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Multi-Level Converters for Offshore Wind Farms Interfacing with Synchronous Generators

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ABSTRACT

The integration of offshore wind farms into modern power grids requires advanced power electronic converters to efficiently handle variable wind conditions, maximize energy extraction, and ensure grid stability. Multi-level converters (MLCs) have emerged as a promising solution for interfacing synchronous generators in offshore wind turbines, offering benefits such as reduced harmonic distortion, lower switching losses, and enhanced voltage quality. This paper presents a comprehensive review of multi-level converter topologies suitable for offshore wind applications, discusses control strategies, evaluates performance metrics, and highlights challenges and future trends. The study also emphasizes the importance of optimizing converter design to enhance reliability and efficiency in harsh offshore environments.

KEYWORDS: *Multi-level converters, offshore wind farms, synchronous generators, power electronics, harmonic reduction, grid integration, energy conversion.*

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INTRODUCTION

Offshore wind energy has gained significant attention due to abundant wind resources and minimal land-use conflicts. Synchronous generators (SGs) are often used in large-scale offshore wind turbines for their high power density and controllable reactive power capability. However, connecting SGs directly to the grid poses challenges, including frequency mismatches, voltage fluctuations, and harmonic distortion. Power electronic converters, particularly multi-level converters (MLCs), offer a flexible interface between SGs and the grid, enabling better voltage quality, higher power ratings, and improved system reliability.

MLCs, such as neutral point clamped (NPC), flying capacitor (FC), and cascaded H-bridge (CHB) converters, have distinct advantages over traditional two-level converters. They generate near-sinusoidal waveforms with reduced total harmonic distortion (THD), minimize voltage stress on power devices, and support high-voltage applications without series transformers. For offshore wind farms, these advantages translate into reduced maintenance costs, enhanced energy yield, and compliance with stringent grid codes.

OFFSHORE WIND FARMS AND SYNCHRONOUS GENERATORS

The successful operation of offshore wind farms requires careful integration of mechanical, electrical, and power electronic systems. Among these, the combination of synchronous generators (SGs) with multi-level power converters plays a crucial role in ensuring efficient energy extraction and stable grid interfacing. This section elaborates on the characteristics of offshore wind farms and the role of synchronous generators within these systems.

1. Offshore Wind Farm Characteristics

Offshore wind farms are composed of multiple wind turbines installed in marine environments, typically hundreds of meters from shore. Modern offshore turbines are designed for high-capacity power generation, often ranging from **5 MW to 15 MW per unit**, with some experimental designs exceeding 20 MW. These turbines are interconnected via medium-voltage (MV, typically 33 kV) or high-voltage (HV, 66–220 kV) collector systems that consolidate the power from individual turbines before transmission to onshore substations.

Several key characteristics define offshore wind farms:

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1. **High Variability of Wind Speed and Direction**

Wind in offshore environments exhibits significant temporal and spatial fluctuations. Turbine generators must operate efficiently across a wide range of wind speeds, from cut-in (≈3 m/s) to rated speeds (≈12–15 m/s) and withstand gusts exceeding rated levels. This variability necessitates flexible control systems and power electronics capable of adapting generator output to maximize energy capture without violating grid constraints.

2. **Long-Distance Transmission to Onshore Substations**

Offshore wind farms are often located tens of kilometers from the coast. Power transmission over such distances requires high-voltage AC (HVAC) or high-voltage DC (HVDC) lines. Long transmission distances introduce **voltage drop, reactive power challenges, and power losses**, which must be mitigated by sophisticated converters, reactive power compensation systems, and high-quality insulation in cables and switchgear.

3. **Harsh Environmental Conditions**

Offshore environments subject turbines and electrical systems to **corrosion from saltwater, high humidity, strong winds, waves, and mechanical vibrations**. Electrical components, including generators, converters, and transformers, must be designed for robust operation under these conditions. Materials with high corrosion resistance, vibration-damping mounts, and sealed enclosures are essential to prolong equipment lifespan and reduce maintenance costs.

4. **Grid Code Compliance**

Offshore wind farms must comply with regional grid codes, which often require low-voltage ride-through (LVRT) capability, reactive power support, and harmonic mitigation. These requirements influence both generator design and the selection of power electronic interfaces, making multi-level converters a preferred solution for meeting such stringent standards.

2. Synchronous Generators in Wind Turbines

Synchronous generators are commonly used in offshore wind turbines, either as **direct-driven permanent magnet synchronous generators (PMSGs)** or as **gearbox-coupled wound-rotor synchronous machines**. They offer several advantages over induction generators:

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1. **High Efficiency Over a Wide Speed Range**

Synchronous generators provide near-constant efficiency across the operating speed range. This is particularly advantageous in offshore turbines, where wind speed variability demands efficient energy conversion at both partial and rated loads. Direct-drive PMSGs eliminate the gearbox, reducing mechanical losses and maintenance requirements, while gearbox-coupled SGs allow smaller generator sizes for the same power rating.

2. **Capability to Provide Reactive Power Support**

Unlike induction generators, synchronous generators can actively regulate reactive power output through excitation control. This capability is crucial for maintaining **voltage stability and power factor** in offshore grid networks, especially when multiple turbines operate in parallel. It also supports compliance with LVRT and other grid code requirements.

3. **Robust Design for Large-Scale Offshore Deployment**

SGs are mechanically and thermally robust, making them suitable for the challenging offshore environment. Their construction allows reliable operation over decades with minimal maintenance, which is essential given the difficulty and cost of accessing offshore turbines for repairs.

However, synchronous generators operate at variable rotor speeds depending on wind conditions, while the grid requires constant frequency. Therefore, **advanced power electronic converters are necessary** to:

- Match the variable generator frequency to the fixed grid frequency.
- Regulate output voltage under varying wind conditions.
- Minimize harmonics and optimize energy extraction.

Multi-level converters provide the ideal solution by offering high-quality voltage synthesis, modular scalability, and efficient power transfer, enabling synchronous generator-based offshore turbines to meet modern grid integration standards.

MULTI-LEVEL CONVERTER TOPOLOGIES

Multi-level converters (MLCs) have become a cornerstone in high-voltage, high-power applications such as offshore wind farms. By synthesizing voltage waveforms from multiple

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discrete voltage levels, MLCs effectively **reduce harmonic distortion, lower switching losses, and improve overall power quality**, which is critical for grid-connected synchronous generator-based systems. Unlike traditional two-level converters, which switch directly between the DC rail voltages, MLCs divide the voltage into several steps, creating a near-sinusoidal waveform. This approach reduces **total harmonic distortion (THD)**, minimizes **electromagnetic interference (EMI)**, and enhances reliability in high-voltage environments.
The primary multi-level converter topologies used in offshore wind farms are: **Neutral Point Clamped (NPC)**, **Flying Capacitor (FC)**, and **Cascaded H-Bridge (CHB)** converters. Each topology has unique advantages and limitations that determine its suitability for offshore applications.

1. Neutral Point Clamped (NPC) Converters

Neutral Point Clamped converters, also known as **diode-clamped converters**, are widely used in medium-voltage applications. In this topology, **clamping diodes** are connected to the neutral point of a DC-link capacitor bank to divide the DC bus voltage into multiple levels. This arrangement limits the voltage stress across each power semiconductor switch, allowing operation at **higher voltages** without requiring devices rated for full DC bus voltage.

Key Features and Advantages:

1. **Reduced Voltage Stress per Switch**

Each switch experiences only a fraction of the total DC voltage, enabling the use of commercially available IGBTs or MOSFETs for medium-voltage applications. This also reduces thermal stress and improves device reliability.

2. **Low Harmonic Distortion**

NPC converters generate stepped voltage waveforms that closely approximate sinusoidal AC output, which **reduces total harmonic distortion (THD)** and mitigates the need for large filter components. This is particularly important in offshore wind farms where grid codes impose strict limits on harmonic injection.

3. **Proven Industrial Adoption**

NPC converters are well-established in the industry, with extensive operational data in renewable energy and HVDC systems, making them a reliable choice for offshore wind

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applications.

Limitations:

- **Complex Diode Arrangement for High Levels:** As the number of voltage levels increases, the number of clamping diodes grows significantly, leading to increased complexity and potential reliability issues.
- **Limited Scalability:** NPC topologies are typically limited to **5–7 levels**, making them less suitable for ultra-high-voltage offshore applications without modular expansion.

Practical Application in Offshore Wind:

NPC converters are often used for medium-voltage offshore turbines (≈3–6 MW), offering a balanced compromise between performance, complexity, and cost.

2. Flying Capacitor (FC) Converters

Flying Capacitor converters utilize a series of capacitors to generate **intermediate voltage levels**. Each switching device can connect to multiple capacitor voltages, producing stepped waveforms that approach a sinusoidal shape. Unlike NPC converters, FC converters provide **more flexibility in selecting voltage levels** and can tolerate individual switch failures without immediate system shutdown.

Key Features and Advantages:

1. **Flexible Voltage Level Selection**

The number of levels in FC converters can be increased by adding capacitors and switches, offering **fine-grained control** over output voltage amplitude and waveform shape.

2. **High-Quality Output Waveform**

The additional voltage levels reduce harmonic distortion, resulting in **very low THD**, which is essential for compliance with offshore grid codes.

3. **Fault Tolerance**

Open-circuit switch faults can often be bypassed by adjusting switching sequences, enhancing reliability in remote offshore environments where maintenance is challenging.

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Limitations:

- **Complex Capacitor Voltage Balancing:** Maintaining uniform voltage across multiple capacitors requires sophisticated control algorithms, which increases design complexity.
- **High Component Count and Maintenance:** The large number of switches and capacitors increases system size, cost, and maintenance demands, which can be a challenge in offshore settings.

Practical Application in Offshore Wind:

FC converters are suitable for **medium-to-high voltage turbines** (5–10 MW), where precise voltage control and low harmonic injection are critical, but the high component count must be justified by performance improvements.

3. Cascaded H-Bridge (CHB) Converters

Cascaded H-Bridge converters are modular structures composed of multiple **single-phase H-bridge cells** connected in series. Each H-bridge can generate positive, negative, or zero voltage, and by combining several bridges, the CHB can produce a multi-level AC output with extremely low harmonic content.

Key Features and Advantages:

1. **Modular Design**

CHB converters are highly modular, allowing easy expansion to higher voltage levels by adding additional H-bridge cells. This modularity is ideal for offshore wind farms, where turbines can be standardized and scaled.

2. **Scalability to High Voltages**

By connecting multiple H-bridge cells in series, CHB converters can achieve **very high voltage outputs** without requiring transformers, which reduces weight and cost.

3. **Low Harmonic Distortion Without Transformers**

The stepped output waveform of CHB converters approximates a sinusoid closely, reducing the need for bulky AC filters and making them well-suited for grid integration of offshore wind farms.

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Limitations:

- **Higher Number of Power Devices:** Each H-bridge contains four switches, so multiple cascaded cells result in a large number of devices, increasing system complexity.
- **Complex Control and Synchronization:** Precise timing and modulation of each H-bridge module are essential to achieve the desired voltage waveform, requiring advanced digital controllers.

Practical Application in Offshore Wind:

CHB converters are preferred for **large-scale offshore turbines** (>10 MW) and **high-voltage collector systems**, where modularity, low THD, and transformerless operation provide significant operational and economic benefits.

Table 1: Comparison of Multi-Level Converter Topologies

Feature	NPC	Flying Capacitor	Cascaded H-Bridge
Voltage Levels	Medium (3–7)	Medium-High	High (>10)
Harmonic Performance	Good	Excellent	Excellent
Device Stress	Low	Medium	Low
Modularity	Low	Medium	High
Complexity	Medium	High	Medium

CONTROL STRATEGIES FOR MLCS IN OFFSHORE WIND

Multi-level converters (MLCs) form the interface between synchronous generators (SGs) in offshore wind turbines and the electrical grid. While MLC topologies define the hardware, **control strategies determine how effectively these converters operate**, influencing energy efficiency, power quality, and compliance with grid codes. Offshore wind farms face unique challenges such as **variable wind speeds, fluctuating generator output, long transmission distances, and harsh environmental conditions**, which necessitate advanced, adaptive, and reliable control strategies.

Effective control of MLCs encompasses **voltage regulation, frequency matching, reactive power support, harmonic suppression, and fault ride-through capability**. Three widely

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employed strategies are **Pulse Width Modulation (PWM)** techniques, **Direct Power Control (DPC)**, and **Model Predictive Control (MPC)**.

1. Pulse Width Modulation (PWM) Techniques

PWM is the most common technique for controlling the output voltage of power electronic converters. By adjusting the **switching times of semiconductor devices**, PWM shapes the output waveform, achieving near-sinusoidal voltage and reducing harmonics.

Key PWM Techniques for Offshore Wind MLCs:

1. **Sinusoidal PWM (SPWM)**

- SPWM generates a modulated pulse waveform by comparing a sinusoidal reference signal with a high-frequency triangular carrier.
- **Advantages:**
- Simple implementation and control.
- Widely supported by industrial digital signal processors (DSPs) and microcontrollers.
- Moderate THD reduction suitable for medium-voltage applications.

- **Limitations:**
- Harmonic content increases at higher voltage levels and switching frequencies.
- Less effective for ultra-high voltage offshore applications.

2. **Space Vector PWM (SVPWM)**

- SVPWM treats the three-phase output voltage as a **vector in a two-dimensional α-β plane** and selects switching states to approximate the desired vector trajectory.
- **Advantages:**
- Optimized switching sequence reduces harmonic distortion.
- Lower switching losses compared to SPWM at equivalent modulation indices.
- Better utilization of the DC bus voltage, allowing higher output voltage.

- **Application in Offshore Wind:**
- SVPWM is preferred for **high-power multi-level converters**, such as CHB or FC converters, where both efficiency and THD reduction are critical.

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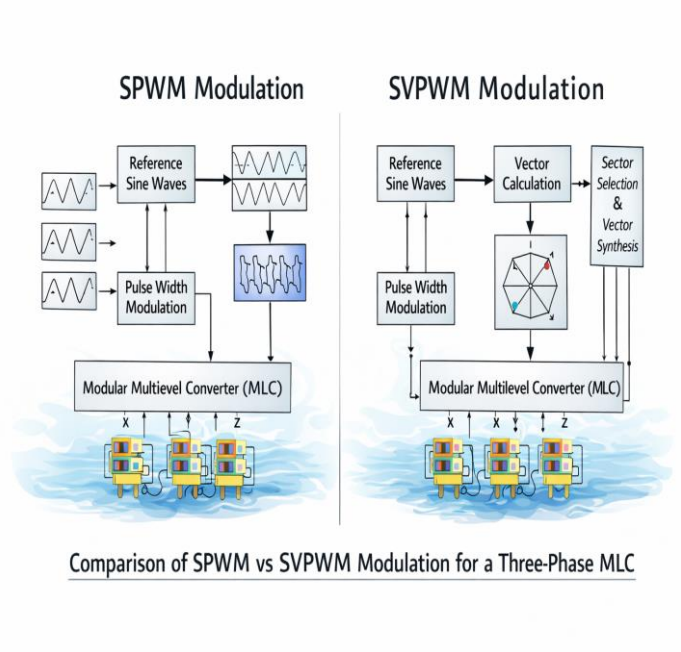


Figure 1 Suggestion: Block diagram showing SPWM vs SVPWM modulation for a three-phase MLC.

2. Direct Power Control (DPC)

Direct Power Control (DPC) is an advanced technique that **directly regulates active (P) and reactive (Q) power** without using traditional inner current loops. DPC is particularly suitable for **variable-speed synchronous generators** in offshore turbines.

Key Features of DPC:

- **Direct Regulation of P and Q:**

The converter output is modulated to maintain desired power flow, improving dynamic response to wind speed fluctuations.

- **Fast Transient Response:**

DPC reacts immediately to disturbances, such as sudden wind gusts, minimizing overshoot in voltage or power.

- **Reduced Computational Complexity:**

By eliminating the need for nested current control loops, DPC simplifies control architecture, which is beneficial for real-time offshore applications.

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- **Integration with Multi-Level Converters:**

DPC can be extended to multi-level topologies by defining **power vectors corresponding to each switching state** of the MLC, optimizing energy transfer and maintaining low THD.

Challenges:

- Requires accurate measurement of voltages and currents.
- Sensitive to parameter variations, such as grid impedance changes.

3. Model Predictive Control (MPC)

Model Predictive Control is a **predictive strategy** that calculates the optimal switching actions of the MLC by forecasting the system's future behavior over a short time horizon. MPC has gained popularity in offshore wind applications due to its **dynamic adaptability and constraint-handling capability**.

Advantages of MPC for Offshore Wind MLCs:

1. **Fast Transient Response:**

MPC evaluates possible switching states and selects the one that minimizes the predicted error between reference and actual variables (voltage, current, or power). This allows the system to react quickly to sudden wind fluctuations or grid disturbances.

2. **Constraint Handling:**

MPC can include **operating constraints** such as voltage limits, current limits, switching frequency limits, and fault tolerance. This ensures safe operation under harsh offshore conditions.

3. **Improved Reliability:**

By optimizing switching sequences in real-time, MPC reduces switching losses, thermal stress on devices, and harmonics, prolonging converter lifetime and reducing maintenance frequency.

4. **Enhanced Power Quality:**

MPC can minimize THD without requiring high switching frequencies, making it particularly suitable for **high-voltage, high-power MLCs**, such as cascaded H-bridge converters in offshore wind farms.

Implementation Considerations:

- MPC requires **accurate system modeling** of both the synchronous generator and MLC.

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- Computational requirements are higher than PWM or DPC, necessitating powerful onboard DSPs or FPGAs.
- Often combined with state observers or sensor fusion techniques to improve robustness against measurement noise and parameter variations.

Figure 7 Suggestion: Block diagram of MPC applied to a multi-level converter, showing predictive horizon, cost function minimization, and optimal switching selection.

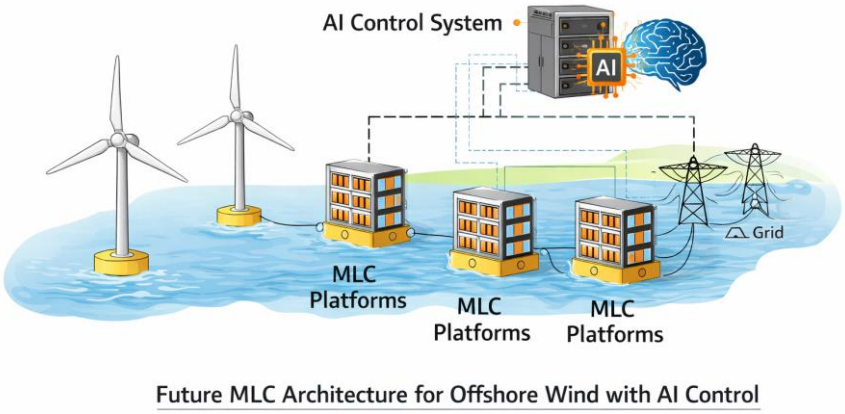


Figure 2: Control Framework for MLC-based Offshore Wind Interface

PERFORMANCE METRICS AND EVALUATION

Performance evaluation of MLCs for offshore wind systems focuses on the following metrics:

- **Total Harmonic Distortion (THD):** Reduced THD improves power quality and compliance with grid codes.
- **Efficiency:** Conversion efficiency must remain high under variable wind speeds.
- **Reliability:** Offshore environment demands robust designs resistant to moisture, vibration, and temperature fluctuations.
- **Scalability:** Converters must handle multi-megawatt outputs with minimal incremental complexity.

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Table 2: Performance Metrics of MLC Topologies for Offshore Wind

Metric	NPC	FC	CHB
THD (%)	5–8	2–5	2–4
Efficiency (%)	96–97	95–96	96–97
Voltage Rating (kV)	Medium	Medium	High
Component Count	Medium	High	High
Maintenance Demand	Medium	High	Medium

CHALLENGES AND SOLUTIONS

1. Harsh Offshore Environment

Corrosion, saltwater exposure, and vibration affect MLC reliability. Solutions include:

- Coated PCBs and sealed enclosures.
- Vibration-resistant mounting and cooling.

2. High Voltage Operation

Offshore wind turbines often operate at 33–66 kV collection voltages. Strategies to manage voltage stress:

- Modular cascaded designs.
- Use of SiC/GaN devices for high-voltage, high-efficiency operation.

3. Grid Code Compliance

Wind farm converters must provide fault ride-through and reactive power support. MLCs with advanced control schemes enable:

- Low-voltage ride-through (LVRT).
- Voltage regulation and harmonic suppression.

7. Future Trends

Future research is focusing on:

- Wide-bandgap semiconductors (SiC, GaN) for higher efficiency and compact designs.
- Artificial intelligence-based predictive control for optimal energy capture.
- Modular multilevel converter (MMC) topologies for ultra-high voltage offshore applications.

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- Hybrid energy systems integrating offshore wind with storage and wave energy.

Figure 2: Future MLC Architecture for Offshore Wind with AI Control

CONCLUSION

Multi-level converters are key enablers for integrating synchronous generator-based offshore wind farms into modern power grids. They offer superior voltage quality, reduced harmonics, and scalability for high-voltage applications. NPC, FC, and CHB topologies each present unique benefits and challenges, with CHB and FC being particularly promising for multi-megawatt offshore installations. Advanced control strategies, such as SVPWM, MPC, and DPC, enhance dynamic response, power quality, and reliability. Future developments, including wide-bandgap devices and AI-driven predictive controls, will further optimize offshore wind energy conversion, contributing to a more sustainable and resilient energy infrastructure.

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