The American Journal of Engineering and Technology
ISSN 2689-0984 Volume 08 - 2026

Converter Employing Nearest Level Modulation Without Capacitor Voltage Sensing

Dr. Reza Karimi
Department of Electrical Engineering
Institute of Advanced Engineering Technologies
Tehran, Iran

Dr. Nima Farhadi
Department of Mechanical and Industrial Engineering
Center for Engineering Innovation and Technology Research
Isfahan, Iran

Received: 24 Mar 2026 | Received Revised Version: 29 Apr 2026 | Accepted: 24 May 2026 | Published: 01 June 2026

Volume 08 Issue 06 2026 |

Abstract

Modular Multilevel Converters (MMCs) have emerged as one of the most significant power electronic converter topologies for medium- and high-voltage applications due to their scalability, modularity, superior output waveform quality, and reduced harmonic distortion. Despite their advantages, conventional MMC control strategies typically depend on continuous capacitor voltage measurement for balancing energy among submodules. Such requirements increase system complexity, sensing costs, communication burden, and susceptibility to measurement inaccuracies. This study presents a comprehensive review and conceptual research framework for an advanced control strategy applied to a 21-level MMC employing Nearest Level Modulation (NLM) without direct capacitor voltage sensing. The proposed framework integrates modulation optimization, circulating current suppression, sensorless balancing mechanisms, and adaptive control principles to achieve stable converter operation while reducing hardware requirements. A detailed synthesis of existing MMC control approaches is conducted, emphasizing modulation methods, predictive control techniques, voltage balancing mechanisms, and renewable-energy-oriented MMC applications. Based on identified research gaps, a sensorless NLM-based control architecture is formulated and analyzed. The framework demonstrates how switching state selection, energy distribution estimation, and current-based balancing algorithms can maintain capacitor voltage equilibrium without dedicated voltage sensors. The study further discusses expected performance improvements in switching losses, harmonic quality, computational efficiency, reliability, and scalability. Findings indicate that sensorless NLM control can provide a practical and economically viable alternative for next-generation MMC systems deployed in smart grids, HVDC transmission, renewable energy integration, and industrial drive applications. The research contributes a structured theoretical foundation for future implementation and validation of advanced MMC control systems.

Keywords: Modular Multilevel Converter, Nearest Level Modulation, Sensorless Control, Capacitor Voltage Balancing, Multilevel Power Converter, HVDC Systems, Circulating Current Suppression, Advanced Power Electronics, Renewable Energy Integration, MMC Control Framewor

Cite This Article: Karimi, D. R., & Farhadi , D. N. (2026). Converter Employing Nearest Level Modulation Without Capacitor Voltage Sensing. The American Journal of Engineering and Technology, 8(06), 1–12. Retrieved from https://www.theamericanjournals.com/index.php/tajet/article/view/8023

1. Introduction

Background

The rapid growth of renewable energy systems, smart grid infrastructures, medium-voltage industrial drives, and high-voltage direct current (HVDC) transmission networks has intensified the demand for advanced power conversion technologies capable of delivering superior efficiency, scalability, and power quality. Among the numerous multilevel converter topologies developed over the past two decades, the Modular Multilevel Converter (MMC) has established itself as one of the most effective solutions for high-power applications due to its modular architecture and excellent harmonic performance (Lesnicar and Marquardt, 2003).

The introduction of MMC technology represented a significant advancement in multilevel power conversion because it enabled the generation of high-quality voltage waveforms through cascaded submodule structures while maintaining flexibility and scalability. Unlike conventional two-level and three-level converters, MMCs distribute voltage stress across multiple submodules, thereby improving efficiency and reducing switching losses (Rodriguez et al., 2007).

The increasing adoption of MMC systems in HVDC transmission networks, renewable energy integration platforms, and industrial applications has stimulated extensive research on converter control strategies. Effective control is essential because MMC performance depends heavily on maintaining balanced capacitor voltages, suppressing circulating currents, minimizing harmonic distortion, and ensuring stable power transfer (Hagiwara and Akagi, 2009).

Traditionally, capacitor voltage balancing has relied on direct measurement of individual submodule capacitor voltages. Although effective, this approach introduces substantial sensing requirements, increased hardware complexity, communication overhead, and maintenance costs. As converter levels increase, the number of sensors grows proportionally, creating significant implementation challenges in practical systems (Barnklau et al., 2013).

For a 21-level MMC configuration, numerous submodule capacitors must be monitored simultaneously. Such monitoring not only increases system cost but also affects reliability because sensor failures can compromise converter operation. Consequently, there is growing interest in developing sensorless control approaches capable of maintaining voltage balance without direct capacitor voltage measurements.

Nearest Level Modulation (NLM) has emerged as an attractive modulation technique for MMC applications due to its low switching frequency characteristics and ability to generate high-quality output waveforms. Compared with conventional PWM techniques, NLM significantly reduces switching losses while preserving waveform quality (Tu et al., 2011). However, integrating NLM with sensorless capacitor balancing remains a challenging research problem requiring sophisticated control architectures.

Recent advances in renewable-energy-integrated MMC systems further highlight the importance of robust control methodologies. Chao et al. (2023) demonstrated that advanced disturbance rejection and oscillation suppression strategies significantly improve system stability in MMC-HVDC applications, emphasizing the need for intelligent control mechanisms capable of operating under dynamic grid conditions. Similar observations indicate that future MMC controllers must combine efficiency, robustness, and reduced hardware dependence.

1.2 Problem Statement

Although existing MMC control systems achieve satisfactory performance, most rely heavily on capacitor voltage sensors for balancing operations. This dependence creates several limitations:

First, the number of required sensors increases significantly with converter levels. A 21-level MMC contains numerous capacitive submodules requiring continuous monitoring.

Second, sensor installation and maintenance contribute substantially to overall system cost.

Third, measurement delays and sensor inaccuracies can degrade control performance.

Fourth, communication bandwidth requirements increase as additional sensor data must be transmitted and processed in real time.

These challenges motivate the development of advanced sensorless control frameworks capable of maintaining voltage balance while eliminating direct capacitor voltage measurements.

1.3 Research Objectives

The primary objectives of this study are:

1. To analyze existing MMC control strategies and modulation techniques.

2. To evaluate the role of Nearest Level Modulation in high-level MMC systems.

3. To identify limitations associated with capacitor voltage sensing approaches.

4. To develop a conceptual framework for sensorless capacitor balancing in a 21-level MMC.

5. To assess the expected operational benefits of the proposed control architecture.

1.4 Scope and Significance

This research focuses on the theoretical development and analytical evaluation of an advanced control framework for a 21-level MMC employing NLM without capacitor voltage sensing. The study synthesizes existing literature and proposes a structured control architecture applicable to HVDC systems, renewable energy integration platforms, and industrial power conversion systems.

The significance of this work lies in its potential to reduce converter complexity while maintaining operational reliability. Such developments can support broader adoption of MMC technology in cost-sensitive and large-scale energy infrastructures.

2. Literature Review

2.1 Evolution of Modular Multilevel Converter Technology

The foundation of MMC technology was established by Lesnicar and Marquardt (2003), who introduced a modular converter topology capable of operating across a wide power range. Their pioneering work demonstrated the feasibility of constructing large-scale power converters using cascaded submodules, providing the basis for modern MMC systems.

The modular structure offered several advantages, including improved scalability, reduced switching losses, enhanced fault tolerance, and superior harmonic performance. These characteristics quickly attracted attention from researchers and industry practitioners seeking alternatives to conventional converter architectures.

Subsequently, Hiller et al. (2009) proposed highly modular medium-voltage converter structures tailored for industrial drive applications. Their work demonstrated the adaptability of MMC concepts to industrial environments requiring high reliability and operational flexibility.

Rodriguez et al. (2007) further expanded understanding of multilevel converter technologies by evaluating various voltage-source converter topologies for medium-voltage applications. Their comparative analysis highlighted the advantages of modular structures in achieving high-quality voltage generation while reducing harmonic distortion.

Collectively, these studies established MMCs as a leading solution for medium- and high-voltage power conversion.

2.2 Control Strategies for MMC Systems

Control methodologies represent one of the most extensively investigated aspects of MMC technology. Effective control systems must simultaneously regulate output voltage, maintain capacitor voltage balance, suppress circulating currents, and ensure stable power transfer.

Hagiwara and Akagi (2009) conducted one of the earliest comprehensive investigations into pulse-width-modulated MMC operation. Their experimental results confirmed that appropriate control algorithms could achieve stable capacitor voltage balancing and high-quality output waveforms.

Barnklau et al. (2013) later introduced a model-based control scheme for MMC systems. Their approach utilized mathematical models to predict converter behavior and improve dynamic performance. Model-based control demonstrated significant potential for enhancing stability and reducing transient disturbances.

The transition toward predictive control methodologies represented another major development. Qin and Saeedifard (2012) proposed predictive control techniques for MMC-based HVDC systems, demonstrating improved response speed and enhanced control accuracy. Predictive approaches enable controllers to anticipate future converter states and optimize switching decisions accordingly.

Similarly, Aguilera et al. (2015) applied predictive control principles to cascaded H-bridge converters, showing how power balancing objectives could be achieved through optimized switching state selection. Although focused on a different converter topology, their findings offer valuable insights applicable to MMC balancing mechanisms.

These studies collectively reveal a progression from conventional feedback control toward intelligent predictive frameworks capable of improving dynamic performance.

2.3 Modulation Techniques in MMC Applications

Modulation strategies directly influence converter efficiency, switching losses, harmonic distortion, and capacitor voltage balancing.

Pulse Width Modulation (PWM) has traditionally served as the dominant modulation approach in power electronic converters. Li et al. (2012) developed an improved PWM method for modular multilevel converters, demonstrating enhanced switching performance and waveform quality.

Mei et al. (2014) proposed a selective loop bias mapping phase disposition PWM technique capable of maintaining dynamic voltage balance. Their work highlighted the importance of modulation design in achieving stable converter operation.

Despite the effectiveness of PWM-based methods, high switching frequencies contribute to increased losses, particularly in large-scale MMC systems. To address this issue, Tu et al. (2011) introduced reduced switching-frequency modulation techniques combined with circulating current suppression strategies.

Nearest Level Modulation emerged as a highly attractive alternative because it significantly reduces switching frequency while maintaining excellent harmonic performance. Instead of generating continuous PWM pulses, NLM selects voltage levels nearest to the reference signal, reducing switching events and associated losses.

The growing popularity of NLM reflects industry demand for energy-efficient converter operation, particularly in HVDC and renewable energy applications.

2.4 Capacitor Voltage Balancing Challenges

One of the defining characteristics of MMC operation is the requirement to maintain balanced capacitor voltages across all submodules.

Voltage imbalance can produce unequal power distribution, increased harmonic distortion, excessive device stress, and potential system instability. Consequently, most existing control systems employ direct voltage measurement to monitor capacitor states.

However, direct sensing introduces practical challenges. Large-scale MMC systems may contain dozens or hundreds of capacitors requiring continuous monitoring. The resulting sensor networks increase installation costs, communication complexity, and maintenance requirements.

Existing balancing techniques typically utilize sorting algorithms that rank capacitor voltages and determine insertion priorities. While effective, these methods depend fundamentally on accurate voltage measurements.

The literature reveals a significant gap regarding sensorless balancing strategies capable of maintaining voltage equilibrium without direct capacitor measurements. This gap is particularly evident in high-level MMC configurations employing NLM techniques.

2.5 MMC Applications in Renewable Energy and HVDC Systems

MMC technology plays a central role in renewable energy integration and HVDC transmission infrastructure.

Qin and Saeedifard (2012) demonstrated the suitability of MMCs for back-to-back HVDC systems, highlighting their capability to support large-scale power transfer with high efficiency.

Recent developments by Chao et al. (2023) further emphasized the importance of advanced control strategies in renewable-energy-integrated MMC-HVDC systems. Their active disturbance rejection control methodology successfully suppressed sub-synchronous oscillations arising from renewable energy interactions. The study illustrates how robust control architectures contribute to system stability under fluctuating operating conditions (Chao et al., 2023).

Furthermore, the increasing penetration of renewable energy sources introduces additional control challenges associated with intermittency and grid disturbances. Chao et al. (2023) demonstrated that advanced control frameworks can mitigate these effects while maintaining stable power exchange. Their findings provide important theoretical support for sensorless MMC control approaches capable of adapting to dynamic operating environments.

2.6 Research Gap Identification

The literature review reveals several important research gaps:

First, most capacitor balancing strategies rely heavily on direct voltage measurements.

Second, existing sensorless approaches remain limited and insufficiently developed for high-level MMC configurations.

Third, integration of Nearest Level Modulation with sensorless balancing mechanisms has received relatively little attention.

Fourth, existing studies primarily focus on balancing accuracy rather than reducing hardware complexity.

Fifth, advanced disturbance-rejection capabilities identified by Chao et al. (2023) have not been fully integrated into sensorless NLM-based MMC frameworks.

Therefore, a comprehensive control architecture combining NLM, sensorless balancing, adaptive current regulation, and disturbance rejection mechanisms represents a valuable research direction capable of advancing next-generation MMC technology.

3. Methodology

3.1 Research Design and Methodological Framework

This study adopts a research-and-review methodology combined with a conceptual engineering framework to develop an advanced control strategy for a 21-level Modular Multilevel Converter (MMC) employing Nearest Level Modulation (NLM) without capacitor voltage sensing. Rather than relying on direct hardware experimentation, the methodology synthesizes established MMC theories, modulation techniques, balancing principles, predictive control approaches, and disturbance rejection mechanisms reported in the selected literature.

The methodological objective is to establish a control architecture capable of achieving three simultaneous goals:

1. High-quality multilevel voltage generation.
2. Stable capacitor energy balancing without direct voltage measurements.
3. Reduced switching losses and improved converter efficiency.

The framework integrates theoretical concepts from modular converter topology design (Lesnicar and Marquardt, 2003), model-based control (Barnklau et al., 2013), predictive balancing approaches (Qin and Saeedifard, 2012; Aguilera et al., 2015), modulation optimization (Tu et al., 2011), and advanced disturbance rejection methodologies (Chao et al., 2023).

The proposed methodology consists of five interconnected layers:

- Converter topology layer
- Nearest level modulation layer
- Sensorless balancing layer
- Circulating current suppression layer
- Adaptive control and disturbance rejection layer

Together, these layers form a comprehensive control framework capable of supporting high-performance operation in a 21-level MMC system.

3.2 Architecture of the 21-Level MMC

The proposed converter consists of upper-arm and lower-arm submodule branches arranged in a conventional MMC structure. Each arm contains multiple half-bridge submodules connected in series along with arm inductors.

The output voltage is synthesized through selective insertion and bypassing of submodules. By controlling the number of active submodules, the converter generates 21 distinct voltage levels, thereby approximating a sinusoidal waveform.

Compared with lower-level converters, the 21-level structure provides:

- Lower total harmonic distortion (THD)
- Reduced filter requirements
- Improved voltage quality
- Lower electromagnetic interference
- Enhanced scalability

The modular architecture permits independent submodule operation while maintaining coordinated arm-level control.

The converter state vector can be represented by the relationship between inserted submodules and generated output voltage. The control system continuously determines the optimal number of inserted submodules required to track the reference waveform while simultaneously maintaining energy equilibrium.

A key challenge emerges because capacitor voltage information is not directly available. Therefore, the proposed framework replaces conventional voltage sensing with indirect energy estimation and current-based balancing mechanisms.

3.3 Operational Principle of Nearest Level Modulation

Nearest Level Modulation serves as the primary switching strategy within the proposed architecture.

Unlike pulse width modulation approaches that generate switching actions at high carrier frequencies, NLM directly selects the voltage level closest to the reference waveform.

For each sampling instant:

- The reference voltage is generated.
- The required insertion level is calculated.
- The nearest available voltage state is selected.
- Corresponding submodules are inserted.

The process minimizes switching transitions and significantly reduces switching losses.

The output voltage approximation follows a staircase waveform that closely resembles a sinusoidal signal due to the large number of available levels.

Several advantages justify the selection of NLM:

Reduced Switching Frequency

Each semiconductor device experiences fewer switching events than PWM-based systems. This directly reduces:

- Switching losses
- Thermal stress
- Cooling requirements

Improved Converter Efficiency

Lower switching activity improves overall system efficiency, making NLM particularly suitable for high-power applications.

Simplified Implementation

NLM eliminates carrier generation and comparison processes required in PWM systems.

Scalability

Performance improves naturally as converter levels increase, making NLM highly compatible with 21-level MMC architectures.

The modulation framework therefore serves as the foundation upon which sensorless balancing mechanisms are developed.

3.4 Sensorless Capacitor Energy Estimation Framework

The most innovative component of the proposed methodology is the elimination of direct capacitor voltage measurements.

Traditional MMC controllers continuously measure individual capacitor voltages and use sorting algorithms to determine insertion priorities.

The proposed framework replaces direct measurement with energy estimation.

Fundamental Assumption

The capacitor energy variation depends on:

- Arm current
- Submodule insertion status
- Operating duration

Since arm currents remain measurable, capacitor energy behavior can be estimated mathematically.

The energy stored in a capacitor is proportional to its voltage magnitude.

Rather than measuring voltage directly, the controller estimates capacitor energy changes using current flow information and switching states.

For each submodule:

Energy Estimate = Previous Energy + Current Contribution − Discharge Contribution

The estimator continuously updates the energy state of every submodule.

This approach significantly reduces sensor dependency while maintaining awareness of capacitor charging and discharging trends.

Estimation Process

The process follows four stages:

Stage 1: Current Acquisition

Arm current sensors collect real-time current measurements.

Stage 2: Switching State Monitoring

The controller records submodule insertion and bypass status.

Stage 3: Energy Calculation

Charging and discharging intervals are estimated.

Stage 4: State Update

Submodule energy values are updated dynamically.

The resulting energy profile replaces direct voltage measurements in balancing decisions.

3.5 Sensorless Balancing Algorithm

Capacitor balancing represents the primary operational challenge in sensorless MMC control.

To address this challenge, a dynamic balancing algorithm is introduced.

The balancing strategy ranks submodules according to estimated energy states rather than measured voltages.

Charging Mode

When arm current charges capacitors:

- Submodules with lower estimated energy are prioritized.
- Additional charging opportunities are allocated to weak-energy cells.

Discharging Mode

When arm current discharges capacitors:

- Submodules with higher estimated energy are selected.
- Excess energy is redistributed naturally.

This process gradually equalizes stored energy across all submodules.

The balancing mechanism operates continuously and does not require explicit capacitor voltage feedback.

Over extended operating intervals, the energy distribution converges toward equilibrium.

Compared with conventional sorting algorithms, the proposed method reduces:

- Sensor count
- Communication complexity
- Data processing requirements

while preserving balancing performance.

3.6 Circulating Current Suppression Strategy

Circulating currents are internal currents flowing between converter arms without contributing to load power transfer.

These currents produce:

- Additional losses
- Thermal stress
- Capacitor ripple
- Reduced efficiency

Tu et al. (2011) demonstrated the importance of suppressing circulating currents in MMC operation.

The proposed methodology incorporates a circulating current controller operating independently from the voltage generation process.

The suppression mechanism includes:

Current Detection

Arm currents are continuously monitored.

Harmonic Extraction

Internal circulating current components are identified.

Compensation Signal Generation

A compensating voltage signal is produced.

Corrective Injection

The compensation signal is incorporated into the modulation reference.

The result is substantial reduction of internal current oscillations.

This contributes to:

- Improved efficiency
- Reduced capacitor stress
- Enhanced balancing performance

3.7 Model-Based Predictive Control Integration

The proposed framework incorporates predictive control concepts inspired by Barnklau et al. (2013), Qin and Saeedifard (2012), and Aguilera et al. (2015).

Predictive control enables the controller to evaluate future converter behavior before selecting switching states.

The methodology employs three prediction stages:

System State Prediction

Future arm current behavior is estimated.

Energy Evolution Prediction

Future submodule energy distribution is forecasted.

Switching Evaluation

Alternative switching combinations are assessed.

The controller selects the switching configuration that minimizes a cost function consisting of:

- Tracking error
- Energy imbalance
- Circulating current magnitude
- Switching transitions

The predictive mechanism enhances dynamic performance and improves balancing accuracy under rapidly changing operating conditions.

3.8 Adaptive Disturbance Rejection Mechanism

Modern MMC systems increasingly operate in renewable energy environments characterized by:

- Wind fluctuations
- Solar intermittency
- Grid disturbances
- Load variations

Chao et al. (2023) demonstrated that active disturbance rejection strategies effectively improve MMC-HVDC stability under dynamic conditions.

Building on these findings, the proposed framework incorporates an adaptive disturbance rejection layer.

The disturbance observer estimates:

- External disturbances
- Parameter variations
- Unmodeled dynamics

The controller then compensates for these effects before they influence converter performance.

Key objectives include:

- Improved robustness
- Enhanced transient response
- Reduced oscillatory behavior
- Stable renewable energy integration

The incorporation of disturbance rejection concepts strengthens the sensorless framework by improving reliability during uncertain operating conditions (Chao et al., 2023).

3.9 Control Coordination Strategy

The proposed framework employs hierarchical control.

Primary Layer

Responsible for:

- Output voltage regulation
- Power tracking

Secondary Layer

Responsible for:

- Sensorless balancing
- Energy equalization

Tertiary Layer

Responsible for:

- Disturbance rejection
- Adaptive optimization

Information exchange occurs continuously among layers.

This hierarchical structure prevents conflicts between balancing objectives and voltage regulation objectives.

Consequently, converter stability is maintained even during transient events.

3.10 Expected Performance Metrics

To evaluate the effectiveness of the proposed framework, the following performance indicators are defined:

Voltage Quality

Measured through:

- Total Harmonic Distortion
- Voltage tracking accuracy

Balancing Effectiveness

Measured through:

- Energy distribution uniformity
- Capacitor balancing convergence

Efficiency

Measured through:

- Switching losses
- Converter power losses

Dynamic Performance

Measured through:

- Settling time
- Overshoot
- Disturbance recovery

Reliability

Measured through:

- Sensor reduction
- Fault tolerance
- Operational stability

These metrics provide a comprehensive basis for evaluating future implementation studies.

4. Results

The proposed advanced control framework was analytically evaluated based on its expected operational behavior, theoretical consistency with existing MMC control principles, and alignment with established modulation and balancing methodologies reported in the literature. The findings indicate that the integration of Nearest Level Modulation (NLM), sensorless capacitor energy estimation, predictive balancing, circulating current suppression, and adaptive disturbance rejection creates a cohesive control architecture capable of addressing several limitations associated with conventional MMC systems.

The first major finding concerns voltage waveform quality. The 21-level converter structure inherently produces a staircase waveform that closely approximates a sinusoidal output. Combined with NLM, the converter can achieve low harmonic distortion while operating at significantly lower switching frequencies than conventional PWM-based approaches. This observation is consistent with previous findings regarding reduced switching-frequency operation in MMC systems (Tu et al., 2011). The high number of voltage levels contributes to smoother voltage transitions and reduced filtering requirements.

A second finding relates to capacitor balancing performance. The proposed sensorless framework demonstrates that capacitor voltage balancing can theoretically be achieved through energy estimation and current-based balancing mechanisms without requiring direct capacitor voltage measurements. By continuously estimating energy variations using arm current information and submodule switching states, the controller maintains an updated representation of submodule energy distribution. This estimated energy information enables balancing decisions comparable to those achieved through traditional voltage-sorting techniques.

The third finding concerns system efficiency. Because NLM minimizes switching transitions, semiconductor switching losses are expected to decrease substantially. Reduced switching activity also lowers thermal stress on power devices, potentially extending converter lifespan and improving overall system reliability. These advantages become increasingly significant as converter ratings and voltage levels increase.

Another important finding involves circulating current management. The integration of circulating current suppression mechanisms reduces internal converter losses and limits unwanted capacitor ripple effects. As a result, balancing performance improves while converter efficiency increases. The suppression strategy further contributes to stable operation during load variations and transient conditions.

The adaptive disturbance rejection layer represents an additional contribution of the proposed framework. Building upon concepts demonstrated in MMC-HVDC renewable energy systems (Chao et al., 2023), the controller exhibits enhanced robustness against grid disturbances, renewable energy fluctuations, and parameter uncertainties. This capability is particularly important in modern power systems characterized by increasing renewable energy penetration and variable operating conditions.

Finally, the overall framework demonstrates strong scalability. Since the balancing strategy depends primarily on current measurements and switching state information rather than large sensor networks, the architecture remains practical for higher-level MMC configurations. Consequently, the proposed framework offers a promising pathway toward cost-effective and reliable implementation of future high-power MMC systems.

5. Discussion

The findings suggest that the proposed sensorless control framework addresses one of the most persistent challenges in MMC technology: the dependence on extensive capacitor voltage sensing infrastructure. Traditional MMC control methods achieve accurate balancing by continuously monitoring capacitor voltages; however, such approaches become increasingly complex as converter levels increase. The proposed framework demonstrates that energy estimation can serve as a viable alternative for balancing control while significantly reducing hardware requirements.

From a theoretical perspective, the framework extends the modular converter concepts introduced by Lesnicar and Marquardt (2003) by incorporating modern sensorless control principles. The resulting architecture aligns with contemporary trends in intelligent power electronics, where control algorithms increasingly compensate for reduced hardware complexity through advanced computational techniques.

The integration of predictive control concepts also represents a significant advancement. Previous studies emphasized the effectiveness of model-based and predictive control strategies in MMC applications (Barnklau et al., 2013; Qin and Saeedifard, 2012; Aguilera et al., 2015). By combining predictive balancing with NLM operation, the proposed framework improves decision-making capabilities while maintaining low switching losses. This combination creates a favorable balance between performance and efficiency.

Comparison with PWM-based balancing strategies reveals additional benefits. While PWM techniques provide excellent controllability, they often require higher switching frequencies and consequently incur greater switching losses (Li et al., 2012; Mei et al., 2014). The use of NLM reduces these losses while preserving acceptable waveform quality, making it particularly attractive for high-power applications where efficiency is a critical concern.

The incorporation of disturbance rejection concepts inspired by Chao et al. (2023) further strengthens the framework. Renewable-energy-integrated power systems frequently experience fluctuating operating conditions that challenge conventional controllers. The adaptive disturbance rejection mechanism enhances system resilience and enables stable operation despite uncertainties. The repeated relevance of disturbance rejection in MMC research highlights its importance for future converter developments (Chao et al., 2023).

Despite its advantages, the proposed framework possesses several limitations. First, balancing accuracy depends heavily on the precision of energy estimation algorithms. Any cumulative estimation error may gradually affect balancing effectiveness. Second, predictive control algorithms introduce computational requirements that may increase controller complexity. Third, practical implementation would require careful calibration to ensure stable operation under varying operating conditions.

Another limitation concerns extreme transient scenarios. Although disturbance rejection mechanisms improve robustness, exceptionally rapid disturbances may challenge estimation accuracy and temporarily reduce balancing performance. Future research should therefore investigate hybrid estimation techniques capable of maintaining accuracy under severe dynamic conditions.

Overall, the discussion indicates that sensorless balancing combined with NLM represents a promising direction for MMC control development. The framework offers a meaningful compromise between performance, efficiency, scalability, and implementation cost while supporting emerging applications in HVDC transmission, smart grids, and renewable energy integration.

6. Conclusion

This study presented a comprehensive research and review investigation of an advanced control framework for a 21-level Modular Multilevel Converter employing Nearest Level Modulation without capacitor voltage sensing. The research addressed a critical challenge in MMC technology by proposing a sensorless balancing architecture capable of reducing hardware complexity while maintaining effective converter operation.

The literature review revealed that conventional MMC systems predominantly rely on capacitor voltage measurements for balancing purposes. Although effective, such approaches increase system cost, communication requirements, and maintenance complexity. Existing studies have extensively investigated predictive control, model-based control, modulation optimization, and disturbance rejection techniques; however, limited attention has been given to integrated sensorless balancing strategies for high-level MMC configurations.

To address this gap, a hierarchical control framework was developed consisting of Nearest Level Modulation, sensorless energy estimation, predictive balancing, circulating current suppression, and adaptive disturbance rejection mechanisms. The framework replaces direct capacitor voltage measurements with energy estimation based on arm current information and switching state analysis. This approach significantly reduces sensor dependency while preserving balancing functionality.

The analytical findings indicate that the proposed framework can achieve high-quality voltage generation, effective energy balancing, reduced switching losses, improved efficiency, and enhanced robustness against disturbances. The use of NLM contributes to lower switching frequencies, while predictive control enhances dynamic performance. Furthermore, adaptive disturbance rejection principles derived from recent MMC-HVDC research improve converter stability under renewable-energy-driven operating conditions (Chao et al., 2023).

The study contributes to the growing body of knowledge on intelligent MMC control by providing a structured sensorless framework that balances performance and implementation practicality. The proposed architecture is particularly relevant for future smart grid applications, HVDC transmission systems, industrial drives, and renewable energy integration platforms.

Future research should focus on detailed simulation studies, hardware-in-the-loop validation, experimental implementation, advanced estimation algorithms, and artificial intelligence-assisted balancing techniques. Such investigations will further establish the feasibility and practical advantages of sensorless MMC control systems for next-generation power electronic applications.

References

1. Abdulbaqi, A.S. et al. (2023). Innovative control strategies for dynamic load management in smart grid techniques incorporating renewable energy sources. KHWARIZMIA, 2023, 73-83.
2. Aguilera, R.P.; Yu, Y.; Acuna, P.; Konstantinou, G.; Townsend, C.D.; Wu, B.; and Agelidis, V.G. (2015). Predictive control algorithm to achieve power balance of cascaded H-bridge converters. Proceedings of the 2015 IEEE International Symposium on Predictive Control of Electrical Drives and Power Electronics (PRECEDE), Valparaiso, Chile, 49-54.
3. Barnklau, H.; Gensior, A.; and Rudolph, J. (2013). A model-based control scheme for modular multilevel converters. IEEE Transactions on Industrial Electronics, 60(12), 5359-5375.
4. Chao, W.; Deng, C.; Huang, J.; Dai, L.; Min, Y.; Cheng, Y.; Wang, Y.; and Liao, J. (2023). A sub-synchronous oscillation suppression strategy based on active disturbance rejection control for renewable energy integration system via MMC-HVDC. Electronics, 12(13), 2885.
5. Hagiwara, M.; and Akagi, H. (2009). Control and experiment of pulsewidth-modulated modular multilevel converters. IEEE Transactions on Power Electronics, 24(7), 1737-1746.
6. Hiller, M.; Krug, D.; Sommer, R.; and Rohner, S. (2009). A new highly modular medium voltage converter topology for industrial drive applications. Proceedings of the 2009 13th European Conference

on Power Electronics and Applications, Barcelona, Spain, 1-10.

7. Lesnicar, A.; and Marquardt, R. (2003). An innovative modular multilevel converter topology suitable for a wide power range. Proceedings of the 2003 IEEE Bologna Power Tech, Bologna, Italy, 272-277.

8. Li, Z.; Wang, P.; Zhu, H.; Chu, Z.; and Li, Y. (2012). An improved pulse width modulation method for chopper-cell-based modular multilevel converters. IEEE Transactions on Power Electronics, 27(8), 3472-3481.

9. Mei, J.; Shen, K.; Xiao, B.; Tolbert, L.M.; and Zheng, J. (2014). A new selective loop bias mapping phase disposition PWM with dynamic voltage balance capability for modular multilevel converter. IEEE Transactions on Industrial Electronics, 61(2), 798-807.

10. Qin, J.; and Saeedifard, M. (2012). Predictive control of a modular multilevel converter for a back-to-back HVDC system. IEEE Transactions on Power Delivery, 27(3), 1538-1547.

11. Rodriguez, J.; Bernet, S.; Wu, B.; Pontt, J.O.; and Kouro, S. (2007). Multilevel voltage-source-converter topologies for industrial medium-voltage drives. IEEE Transactions on Industrial Electronics, 54(6), 2930-2945.

12. Tu, Q.; Xu, Z.; and Xu, L. (2011). Reduced switching-frequency modulation and circulating current suppression for modular multilevel converters. IEEE Transactions on Power Delivery, 26(3), 2009-2017.