



## Next-Gen Inverter Topologies and Control for Utility-Scale Solar

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**Abstract** - Solar energy has ceased to be a secondary energy source and is becoming an essential part of the contemporary power grid with a growing need to have a sustainable source of generation. However, the system of integrating utility-scale photovoltaic systems with the existing electrical systems presents sophisticated engineering challenges. These challenges are particularly acute when attempting to meet the increasingly stringent grid-code requirements and evolving operational benchmarks mandated by utility providers. One way to make it work is by using multilevel inverters, which are very efficient. In this study, we look at the different designs and technical challenges of these inverters, and the control systems needed to make sure large solar power plants run smoothly. The study focuses on the technical peculiarities of utility-scale plants and the strategies of streamlining the interaction of such plants with the power grid. These reasons are necessary since solar energy is no longer a bargaining component of the global energy policy. The only assurance of effective ability of utility scale systems to scale up in an efficient manner whilst ensuring long-term operational reliability is the development of such robust frameworks.

**Key Words** : Large-scale Photo voltaic power plants, high-power multilevel inverters, grid-integrated control systems, advanced pulse width modulation techniques, high-capacity power conversion architectures.

### 1. Introduction

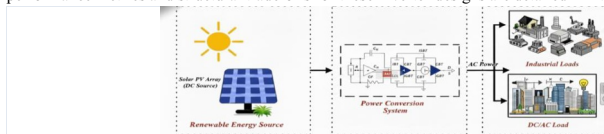
The development of modern civilization is fully based on the effectiveness of energy production and distribution in the world. In order to fight climate change, we are witnessing a tremendous transition to renewable energy, and the world solar capacity is predicted to reach over 2,000 GW by the end of 2025 [2]. Photovoltaic (PV) technology has become the leading technique of direct conversion of solar to electrical power in this changing energy environment. Additionally, the incorporation of advanced deep neural networks has also contributed to the stability of such systems by increasing the quality of islanding detection of inverter-based generation systems [1].

#### 1.1 The Function of High-Power Inverters in LS-PV-PP

Large-Scale Photovoltaic Power Plants (LS-PV-PP) represent a sustainable and highly efficient approach to utility-grade solar energy harvesting. These infrastructures generally employ PV module arrays that supply a common DC bus typically operating within a 400V to 700V range which is subsequently interfaced with a central inverter system for precise grid synchronization. In this context, high-power multilevel inverters (MLIs) serve as the fundamental power conversion units, effectively managing capacities ranging from 0.4 MW to 40 MW [3]. Current trends suggest that high-gain switched-capacitor MLIs specifically those using neural network-based selection—are becoming vital for meeting the rigorous grid efficiency standards of 2026 [11].

#### 1.2 Engineering Hurdles and Practical Field Constraints

Multilevel inverters offer better power quality, but they create specific difficulties in the field. The main issue is hardware complexity, which forces the use of more advanced control logic and better thermal management [5]. Designing these systems is a balancing act between several performance targets. It is essential to ensure operational safety, maintain galvanic isolation, and implement effective maximum power point tracking (MPPT) to optimize energy extraction from the PV arrays. Some recent studies have shown that just making clean AC waveforms isn't enough to solve the energy crisis. Theory is not enough, we need to demonstrate the long-term stability of 9-level and 19-level inverter designs with the help of real laboratory stress tests. This form of physical testing alone can ensure that such systems will be able to withstand the severe unpredictable conditions of the real world. The only solution is to transition to hardware realization to ensure that these technologies can support the current energy loads and offer power that is really sustainable. The specific performance metrics and structural trade-offs for these inverter designs are detailed in **Table 1**.



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Fig. 1. Functional Layout of a Comprehensive Solar PV Power Generation Network.

## 2. Categorizing High-Capacity Inverters

High-power inverters have become increasingly popular in the solar industry because they can handle massive DC inputs with very little energy loss. Generally, we classify these systems based on three main pillars: their circuit design (topology), the control systems they use, and their specific modulation techniques.

### 2.1 Current Source Inverters (CSI)

CSI systems work by using a steady flow of current at the start. Despite the fact that these architectures have high operational resilience and high performance in the case of fault tolerance as short circuits, their usage in utility-scale solar projects is limited. This is mainly due to the fact that they are less efficient in comparison to others and that they also demand large and heavy mass components. The resulting large physical footprint reduces their feasibility for high-capacity installations designed for widespread power distribution.

### 2.2 Operational Characteristics of Voltage Source Inverters (VSI)

Within a Voltage Source Inverter (VSI) architecture, the power conversion stage is interfaced with a constant DC voltage source, making it a standard configuration in the renewable energy industry. Such an inclination can be explained by the fact that the system itself is very reliable, its design process is quite simple, and the dynamic response to the changes in load is very high. However, when these architectures are expanded to multi-megawatt utility applications, they often need additional stabilization hardware to provide operational integrity and obtain flawless grid integration. This auxiliary hardware can be used to avoid problems that can occur with such large amounts of power. Despite these limitations, Voltage Source Inverters remain popular with renewable energy engineers, who like them the most because of their ease of operation and reliability.

### 2.3 Structural Framework of Multilevel Inverter (MLI) Systems

MLI technology was developed to fix the shortcomings of older two-level inverters. By utilizing a configuration of stacked DC voltage levels, these systems generate a 'staircase' output waveform that closely approximates a pure sine wave[4]. The direct benefit of selected stacked topology is that power quality is enhanced, and there is reduced thermal and mechanical stress on internal components. Moreover, this design is a big reduction of electromagnetic interference (EMI), which has been a failure mode of high-power systems.

## 3. Core Topology Frameworks For Multilevel Inverter Design

### 3.1 Configurations with a neutral point clamp (NPC)

The NPC topology is also known as a three-level inverter, and is operating on the principle of building an intermediate voltage state at the neutral node, coupled to the DC link via specialized clamping diodes. This is a highly used layout because it has better voltage regulation and high operational efficiency because it shares the voltage stress efficiently among the switching devices. The NPC architecture is able to reduce the  $dv/dt$  gradient across switches to reduce any possible semiconductor degradation and increases the useful life of the power modules, increasing system stability. It is precisely these structural advantages that make NPC designs the preferred design when it comes to high-power industrial systems. Because they handle voltage stress so effectively, they remain a go-to architecture for heavy-duty power conversion.

### 3.2 Frameworks for Cascaded H-Bridge Design

A Cascaded H-Bridge (CHB) design is a design that requires a series of H-bridge units. This design with each individual module operated with a four-switch layout in a typical H-bridge bridge arrangement was often chosen in Large-Scale Photovoltaic Power Plants (LS-PV-PP) since it has a smaller count of semiconductors and less complex DC-link layouts, which reduce the cost of the manufacturing [8]. The CHB architecture is the best to work with high-power solar harvesting due to its features. It gives the efficiency and cost effectiveness required to take massive solar projects out of the design level and into a reality of commercial operation.

### 3.3 Flying Capacitor (FC) Design Architectures

The FC architecture uses a series of capacitors that switch in and out to build the stepped voltage waveform. Though this design is very efficient in reducing switching losses and improving fidelity of waveforms, the design will pose major control complexity. Balancing of a specific capacitor voltage requires a complex and very precise modulation algorithm.

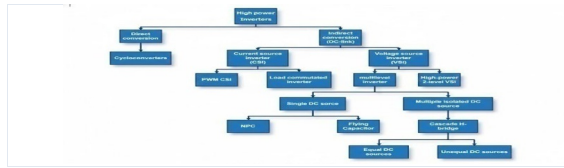


Fig. 2. Categorizing High-Power Inverter Architectures for Solar and Industrial Grids

Table 1: Performance Metrics and Structural Trade-offs of Inverter Designs

Reference	Merits	Drawbacks
[4]	High-quality AC; aids crisis +1	Lab validation hurdles +1
[4]	Low TSV; manages leakage	Poor scaling/dynamics
[8]	Stabilizes DC-link volts	Global balance difficulty
[11]	Single DC; scales to 19-L	Field integration issues
[11]	Low THD; balanced heat	Complex control needed
[12]	Single-stage buck/boost	Filter sizing is critical

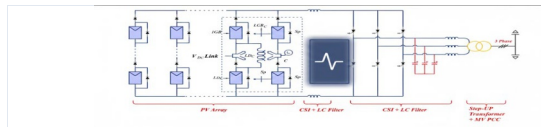


Fig. 3. Standard Operational Layout of a Current Source Inverter (CSI) within a Utility-Scale Solar Infrastructure.

#### 4. Control Methodologies For High-Capacity Converters

The constant stability and systemic performance of Large-Scale Photovoltaic Power Plants (LS-PV-PPs) are inherently connected with the incorporation of the sophisticated control structures [9]. These control systems aim at the monitoring and control of core parameters such as voltage, frequency and current. It is this continuous checking that keeps the whole plant in time with the utility grid even in case of sudden changes.

##### 4.1 Application of Adaptive and Fuzzy Logic Control (FLC) to Grid Stability.

Adaptive frameworks and Fuzzy Logic Control (FLC) work by constantly tuning system variables using live sensor data. This iterative process is what allows the inverter to stay stable and react quickly to unexpected changes in the grid environment..FLC is especially effective at mitigating power oscillations caused by stochastic weather patterns and shifting environmental variables. It should be observed, however, that these control methodologies may encounter performance thresholds when subjected to extremely high-frequency electrical transients.

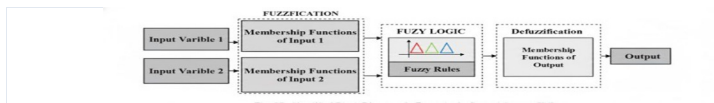


Fig. 4. Schematic of the Decision-Making Architecture and Operational Sequence within a Fuzzy Logic Control (FLC) Framework.

##### 4.2 Advanced Model Predictive Control (MPC) and Associated Variants

Model Predictive Control (MPC) has emerged as a prominent methodology owing to its remarkable capability to preserve system stability amidst highly stochastic operational environments [12]. Its fundamental advantage is the inherent capacity to regulate flying

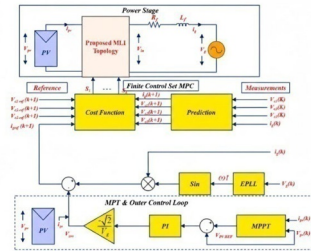
capacitor voltages while simultaneously suppressing Total Harmonic Distortion (THD) autonomously, thereby eliminating the requirement for supplemental hardware components.

**4.3 Executing Finite Control Set Model Predictive Control (FCS-MPC) in Hardware**

The FCS-MPC variant is particularly noted for its high-precision tracking and nearly instantaneous dynamic response. When applied to ANPC topologies, it can manage multiple control goals through a single processing agent. This makes it incredibly efficient at handling transitions during unexpected system faults.

**Performance Comparison :**

The method used in this study has some big advantages over the usual systems found in research. It can really reduce the total harmonic distortion, or THD, without making the hardware more complicated. Some earlier studies on Space Vector PWM, or SVPWM, showed it was about 15.5% better than SPWM for the main output. The FCS-MPC methodology, as detailed in Table 2, demonstrates superior performance characterized by significantly faster current tracking response and a more robust neutral-point balancing capability. This is a big deal because it means the system can work more efficiently and accurately. A significant advantage of the FCS-MPC framework is its ability to realize these performance gains without necessitating additional physical hardware complexity. Overall, the study shows that the FCS-MPC method is a significant improvement over the standard systems.



**Fig. 5.** Control Logic and Signal Flow for the FCS-MPC Scheme in Grid-Connected PV Units.

**Table 2:** Performance Benchmarking and Trade-off Analysis of Various Control Methods

Ref.	Control Strategy	Technical Advantages & Merits	Design Complexity	Application in LS-PV-PP Systems
[2]	Optimized LVRT	Ensures plant remains online during temporary voltage dips.	Medium	Essential for meeting 2026 Grid Code standards.
[3]	Fault Protection / Rapid Shutdown	Stopping power suddenly is crucial for protecting equipment from big spikes in the power grid.	Medium	Critical for grid-connected systems requiring special fault protection.
[10]	Virtual Voltage Vector	Effectively dampens circulating currents while optimizing THD.	Medium	Optimized for 3L-NPC central inverter setups.
[11]	Robust Deadbeat MPC	Delivers high-precision Neutral Point (NP) stabilization.	Medium	Optimized for multi-source, high-gain converter topologies.
[12]	Model Predictive (MPC)	High-speed current tracking; achieves autonomous capacitor balancing.	High	Targeted for multi-level VSI current regulation.
[12]	Adaptive Power Control	Guarantees stable operation even during partial shading of PV arrays.	High	Ideal for managing unbalanced PV string outputs.

**5. The strategies for enhancing maximum power point tracking in Large scale Photovoltaic systems**

The MPPT algorithms need to extract as much power as possible out of the panels. They keep the system at its peak even as sunlight levels and temperatures change during the day.

**Smart Tracking Methods:** The controller uses AI-based techniques—specifically Fuzzy Logic, Neural Networks, and Particle Swarm Optimization[6],[7]—to handle difficult grid conditions. These advanced techniques enable the system to change dynamically in case the standard linear tracking cannot locate the peak power point.

These tools are highly effective at identifying the optimal power point, particularly during challenging conditions like partial shading. This ensures the system remains efficient even under non-ideal circumstances. Using these smart techniques is the only way to keep the system at peak output when weather and sunlight levels are constantly shifting. This ensures that the inverter doesn't lose efficiency during sudden cloud cover or temperature spikes.

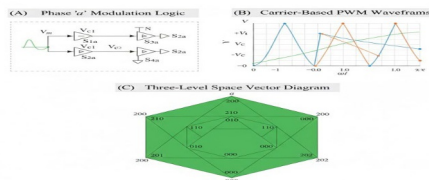
**Hybrid Methods:** Combining different algorithms, like linking FLC with the standard P&O method, results in a more adaptable system. This setup bridges the gap between fast response times and the need for precision once the peak power point is reached.

### 6. Precise Modulation Techniques for High-Efficiency Power Conversion

In high-power inverter design, the real challenge is managing the trade-off between energy efficiency and how the system actually performs under load. Getting this right is critical for any industrial-scale application. The primary objective is the simultaneous mitigation of switching losses and the minimization of Total Harmonic Distortion (THD). For Large-Scale Photovoltaic Power Plants (LS-PV-PPs), specific modulation frameworks are selected for their capacity to enhance grid synchronization and waveform fidelity. This ensures the delivery of high-quality power suitable for grid integration. By optimizing these parameters, such modulation schemes serve as a critical factor in the overall performance enhancement of the conversion system.

One of the well-known principles is Sinusoidal Pulse Width Modulation (SPWM), in which a sinusoidal reference wave is compared with power carrier signals with high frequencies in order to produce switching pulses [13]. This principle is popular because of its simple implementation and good harmonic attenuation, whereas it is a solid criterion in converting power. Its simplicity and consistent performance have established SPWM as a preferred option for basic output control in various inverter applications.

- Space Vector PWM (SVPWM) represents three-phase voltages as a single rotating vector within a complex hexagonal plane [10]. A primary advantage of the SVPWM technique is its ability to provide a fundamental output voltage approximately 15.5% higher than traditional SPWM, while simultaneously mitigating thermal stress on power switches and minimizing torque pulsations.
- Selective Harmonic Elimination (SHE) is an advanced modulation strategy that involves solving transcendental non-linear equations to suppress specific low-order harmonics. While this technique yields superior power quality, its real-time application is often constrained by high computational intensity, which may exceed the processing capabilities of standard digital controllers. Although SHE ensures high spectral purity and efficiency, the complexity of the underlying calculations remains a significant implementation challenge for hardware with limited processing power. A comprehensive evaluation of these modulation schemes for utility-scale PV systems is presented in **Table 3**.



**Fig. 6.** Comparative Visual of Multicarrier PWM Waveform Generation and the Associated Space Vector Hexagon for Three-Level Topologies.

**Table 3: Evaluation Of Modulation Schemes For Utility-Scale PV**

Modulation Strategy Harmonic Mitigation Conversion Efficiency Implementation Complexity Application Suitability in Utility-Scale Solar

Modulation Technique	Harmonic Performance	Voltage Utilization	Design Complexity	Primary Application & Industry Context
SPWM	Moderate	Moderate	Low	Primarily chosen for its design simplicity in low-to-medium power configurations.

SVPWM	Superior	Exceptional	Moderate	Current industry benchmark for achieving high-power, utility-grade grid stability.
SHE / SHEPWM	Highly Targeted	Exceptional	High	The best choice for systems with strict regulatory requirements needing precise elimination of low-order harmonics.

### 7. Current Implementation Barriers and Future Development Paths

While the technological evolution of high-power inverters is substantial, various practical impediments persist, effectively steering the trajectory of future engineering research.

- **Architectural and Design Constraints:** The elevated component density—particularly the dependence on expansive switch arrays, capacitors, and diodes—intrinsically increases design complexity and the initial capital expenditure for utility-scale installations.
- **Scalable Efficiency:** Although modern technology has improved, switching and conduction losses remain a major problem. These inefficiencies can substantially degrade the cumulative performance of the power plant when scaled to meet industrial-grade demand requirements.
- **Computational Latency:** The implementation of sophisticated control architecture, including FCS-MPC requires a large processing overhead. Otherwise, such a computational load may cause latency, which may affect the reliability of the real-time operation of the system.

The Way Forward: Future research efforts ought to focus on the incorporation of the AI-based control systems in order to boost real-time adaptive solutions. In addition to the inverter itself, it is necessary to develop superior cooling, and enhance Battery Energy Storage System (BESS) connections. It is these upgrades that will eventually enable the grid to be tough enough to meet variable loads of the sun.

### 8. Concluding Remarks

As the world moves towards renewable increasingly, the selection of inverter design and the control configuration is now more than ever before. The success of large-scale solar depends heavily on which hardware and software configurations we prioritize today. Recent research underscores the methodologies required to align power electronics capabilities with escalating global energy demands through 2026. It highlights two key technologies: advanced FCS-MPC and AI-integrated MPPT. These advanced methodologies significantly outperform conventional control schemes, providing the requisite stability and efficiency for utility-scale solar installations. This shift is a significant step toward making modern power grids truly sustainable. By using AI and advanced control schemes, we can push PV plant efficiency high enough to actually keep up with the world's growing need for power. This book represents an unambiguous direction on how to use such technologies to create a more sustainable energy future. With AI-powered MPPT and the implementation of FCS-MPC, we will be able to have a more stable and efficient grid. These advances are essential towards reducing our dependence on fossil fuels and achieving carbon reduction goals in the world.

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