Section V concludes the paper.

## II. Literature Review

Multilevel converter technology has evolved significantly over the past three decades and is now regarded as one of the most important developments in medium- and high-power power electronics. A broad review by Sunddhararaj *et al.* surveys multilevel inverter topologies, switching strategies, and applications, and shows that multilevel inverters offer lower THD, reduced filter size, lower switching losses, and better output waveform quality than conventional two-

level converters. The review also highlights their relevance in industrial motor drives, renewable-energy conversion, and FACTS applications.

Recent work by Benevieri *et al.* provides a comprehensive review of advances in multilevel converters and confirms that multilevel topologies remain central to high-power and high-voltage applications because they improve voltage quality, reduce harmonic content, and distribute semiconductor stress across multiple devices. The same review also points out that future progress is strongly tied to improved modulation, capacitor balancing, and advanced control schemes, especially in systems with dynamic load variations such as motor drives.

Among the available multilevel topologies, the **neutral-point-clamped (NPC)** converter is one of the most established for medium-voltage drives. A dedicated survey on capacitor voltage control in NPC converters by Alepuz *et al.* emphasizes that NPC converters are attractive for industrial applications because of their mature structure and efficiency, but neutral-point voltage balancing remains a central challenge, particularly under overmodulation, low-frequency operation, and varying load conditions. This balancing issue directly affects motor-drive power conditioning because dc-link imbalance distorts the output voltage and can increase torque ripple and current distortion.

For **flying-capacitor (FC)** converters, Stala reviews natural capacitor-voltage balancing and notes that one of the main attractions of FC topologies is the potential for inherent voltage balancing under suitable switching conditions. However, the topology also introduces a large capacitor count and associated control complexity. In the context of motor drives, FC converters can improve waveform quality and provide redundant switching states, which can be exploited for power conditioning and fault tolerance, but practical deployment depends heavily on balancing and modulation strategy.

A major practical issue across many multilevel converter families is **capacitor voltage balancing**. Wu *et al.* review balancing strategies under selective harmonic elimination PWM and show that balancing becomes especially challenging at low switching frequency and in high-power systems. Their work underscores that the power-conditioning quality of multilevel converters is inseparable from capacitor-voltage management because imbalance can compromise harmonic performance and voltage symmetry.

Control strategy is another critical research direction. Harbi *et al.* review **model predictive control (MPC)** for multilevel inverters and show that MPC is particularly attractive for multilevel applications because it can handle multiple objectives simultaneously, including current tracking, capacitor balancing, common-mode voltage reduction, and switching-frequency minimization. For motor drives, this is highly relevant because the converter must often satisfy torque, current, and dc-link constraints simultaneously. The same review also identifies computational burden and cost-function design as key implementation challenges.

Similarly, Yaramasu *et al.* discuss predictive control of multilevel diode-clamped converters and highlight the suitability of multilevel converters for high-power industrial applications such as motor drives, traction, and regenerative systems. Their work shows that predictive control can be formulated to jointly manage current regulation, dc-capacitor balancing, switching reduction, and common-mode voltage mitigation—precisely the set of tasks expected from a power-conditioning stage in modern motor drives.

A review of single-DC-source multilevel inverters by Trabelsi *et al.* also emphasizes the centrality of balancing and control techniques, especially when the converter is expected to operate in dynamic environments such as transport electrification or distributed energy systems. The literature therefore converges on a common conclusion: **multilevel converters improve power quality and efficiency in motor drives, but their practical success depends on effective balancing, modulation, and control integration.**

## Literature Gap

Despite the extensive literature on multilevel converter topologies, many studies focus on either topology comparison or isolated control strategies rather than on the **combined role of multilevel converters as power-conditioning**

**interfaces for motor drives.** A unified motor-drive-oriented framework that explicitly links topology choice, harmonic mitigation, dc-link stabilization, current conditioning, and control strategy is still useful for academic and applied research. This paper addresses that need by presenting a consolidated power-conditioning perspective.

### III. Methodology and Proposed Multilevel Converter-Based Power Conditioning Model

#### A. System Overview

The proposed motor-drive power-conditioning architecture consists of the following major subsystems:

1. **Input power stage:** AC grid supply or dc source (battery/renewable/rectified front end).
2. **Front-end rectifier or active power-conditioning stage** (optional depending on application).
3. **DC-link energy buffer** with capacitors and voltage-sensing circuitry.
4. **Multilevel inverter stage** based on NPC, FC, CHB, or MMC topology.
5. **Motor drive unit**, such as an induction motor (IM), permanent magnet synchronous motor (PMSM), or synchronous reluctance motor.
6. **Control layer** implementing PWM/MPC/FOC/DTC logic and capacitor-voltage balancing.
7. **Feedback system** measuring motor currents, speed, dc-link voltages, and converter states.

The role of the multilevel converter in this architecture is not limited to voltage-frequency conversion. Instead, it acts as a **power-conditioning core** that shapes the voltage and current waveforms delivered to the motor, maintains capacitor or neutral-point voltage balance, and minimizes disturbances that would otherwise degrade drive performance.

#### B. Power-Conditioning Functions of the Proposed Model

The proposed multilevel converter-based power-conditioning model is designed to perform the following functions:

##### 1) Harmonic Mitigation

By generating a stepped output voltage waveform with multiple levels, the converter reduces low-order harmonic content in the motor phase voltage and current. This directly improves stator current quality and reduces motor losses.

##### 2) DC-Link Voltage Regulation

In multilevel topologies, maintaining balanced dc-link or submodule capacitor voltages is essential for stable operation. The control strategy must continuously monitor and regulate capacitor voltages to preserve waveform symmetry and avoid over-stressing semiconductor devices.

##### 3) Current Conditioning

The converter is controlled to ensure sinusoidal motor currents with minimal ripple, which helps reduce copper losses, torque pulsations, and thermal stress.

##### 4) Common-Mode Voltage Suppression

Multilevel switching states can be selected to reduce common-mode voltage and associated bearing current problems in motor drives.

## 5) Torque Ripple Minimization

Cleaner current waveforms and accurate vector control improve electromagnetic torque smoothness, which is especially important in precision drives and traction applications.

## 6) Reactive Power and Dynamic Support

In grid-connected or active-front-end drive systems, the converter can be controlled to regulate reactive power and support improved grid-side power factor.

## C. Candidate Multilevel Topologies for the Proposed System

The proposed framework can be realized using several multilevel topologies depending on the voltage level, isolation availability, cost constraints, and modularity needs.

### 1) Neutral-Point-Clamped (NPC) Converter

NPC converters are attractive for medium-voltage industrial drives because they offer lower device voltage stress and good waveform quality. However, neutral-point balancing must be carefully managed, especially under variable-speed motor operation.

### 2) Flying-Capacitor (FC) Converter

FC converters offer redundant switching states that can be exploited for balancing and harmonic control. They can be suitable where flexibility and fault tolerance are priorities, although the capacitor count can be high.

### 3) Cascaded H-Bridge (CHB) Converter

CHB converters are highly modular and can achieve excellent waveform quality with low THD. They are especially attractive when isolated dc sources are available or can be derived from modular front ends.

### 4) Modular Multilevel Converter (MMC)

MMC is one of the most scalable and waveform-friendly multilevel topologies. It is highly promising for medium-voltage and high-power drives, though it introduces a high sensor count and significant control complexity.

## D. Control and Modulation Strategy

The proposed methodology combines a **multilevel inverter topology** with a **multi-objective control framework**. The control layer has two broad tasks:

1. **motor-drive control**, and
2. **power-conditioning control**.

### 1) Motor-Drive Control Layer

This layer may use **field-oriented control (FOC)** or **direct torque control (DTC)** to generate torque and flux references based on speed commands.

## 2) Power-Conditioning Control Layer

This layer is responsible for:

- capacitor or neutral-point voltage balancing,
- switching state selection,
- harmonic minimization,
- current tracking, and
- common-mode voltage control.

## 3) PWM / Modulation Options

The following modulation methods are considered suitable:

- **Sinusoidal PWM (SPWM):** simple and widely used.
- **Space Vector PWM (SVPWM):** better dc-bus utilization and lower THD.
- **Selective Harmonic Elimination (SHE):** useful in high-power applications with low switching frequency.
- **Model Predictive Control (MPC):** highly suitable when multiple objectives must be handled simultaneously, such as current tracking, voltage balancing, and switching minimization. Recent reviews highlight MPC as a particularly promising technique for multilevel converters because of its multi-objective capability, though computational burden remains a concern.

## E. Mathematical Formulation

For an mmm-level inverter, the phase voltage is synthesized from multiple discrete voltage levels to approximate a sinusoidal reference. The output quality improves as mmm increases. The voltage THD can be expressed as:

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots + V_n^2}}{V_1}$$

where  $V_1$  is the RMS value of the fundamental component and  $V_2 \dots V_n$  are harmonic RMS components.

For a motor drive, the electromagnetic torque quality depends strongly on the quality of the stator current. In a field-oriented representation, the torque of an AC motor can be related to flux and current components; hence reduced current ripple improves torque smoothness. The multilevel converter therefore indirectly improves mechanical performance by improving the electrical waveform supplied to the machine.

## F. Proposed Algorithmic Flow

The proposed control sequence is as follows:

1. Measure motor speed, stator currents, dc-link capacitor voltages, and phase voltages.
2. Compute speed and torque references using the outer-loop controller.
3. Generate current or voltage references using FOC or DTC.
4. Evaluate candidate switching states of the multilevel converter.
5. Apply a modulation or predictive control strategy to select the switching state that minimizes a cost function based on:
  - current tracking error,
  - capacitor voltage imbalance,
  - common-mode voltage,

- switching transitions, and
  - harmonic distortion.
6. Generate gate pulses for the multilevel converter.
  7. Repeat in real time at each sampling interval.

## IV. Results and Discussion

### A. Expected Performance Improvements

Based on the reviewed literature and the proposed framework, the following improvements are expected when multilevel converters are used for motor-drive power conditioning:

#### 1) Reduction in Total Harmonic Distortion

The primary benefit of increasing the number of output voltage levels is a reduction in voltage and current THD. Reviews of multilevel inverter applications consistently report superior waveform quality compared with two-level converters, especially in medium-voltage drive scenarios.

#### 2) Reduced Motor Heating and Insulation Stress

Lower harmonic content reduces copper and stray losses in the motor. In addition, the stepped waveform lowers  $dv/dt$  stress compared with a conventional two-level inverter, which helps preserve motor insulation and reduces the likelihood of bearing-current problems.

#### 3) Lower Switching Stress and Better Efficiency

In multilevel converters, each switch blocks only a portion of the total dc-link voltage, which lowers device stress and allows the use of lower-rated semiconductors in higher-voltage applications. Reduced switching stress and improved waveform quality contribute to better overall converter efficiency.

#### 4) Improved Torque Smoothness

Cleaner phase currents reduce torque ripple. This is especially valuable in traction drives, robotic systems, elevators, and precision industrial drives where torque pulsation can degrade performance or create acoustic noise.

#### 5) Better Dynamic Control with MPC

When model predictive control is used, the converter can simultaneously regulate current, balance capacitor voltages, reduce switching frequency, and suppress common-mode voltage. This makes MPC especially suitable for multilevel motor drives that must satisfy multiple power-conditioning objectives in real time.

### B. Comparative Discussion of Topologies

The practical suitability of each topology for motor-drive power conditioning can be summarized qualitatively as follows:

| Topology | Power Quality | Balancing Complexity | Scalability | Suitability for Motor Drives                            |
|----------|---------------|----------------------|-------------|---------------------------------------------------------|
| NPC      | High          | Moderate to High     | Moderate    | Excellent for medium-voltage industrial drives          |
| FC       | High          | High                 | Moderate    | Good where redundancy and flexibility are needed        |
| CHB      | Very High     | Moderate             | High        | Excellent for modular medium-/high-voltage drives       |
| MMC      | Excellent     | High                 | Very High   | Excellent for high-power and future smart-drive systems |

NPC converters are attractive because of their industrial maturity, but they require careful neutral-point balancing. FC converters offer balancing flexibility through redundant states but require many capacitors. CHB converters are modular and provide excellent waveform quality, whereas MMC offers perhaps the best scalability and output quality at the cost of significant control complexity.

### C. Challenges

Despite their advantages, multilevel converters also introduce practical challenges:

#### 1) Capacitor Voltage Balancing

Voltage balancing remains one of the most critical challenges in NPC, FC, CHB, and MMC systems. Multiple review papers identify balancing as a key issue affecting waveform quality and system reliability.

#### 2) Higher Component Count

As the number of levels increases, the number of switches, diodes, capacitors, drivers, and sensors also rises. This increases cost, layout complexity, and maintenance requirements.

#### 3) Complex Control

Advanced balancing and predictive-control algorithms can impose heavy computational requirements, especially in MMC and high-level CHB systems. Harbi *et al.* explicitly identify computational burden and cost-function design as active research issues for MPC-based multilevel control.

#### 4) Fault Diagnosis and Reliability

With more devices and sensors, the probability of component-level faults increases. Robust fault diagnosis and fault-tolerant control therefore become important in safety-critical drive systems.

### D. Practical Interpretation for Motor Drive Design

From a motor-drive engineering perspective, the main takeaway is that **multilevel converters should be viewed as integrated power-conditioning platforms rather than merely inverter topologies**. Their real value lies in the simultaneous improvement of:

- harmonic performance,
- current quality,
- torque smoothness,

- dc-link stability, and
- semiconductor stress management.

For low-power applications, the additional complexity may not always be justified. However, for medium-voltage industrial drives, traction systems, and high-efficiency process applications, the performance gains can outweigh the complexity, especially when supported by modern digital controllers and advanced balancing strategies.

## V. Conclusion

The study showed that multilevel converters—particularly NPC, FC, CHB, and MMC topologies—provide a highly effective solution to the limitations of conventional two-level inverters in medium- and high-power drive systems. By synthesizing stepped output waveforms, these converters significantly improve voltage and current quality, reduce THD, lower  $dv/dt$  stress, and minimize common-mode voltage. These improvements directly enhance motor-drive performance through reduced torque ripple, lower thermal stress, better efficiency, and improved dynamic response. The reviewed literature consistently supports the role of multilevel converters in high-power drive applications and also identifies capacitor balancing, control complexity, and computational burden as the most important design challenges.

A generalized multilevel converter-based power-conditioning model was proposed in which the converter performs not only power conversion but also harmonic suppression, dc-link stabilization, current conditioning, and common-mode voltage mitigation. The integration of advanced control techniques—particularly model predictive control—with classical drive-control methods such as field-oriented control offers a promising route to realizing these functions in a coordinated manner. Future research should focus on low-complexity balancing strategies, fault-tolerant multilevel drive architectures, AI-assisted control, and wide-bandgap semiconductor integration to further improve efficiency and reliability. Overall, multilevel converter-based power conditioning represents a scalable and future-ready architecture for next-generation motor drives in industrial automation, transportation, and smart energy systems.

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