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Cascaded hybrid multilevel inverters: a review of topologies, modulation strategies, power balancing, and renewable energy applications

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ABSTRACT

Cascaded hybrid multilevel inverters (CHMLIs) have attracted considerable research interest because they can generate high-quality output voltage waveforms while reducing selected semiconductor and passive component requirements. By combining different converter cells, voltage-source configurations, or switching strategies, these architectures offer greater flexibility than conventional cascaded multilevel inverters. Nevertheless, their practical implementation introduces challenges involving unequal DC sources, power distribution, switching losses, harmonic distortion, and control complexity. This review examines the development of cascaded hybrid multilevel inverter systems, focusing on topology classification, symmetric and asymmetric configurations, hybrid modulation, selective harmonic elimination, and power-balancing techniques. It also evaluates their suitability for photovoltaic systems, electric drives, energy storage, and grid-connected applications. The literature indicates that asymmetric voltage arrangements can increase the number of output levels with fewer components, whereas symmetric configurations generally provide greater switching-state redundancy and flexibility. Hybrid modulation and intelligent optimization can improve waveform quality and power distribution, although their effectiveness depends on source characteristics and operating conditions. Future research should prioritize reliable power balancing, fault-tolerant operation, reduced-complexity modulation, and experimentally validated system-level comparisons.

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1. INTRODUCTION

Multilevel inverters (MLIs) are important power electronic converters for applications requiring medium- and high-voltage conversion with improved output waveform quality. Unlike conventional two-level inverters, they synthesize stepped voltage waveforms using multiple DC voltage levels, reducing voltage stress on individual switches and potentially lowering output harmonic distortion. These characteristics make MLIs attractive for renewable energy conversion, industrial motor drives, grid-connected systems, and power quality improvement. Classical research established the neutral-point-clamped, flying-capacitor, and cascaded H-bridge structures as the principal foundations of multilevel conversion [1], [2].

Cascaded hybrid multilevel inverters (CHMLIs) extend conventional cascaded architectures by combining different power-cell configurations, voltage ratings, or modulation methods. Their purpose is to increase the number of output voltage levels without proportionally increasing the number of semiconductor devices and isolated DC sources. Hybrid configurations can also combine high-voltage cells operating at low switching frequencies with low-voltage cells operating at higher frequencies. This arrangement creates opportunities to balance output waveform quality, switching losses, and converter cost [3], [4].

Despite these advantages, hybrid cascaded structures introduce several engineering challenges that are not fully addressed by simply increasing the number of voltage levels. Different DC-source magnitudes can

create unequal power distribution among cascaded cells, while the use of dissimilar switching devices can complicate gate-signal coordination. Modulation algorithms must also consider voltage balancing, harmonic suppression, switching frequency, and the operating limits of each cell. These issues motivate a systematic assessment of topology selection and control strategies for practical CHMLI implementation [5]–[7].

This review evaluates the development of cascaded hybrid multilevel inverter systems through four connected research dimensions. First, it examines the structural principles and classifications of hybrid cascaded topologies. Second, it discusses modulation, harmonic reduction, and power-balancing methods. Third, it considers applications in renewable energy, electric vehicles, and grid-connected systems. Finally, it identifies technical limitations and future research directions to connect topology-level improvements with reliable system-level performance.

2. FUNDAMENTAL TOPOLOGIES AND HYBRID CONFIGURATIONS

The cascaded H-bridge (CHB) inverter is a widely investigated multilevel structure because its modular cells can be connected in series to generate multiple output voltage levels. Each H-bridge cell produces positive, negative, or zero voltage according to its switching state, and the series connection combines these individual outputs. A symmetric CHB configuration uses DC sources with equal voltage magnitudes, providing a relatively straightforward modular design. However, increasing the number of voltage levels generally requires additional switches, gate drivers, and isolated DC sources [1], [2], [8].

Asymmetric configurations employ DC sources with different voltage magnitudes to increase the number of obtainable output levels for a given number of cells. Binary, ternary, and other optimized voltage ratios can be used depending on the desired waveform resolution and switching-state structure. This approach can reduce the number of power cells required for a particular voltage level, although it may introduce unequal power sharing and fewer redundant switching states. Comparative analysis of symmetric and asymmetric cascaded inverters shows that topology selection involves a trade-off among voltage resolution, redundancy, distortion, and power distribution [9].

Hybrid cascaded architectures can also combine conventional H-bridge cells with other converter structures, including neutral-point-clamped, switched-capacitor, or voltage-source inverter modules. Such combinations can reduce component requirements or provide additional voltage-boosting capability. A hybrid multilevel converter can assign different switching responsibilities to individual cells, allowing the high-voltage section to operate at lower frequency while the auxiliary section improves waveform resolution. These design principles have been examined in unified analyses of hybrid multilevel converter structures [3], [4], [10].

3. MODULATION AND HARMONIC REDUCTION STRATEGIES

Modulation determines the switching sequence used to synthesize the desired output voltage and is therefore central to CHMLI performance. Carrier-based pulse-width modulation (PWM) is commonly employed because it provides a structured approach to generating switching pulses for cascaded cells. Phase-shifted and level-shifted carrier arrangements can be selected according to the number of cells, voltage ratios, and harmonic requirements. Comparative investigations of symmetric and asymmetric CHB structures demonstrate that carrier disposition and modulation index influence fundamental voltage utilization and harmonic distribution [11], [12].

Selective harmonic elimination PWM (SHE-PWM) provides another important strategy, particularly when switching losses must be limited. It determines switching angles to maintain the desired fundamental voltage while suppressing selected low-order harmonics. Optimization algorithms, including particle swarm optimization and genetic algorithms, have been investigated to solve the nonlinear switching-angle problem. A hybrid asynchronous particle-swarm and genetic algorithm has demonstrated experimentally validated harmonic elimination for cascaded H-bridge configurations [13].

Hybrid modulation combines techniques with different operating characteristics to improve performance across a wider modulation range. Nearest-level control can reduce switching activity in high-voltage cells, while PWM can improve waveform resolution through auxiliary cells. A hybrid nearest-level and PWM strategy has been evaluated for cascaded H-bridge inverters, including operation under selected fault conditions. Its reported experimental validation illustrates the importance of assessing harmonic performance, power losses, and fault response together [14].

Real-time adaptive SHE-PWM addresses a limitation of conventional offline switching-angle calculation. Fixed switching angles may become unsuitable when DC-source voltages or load conditions change during operation. Adaptive methods can update switching angles to preserve the fundamental component and suppress selected harmonics under changing conditions. Experimental work on cascaded full-bridge inverters has demonstrated this principle through dynamic adaptation of switching angles [15].

4. POWER BALANCING AND DC-SOURCE MANAGEMENT

Power balancing is a major challenge in asymmetric and hybrid cascaded inverters because individual cells may operate with different voltage magnitudes and switching patterns. Unequal power distribution can cause different thermal and electrical stresses among semiconductor devices and DC sources. This condition may reduce component lifetime and complicate converter maintenance. Therefore, the modulation strategy should distribute energy among the cascaded cells rather than optimizing output voltage quality alone [6], [7].

Carrier rotation and switching-sequence redistribution have been investigated to improve power balance in hybrid cascaded H-bridge systems. Gong *et al.* [6] examined a 13-level hybrid inverter with a DC voltage ratio of 1:1:1:3 and proposed a carrier-rotation-based strategy to equalize output power among cascaded units. Their work demonstrated that power distribution can be improved while maintaining output waveform quality and avoiding current backflow under the investigated conditions. This result highlights the need to coordinate the modulation sequence with the energy contribution of each cell.

Other approaches seek to coordinate power balance and switching losses through generalized modulation schemes. Ye *et al.* [7] proposed a control strategy for asymmetric cascaded H-bridge inverters that considers both linear power balance and uniform switching loss. Such strategies are particularly relevant when cells have different DC-source ratings or semiconductor operating conditions. However, the effectiveness of any balancing algorithm must be evaluated under source variation, load changes, and transient operation.

5. REDUCED-COMPONENT AND SWITCHED-CAPACITOR HYBRID STRUCTURES

Reducing semiconductor count is an important objective in the development of hybrid multilevel inverter topologies. A higher number of output voltage levels can improve waveform resolution, but conventional cascaded designs often require additional switches and isolated DC supplies. Reduced-switch structures seek to improve the ratio between generated voltage levels and installed components. Nevertheless, a low component count does not automatically guarantee lower overall cost because capacitor sizing, voltage ratings, gate drivers, protection, and control complexity must also be considered [5], [16], [17].

Switched-capacitor cascaded structures provide an alternative means of generating additional voltage levels from a smaller number of DC sources. Their operation involves charging and discharging capacitors through controlled switching paths to obtain stepped output voltages. Vivert *et al.* [17] proposed a hybrid cascaded switched-capacitor inverter designed to reduce semiconductor requirements and generate multiple voltage levels. Their experimental investigation also emphasized the importance of managing capacitor inrush current and reverse current under inductive loading.

The design of reduced-component hybrid structures should therefore consider more than the nominal number of switches. Relevant parameters include total standing voltage, peak inverse voltage, capacitor voltage balancing, source isolation, and conduction-path complexity. A topology that reduces switch count may require higher-rated devices or more demanding capacitor management. Comparative evaluation should consequently use consistent component-counting and loss-calculation methods [5], [16], [17].

6. RENEWABLE ENERGY AND GRID-CONNECTED APPLICATIONS

Photovoltaic systems are suitable applications for cascaded hybrid multilevel inverters because separate PV strings or DC sources can supply individual power cells. This modular arrangement can support distributed power conversion and provide multiple voltage levels for grid connection. It may also reduce the need for bulky line-frequency transformers in some configurations, depending on the selected topology and isolation requirements. Reviews of grid-tied MLI systems identify harmonic performance, DC-source management, converter efficiency, and grid-current quality as important design considerations [18], [19].

Hybrid cascaded inverters have also been investigated for systems combining photovoltaic and wind generation. In these applications, the control system must coordinate variable source power with the load or grid demand. Intelligent optimization and prediction methods can assist in selecting control references and switching states under changing generation conditions. However, reported algorithmic improvements should be distinguished from hardware-validated improvements in conversion efficiency and long-term reliability [20].

Electric vehicle applications provide another opportunity for cascaded multilevel conversion. The use of multiple battery modules as DC sources can support cascaded structures and potentially improve voltage resolution while distributing electrical stress among modules. Stöttner *et al.* [9] compared symmetric and asymmetric cascaded inverter configurations for EV applications, emphasizing the relationships among voltage-level redundancy, power distribution, and output distortion. Their analysis suggests that asymmetric configurations can increase the number of voltage levels, whereas symmetric structures may provide greater redundancy and fault-tolerance opportunities.

Table 1 summarizes the principal CHMLI configurations and their engineering implications. It distinguishes conventional symmetric and asymmetric CHB arrangements from hybrid-cell and switched-capacitor structures. The comparison shows that no single topology simultaneously minimizes component count, switching loss, voltage stress, and control complexity. Therefore, topology selection should be based on application-specific requirements rather than the number of output voltage levels alone [21], [22].

Table 1. Comparative assessment of cascaded hybrid multilevel inverter configurations

Configuration	Main characteristics	Advantages	Main limitations
Symmetric cascaded H-bridge	Equal DC-source magnitudes	Modularity and switching-state redundancy	More cells and isolated sources for higher levels
Asymmetric cascaded H-bridge	Unequal DC-source magnitudes	Higher level count with fewer cells	Unequal power sharing and reduced redundancy
Hybrid cascaded H-bridge	Different cell ratings or switching strategies	Flexible switching-frequency allocation	More complex modulation and coordination
Hybrid nearest-level/PWM	Combines fundamental and carrier-based switching	Wider modulation range and harmonic control	Requires coordinated switching patterns
Switched-capacitor cascaded hybrid	Uses capacitors to generate additional voltage levels	Reduced DC-source and switch requirements in selected designs	Inrush current and capacitor-voltage management
Renewable-integrated CHMLI	Multiple PV, wind, or storage sources	Modular energy conversion and grid interfacing	Source intermittency and DC-link power imbalance

7. RELIABILITY, FAULT TOLERANCE, AND IMPLEMENTATION CHALLENGES

Reliability is a critical consideration because cascaded structures contain multiple semiconductor devices, gate drivers, DC sources, and sensing circuits. A fault in one cell can distort the output waveform or interrupt converter operation if no suitable bypass or reconfiguration strategy is available. Redundant switching states in symmetric configurations can provide opportunities for fault-tolerant operation. However, asymmetric configurations may offer fewer alternative states, making fault management more difficult [9].

Hybrid control strategies can support continued operation when a switching device or cell becomes unavailable. Siddique *et al.* [14] evaluated a hybrid nearest-level and PWM method with a fault-tolerant cascaded H-bridge structure, including simulation and experimental investigation. Their work illustrates that fault-tolerant operation should be considered during topology and modulation design rather than added after the converter has been developed. Protection coordination, fault detection speed, and post-fault output capability remain essential performance indicators.

Thermal management and electromagnetic compatibility also influence the practical suitability of CHMLIs. Different switching frequencies and voltage ratings among cells can create unequal semiconductor losses and temperature distributions. Fast switching transitions may increase electromagnetic interference and common-mode voltage, particularly in systems connected to long cables or sensitive loads. Consequently, thermal design, gate-drive coordination, insulation, filtering, and protection must be considered alongside the electrical topology [2]–[4].

8. RESEARCH GAPS AND FUTURE DIRECTIONS

A major research gap concerns the lack of standardized comparisons among hybrid cascaded inverter topologies. Published studies frequently use different voltage ratings, semiconductor technologies, switching frequencies, modulation indices, and load conditions. This makes direct comparisons of efficiency, total harmonic distortion, component count, and power density difficult. Future research should establish common evaluation conditions and report both simulated and experimental performance using clearly defined metrics [5], [18], [19].

A second research priority is robust power balancing under variable DC-source conditions. Renewable energy sources and battery modules do not always provide equal voltage or power, particularly during partial shading, changing irradiance, or unequal battery state of charge. Advanced modulation and adaptive control should therefore consider source availability, cell temperature, switching loss, and output harmonic requirements simultaneously. Experimental studies should verify these strategies during transient operation and under realistic source disturbances [6], [7], [20].

A third direction involves the development of fault-tolerant and computationally efficient control systems. Increasing the number of cells can improve voltage resolution but also increases the number of switching states and the complexity of modulation. Intelligent optimization may improve switching-angle selection, although computation time and implementation cost should be assessed before practical deployment. Future CHMLI designs should integrate fault detection, cell bypass, voltage balancing, and modulation reconfiguration within a unified control architecture [13]–[15].

9. CONCLUSION

Cascaded hybrid multilevel inverters provide a flexible approach to improving output voltage quality while reducing selected component requirements. Their principal design options include symmetric and asymmetric cascaded H-bridge structures, hybrid converter cells, and switched-capacitor configurations. The reviewed literature demonstrates that modulation strategy, power balancing, and DC-source management are as important as the physical topology in determining converter performance. Therefore, an effective CHMLI design must balance waveform quality, semiconductor utilization, efficiency, reliability, and implementation complexity. Hybrid modulation and intelligent optimization offer promising solutions for harmonic reduction and power distribution among cascaded units. Nevertheless, unequal source voltages, switching losses, capacitor management, and fault tolerance remain important practical challenges. Renewable energy and electric vehicle applications provide strong motivation for further development, but they require validation under realistic operating conditions. Future research should prioritize standardized benchmarking, adaptive power balancing, fault-tolerant control, and experimentally verified designs that demonstrate clear system-level advantages.

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