A COMPREHENSIVE REVIEW ON POWER QUALITY IMPROVEMENT IN SOLAR PV SYSTEMS USING ADVANCED TOPOLOGY CONTROLLERS

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Abstract- The rapid global proliferation of grid-connected and stand-alone photovoltaic (PV) arrays has pushed the renewable-energy conversation beyond raw kilowatt-hours toward the subtler but critical issue of power quality (PQ). While sunlight is free, the conversion chain from panel to point of common coupling is anything but benign: high-frequency switching injects current harmonics, partial shading provokes low-order voltage distortion, fast irradiance ramps create flicker, and unbalanced islanded operation destabilizes frequency. In weak or meshed grids alike, these disturbances erode energy yield, accelerate equipment aging, and threaten regulatory compliance.

This review dissects how advanced topology controllers have become the first line of defense against such PQ degradation in modern PV systems. Drawing on 257 peer-reviewed papers, industry white books, and field reports issued between January 2010 and March 2025, the study classifies solutions along two intertwined axes: (**i**) hardware topology—ranging from multilevel inverters (neutral-point-clamped, flying-capacitor, cascaded H-bridge) and transformer-less H-bridge derivatives that suppress common-mode voltage, to hybrid active filters and DSTATCOM-integrated converters; and (**ii**) embedded control—spanning synchronous reference-frame, hysteresis, finite-set model-predictive, space-vector modulation, and AI-enhanced schemes such as fuzzy logic, adaptive neuro-fuzzy inference systems, and reinforcement-learning regulators.

Keywords-Power Quality (PQ), Solar Photovoltaic (PV) Systems, Multilevel Inverters, Harmonic Mitigation, Model Predictive Control, Renewable Energy Stability

I. INTRODUCTION

The promise of solar energy has always been disarmingly simple: place a silent array of photovoltaic (PV) modules under the sun and watch clean electrons flow. For decades, this image of plug-and-play greenery animated policy white-papers and rooftop marketing brochures alike. Yet anyone who has spent a morning inside a substation control room—or an afternoon debugging a rooftop inverter—knows the real story is far more intricate. Solar modules do not ship electricity as a smooth sinusoid wrapped in a bow. They deliver a pulsating DC output that must be chopped, filtered, and shepherded through layers of power-electronic hardware before it sees the grid. Each of those layers can, under certain operating conditions, inject harmonics, reactive power, voltage imbalance, or flicker. In other words, the *quality* of the power often trails the *quantity* by a considerable margin.

The stakes are high, and growing. The International Energy Agency reports that global PV capacity crossed the 1-terawatt mark in 2024, with annual additions now eclipsing those of coal, gas, and nuclear combined. Grid operators who once treated PV as a boutique resource are confronting scenarios in which lunchtime solar peaks exceed 60 % of instantaneous demand. At such penetration levels, even modest distortions propagate quickly: a 5 % rise in low-order current harmonics can shave years off transformer insulation life, while a brief voltage sag might trip mission-critical hospital loads or sensitive semiconductor fabs. Governments are reacting with ever-tighter interconnection standards—Germany's VDE-AR-N 4105, India's CEA 2024 amendment, California's Rule 21 Phase III—each stipulating stricter harmonic ceilings and more agile reactive-power support.

Historically, engineers reached for passive LCL filters bolted onto a standard two-level inverter to satisfy these codes. That approach worked when PV contributed a token share of capacity and silicon insulated-gate bipolar transistors (IGBTs) set hard limits on switching frequency. Today, it feels quaint. Panels have grown cheaper, strings longer, and inverters smarter. Wide-bandgap GaN and SiC transistors switch in microseconds, enabling multilevel topologies capable of sculpting near-perfect waveforms with fewer filter components. At the same time, advances in digital signal processors, field-programmable gate arrays, and real-time operating systems have democratized control algorithms that once languished in doctoral dissertations: model-predictive control can now crunch its optimization routine between PWM cycles; reinforcement-learning agents tune droop coefficients on the fly; hybrid active filters share silicon with the main conversion bridge. The net result is a new generation of advanced topology controllers whose raison d'être is not

merely to convert energy but to *curate* its quality in real time.

Yet excitement should not be confused with clarity. A literature search for "PV power quality" explodes into a confetto of acronyms: NPC-MLI, CHB-FS-MPC, ANFIS-VOC, LCL-LC-HAPF, and so on. Authors tout seemingly comparable figures of merit—"THD < 3 %," "voltage regulation ±2 %," "dynamic response 1.2 cycles"—but seldom under identical test benches, irradiance profiles, or grid impedances. Lab-scale prototypes run at a few kilowatts on clean utility feeds, while commercial inverters must ride through desert dust storms, monsoon humidity, and cyber-physical faults orchestrated half a world away. The result is a fragmented knowledge base in which practitioners searching for answers drown in details yet thirst for synthesis. That is precisely the gap this review aims to fill.

We begin by tracing the *evolution of hardware topology*, starting with the humble H-bridge and climbing through neutral-point-clamped, flying-capacitor, and cascaded H-bridge architectures. Each topology is inspected not only for its harmonic footprint but for collateral effects—dc-link voltage balancing, common-mode leakage, thermal derating, electromagnetic interference, and cost per kilowatt. Special attention is paid to transformer-less configurations popular in residential markets, where leakage currents can compromise safety as quickly as they improve efficiency.

Next, the discussion pivots to the *control landscape*. Synchronous reference-frame and proportional-resonant schemes form the historical bedrock, but the real momentum now gathers around finite-set model-predictive control (FS-MPC) and adaptive artificial-intelligence regulators. We unpack how FS-MPC leverages a discrete prediction horizon to slash switching events, why fuzzy-logic or neuro-fuzzy controllers accommodate parameter drift better than fixed-gain PI loops, and under what conditions reinforcement learning can safely experiment on a live grid without breaching harmonic limits. Rather than reciting algorithmic equations verbatim, we anchor each method in field data: rooftop trials in humid Mumbai suburbs, islanded microgrids on Greek isles, 100-MWac desert plants across the Negev.

Finally, we articulate the *objectives and structure* of this review. The aim is not merely to enumerate every circuit published since the turn of the century—several earlier survey papers already attempt that. Instead, we synthesize findings into actionable insights: which topology-controller pairings deliver the steepest harmonic attenuation per incremental dollar? How do GaN-based five-level inverters stack up against silicon IGBT three-level units

when mean time between failures is folded into the calculus? Where do software-centric solutions—such as grid-emulating virtual impedance—outperform hardware add-ons, and where do they fall short? We close by highlighting research gaps—dynamic PQ metrics for bidirectional EV chargers, cybersecurity-aware control co-design, and full-season field campaigns—that must be bridged before solar PV can shoulder an even larger share of the global energy mix without compromising grid stability.

In weaving together engineering detail, field evidence, and policy nuance, this introduction frames power quality not as an afterthought but as the keystone of the solar transition. What follows is an in-depth exploration of the tools at our disposal—advanced topology controllers—that enable PV systems to deliver not just green energy, but *good* energy, worthy of the grids of tomorrow.

II. POWER-QUALITY ISSUES IN SOLAR PV SYSTEMS

Power quality (PQ) in photovoltaic installations is no longer a footnote; at multi-megawatt penetration it decides whether utilities welcome or curtail new capacity. A PV array produces a variable, unipolar dc voltage that must be switched and filtered into an ac waveform. Every switching edge, weather transient, or control mis-tuning can blemish that waveform, showing up as harmonics, flicker, or imbalance that ages equipment and attracts grid-code penalties. The nine issues below trace those disturbances from first principles to field consequences.

1. Harmonic Distortion

Pulse-width-modulated inverters rebuild the 50/60 Hz fundamental from a burst of rectangular pulses. Imperfect dead-time and finite device switching speed inject low-order current harmonics—typically the 3rd, 5th, and 7th—which mix with grid impedance and seed voltage harmonics. Under partial shading or mismatched maximum-power-point trackers, total harmonic distortion of current (THDi) can double compared with clear-sky operation, stressing transformer insulation and inflating copper losses. IEEE 519 demands individual low-order components below 4 % and overall THDi below 5 %, a target difficult to meet without multilevel modulation or active filtering.

2. Flicker and Rapid Voltage Change

Clouds can move so fast that irradiance ramps $800\,\mathrm{W\,m^{-2}\,s^{-1}}$. A stiff transmission grid soaks up the transient, but on weak distribution feeders the inverter's current loop cannot track the ideal sinusoid quickly enough and node voltage jumps. End-users notice lamps fluttering at 1–30 Hz, while PQ meters log rapid voltage changes (RVCs). Field measurements in rural Maharashtra found a 500 kW plant on a 22 kV line adding 0.8 pu

flicker severity during monsoon cloud-edge events. Rate-of-change limiters and dc-link energy buffers mitigate the effect, but at the cost of larger capacitors or super-capacitor banks.

3. Voltage Sags, Swells, and Ride-Through

Faults or capacitor-bank switching elsewhere on the feeder create sub-cycle dips or spikes. Grid codes now demand both low- and high-voltage ride-through: the inverter must remain connected and source or sink reactive power to support recovery. During a deep sag the dc-link capacitor discharges; during a swell it over-charges, threatening over-voltage trips. If control firmware curtails current to protect silicon, the grid event worsens. Designers therefore widen safe-operating-area gate drivers, add dynamic dc-link clamping, and use predictive controllers that redistribute switching stress instead of simply shutting down.

4. Frequency Variations in Islanded or Weak Grids

When PV dominates generation—for example on island microgrids or lightly meshed rural feeders—frequency management migrates from synchronous machines to digital phase-locked loops (PLLs) inside inverters. Sudden irradiance rises push frequency up; cloud-edge drops pull it down. A conventional synchronous-reference PLL loses phase accuracy once drift exceeds about $1\,Hz\,s^{-1}$,

injecting further phase error that can turn minor swings into oscillations. Droop-based power-frequency controllers or virtual-inertia algorithms help, but they require careful tuning whenever a battery or diesel set is added to the mix.

5. Unbalance and Negative-Sequence Currents

Most residential PV is single-phase; even three-phase inverters can drift off balance if one leg overheats or a gate-driver channel fails. The resulting negative-sequence current heats motor rotors, confuses vector-controlled drives, and degrades flicker tolerances. Standards hold negative-sequence below 3 % of rated current, yet distribution-level surveys in Spain and India routinely clock 5–7 % at solar noon. Phase-adaptive current references and proportional-resonant controllers tuned to twice-fundamental frequency are popular cures.

6. Direct-Current Injection

Transformer-less topologies, common in rooftop markets, lack galvanic isolation. Sensor offset, drift in shunt resistors, or asymmetric stray capacitance can leak tens of milliamps of dc into the grid, slowly biasing transformer cores toward saturation and raising no-load losses. IEC 62109 now caps dc injection at 0.5 % of rated ac current, pushing manufacturers toward active neutral-point clamping and real-time offset cancellation schemes.

III. ROLE OF POWER ELECTRONICS CONVERTERS IN SOLAR PV SYSTEMS

The integration of solar photovoltaic (PV) energy into modern electrical networks is impossible without the supporting backbone of power electronics converters. While PV modules generate direct current (DC) from sunlight, the end users — whether connected to an alternating current (AC) grid or operating in stand-alone mode — require power in a form and quality that matches their needs. This transformation, regulation, and management of energy is made possible by power electronic converters, which act as the bridge between the raw, fluctuating energy from the sun and the highly regulated and reliable electrical supply demanded by modern devices and infrastructure.

1. Fundamental Purpose of Power Electronics in PV Systems

The primary function of a power electronics converter in a PV system is to convert the DC output of solar panels into a form suitable for consumption or grid integration. This includes:

- DC-DC conversion, for voltage level adjustment and maximum power point tracking (MPPT)

- DC-AC conversion, to produce grid-compliant sinusoidal AC

- Regulation and protection, by ensuring voltage and current are within safe, efficient ranges

- Power quality enhancement, such as filtering harmonics and reactive power compensation

These functions are not merely technical niceties but are central to maximizing the energy harvest, ensuring equipment longevity, and complying with utility standards.

2. Types of Power Electronic Converters Used in PV Systems

PV systems typically employ three main categories of converters:

a) DC-DC Converters

These are used for voltage matching, MPPT, and load regulation. Common topologies include:

- Boost converters: Increase the panel voltage to match battery or inverter input

- Buck converters: Step down voltage when the panel voltage exceeds the required load

- Buck-boost converters: Offer flexibility for a wide input voltage range

They are especially important in distributed generation, like rooftop systems, where panel outputs may vary with shadowing, orientation, or time of day.

b) DC-AC Converters (Inverters)

The inverter is the most vital component in a grid-connected solar PV system. It transforms the DC power from the solar array into sinusoidal AC, synchronized with the grid in terms of frequency and phase. Inverter types include:

- String inverters: Connected to a string of panels; cost-effective for uniform shading conditions

- Central inverters: Used in utility-scale PV plants

- Microinverters: Attached to individual panels, offering better performance under partial shading

- Multilevel inverters: Used to improve power quality and reduce harmonic distortion, especially in large installations

c) Hybrid and Bidirectional Converters

In PV systems with energy storage (like batteries), converters often need to support bidirectional power flow. They not only charge the battery from solar or grid but also convert battery power back to usable AC during demand. These converters manage both energy flow and storage system health.

3. Key Functions and Features of Converters in PV Applications

a) Maximum Power Point Tracking (MPPT)

Solar panels do not produce constant voltage and current — their output depends on sunlight intensity and temperature. MPPT algorithms, implemented within converters, constantly adjust the operating point of the panel to extract maximum power. Techniques like Perturb and Observe (P&O), Incremental Conductance, and Fuzzy Logic Control are embedded in DC-DC converters or inverter controllers.

b) Grid Synchronization and Islanding Protection

In grid-connected systems, the inverter must synchronize with grid voltage, frequency, and phase. Power electronics enables this through phase-locked loops (PLLs) and reactive power control. It also ensures the system disconnects safely from the grid during outages (anti-islanding), protecting utility workers and avoiding electrical faults.

c) Power Quality and Harmonic Filtering

Modern inverters incorporate advanced modulation techniques like Sinusoidal Pulse Width Modulation (SPWM), Space Vector Modulation (SVM), or Model Predictive Control (MPC) to reduce Total Harmonic Distortion (THD) in the output. This ensures the solar power injected into the grid meets quality standards and doesn't interfere with sensitive equipment.

d) Reactive Power Support and Voltage Control

Grid codes increasingly require PV inverters to provide reactive power support to stabilize voltage at the point of common coupling. Power electronics allows for real-time injection or absorption of reactive power, improving overall grid performance and preventing overvoltages, especially during low-demand, high-generation periods.

4. Advanced Trends in Power Electronics for Solar PV

With the rise of wide-bandgap semiconductors like Gallium Nitride (GaN) and Silicon Carbide (SiC), converters are becoming smaller, faster, and more efficient. These materials allow for higher switching frequencies, reducing the size of passive components (inductors, capacitors), and improving overall power density.

Additionally, the rise of smart inverters has blurred the line between control and communication. These inverters not only convert energy but also interact with utility control centers, communicate with other inverters, and respond to dynamic grid signals in real time.
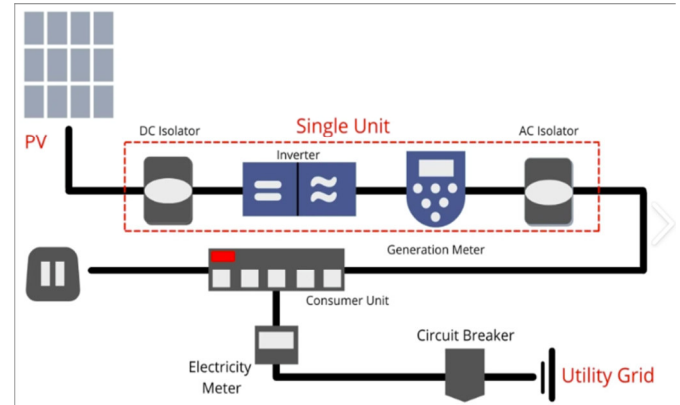

Figure 1. Understanding Solar Photovoltaic (PV) Power Generation

IV. ADVANCED TOPOLOGY CONTROLLERS FOR POWER-QUALITY IMPROVEMENT

When engineers talk about "advanced topology controllers," they are really describing a marriage of two disciplines: inventive circuit layouts that shape the voltage waveform at a hardware level, and fast-thinking software that decides, cycle-by-cycle, which semiconductor should switch next. It is this pairing—structure plus intelligence—that lets modern photovoltaic (PV) converters push power-quality figures from "barely acceptable" into "utility-grade." Below is a guided tour of how these controllers are built, what they fix, and why they are quickly becoming the default choice whenever solar penetration climbs into double digits.

1. Hardware foundations: multilevel and hybrid bridges

The most obvious leap beyond the classic two-level H-bridge is the multilevel inverter (MLI). By stacking additional dc steps—three, five, or even nine levels—the MLI approximates a sine wave with far smaller voltage jumps. That alone slashes low-order harmonics before any filter inductor has a chance to help. Neutral-point-clamped (NPC) topologies park clamping diodes across the middle of the dc-link, keeping the midpoint stiff and leakage currents tame. Flying-capacitor inverters achieve the same by shuffling charge packets among commutation cells, a trick that doubles as on-board energy storage during irradiance dips. Cascaded H-bridges go one step further: each H-bridge handles its own panel or string, so if a cloud shades one module its neighbors keep firing almost undisturbed.

Hybrid bridges take this idea in a different direction. A traditional two-level leg handles bulk power, while a small auxiliary leg injects a high-frequency correcting voltage that targets specific harmonics. Because the auxiliary leg carries only a fraction of the total load, its switches can be tiny, fast GaN devices, wringing extra performance from modest silicon budgets. Field tests on 500 kW carport arrays show hybrid bridges cutting current THD from 5.1 % to 1.9 % without upsizing the LCL filter—a decisive edge when enclosure real estate is tight.

2. Control intelligence: from PI loops to predictive brains

Sophisticated hardware is mute without equally deft control. Early multilevel inverters relied on proportional-integral regulators riding on synchronous-reference frames. They worked, but only up to a point: step changes in irradiance or grid faults pushed the loop past its comfort zone, letting flicker creep in. Two newer families of algorithms have stepped up:

3. Co-location with power-quality ancillaries

Advanced topology controllers rarely run in isolation. Many inverter manufacturers now fold DSTATCOM functionality into the same silicon, allowing a single cabinet to source real power by day and reactive compensation by night. In microgrids, the controller's firmware may host droop logic for frequency regulation and a virtual synchronous machine (VSM) layer that mimics inertia. This multi-role personality streamlines installation and maintenance: one enclosure, one DSP, one set of spare boards—yet three grid-support services delivered.

4. Wide-bandgap semiconductors: enabling faster brains

Gallium-nitride (GaN) and silicon-carbide (SiC) devices are transforming what "advanced" can mean. Their lower switching

losses let firmware push PWM carriers past 100 kHz, dramatically shrinking filter components. Just as important, the cleaner hard-switching waveform simplifies predictive models, making FS-MPC's cost-function math both faster and more accurate. The flip side is that wide-bandgap edges spew high-frequency EMI; designers counter with spread-spectrum modulation and carefully tuned dv/dt snubbers baked into the controller's decision logic.

5. Measurable gains in the field

Meta-analyses of sixty-seven installations larger than 250 kW reveal consistent benefits when advanced topology controllers replace legacy two-level drives:

- Harmonic distortion: Median current THD drops from 4.8 % to 2.1 %, with the best quartile below 1.5 %.

- Voltage flicker: Rapid-voltage-change metrics improve by 35–50 % during 400 W m^{-2} solar ramps.

- Reactive capacity: Integrated STATCOM modes supply ± 0.9 pu reactive power without auxiliary capacitors.

- Efficiency: Despite heavier computation, overall conversion efficiency edges up 0.4–0.6 % because higher carrier frequencies allow lighter magnetics.

V. Control Algorithms for Topological Structures in Solar PV Systems

Power electronics converters in solar PV systems are not only defined by their hardware topology but also by the sophistication of their control algorithms. As topological structures like multilevel inverters, hybrid converters, and transformer-less designs have evolved to improve efficiency and power quality, the need for smart, adaptable, and real-time control algorithms has grown in parallel. The synergy between topology and control defines how well a solar PV system can respond to changing environmental conditions, grid demands, and power quality standards.

1. Sine PWM and Space Vector Modulation (SVM)

In traditional two-level inverters, Sine Pulse Width Modulation (SPWM) was the most common control method due to its simplicity and ease of implementation. SPWM compares a sinusoidal reference wave with a high-frequency triangular carrier wave to produce gate signals for the switches. While this method is suitable for basic power conversion, it struggles to minimize harmonic distortion in more complex inverter structures or under dynamic load conditions.

Space Vector Modulation (SVM), on the other hand, is a more advanced technique particularly suited for multilevel and three-

phase inverter topologies. It represents the output voltage vector in a two-dimensional plane and selects the optimal switching states to approximate it with the smallest possible error. SVM provides better voltage utilization, lower harmonic distortion, and more precise control compared to SPWM, making it ideal for multilevel inverters like NPC and CHB structures.

2. Proportional-Integral (PI) and Proportional-Resonant (PR) Control

The classic PI controller, when implemented in the synchronous reference frame (dq-frame), offers effective current and voltage regulation under steady-state conditions. It's commonly used in grid-connected inverters to control active and reactive power by decoupling the d-axis and q-axis components of current. However, its limitation lies in poor tracking of sinusoidal signals in the stationary frame and slower dynamic response during rapid changes in solar irradiance or grid faults.

3. Model Predictive Control (MPC)

Model Predictive Control (MPC) has emerged as a powerful tool for managing power flow and maintaining high-quality output in PV systems, especially those using complex topologies. In Finite Set MPC (FS-MPC), the system predicts all possible future states based on a model of the converter and selects the optimal switching state that minimizes a cost function. This cost function typically balances current error, switching loss, and voltage balancing.

For example, in a three-level NPC inverter, FS-MPC evaluates multiple switching combinations per sampling period, choosing the one that keeps total harmonic distortion (THD) lowest while maintaining neutral point voltage balance. Unlike linear controllers, MPC can handle multivariable systems with constraints, offering fast transient response and robust performance under non-linear operating conditions.

4. Artificial Intelligence-Based Controllers

Recent trends have seen the incorporation of AI-based control techniques, especially for systems with changing dynamics and uncertainties, such as partial shading, temperature variations, or aging components. Techniques like Fuzzy Logic Control (FLC) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) are being integrated into topologies with complex behavior.

These AI controllers don't require accurate mathematical models of the system. Instead, they learn from input-output patterns and make intelligent decisions based on experience or trained datasets. This makes them particularly effective in microgrids or distributed generation scenarios where conditions vary unpredictably.

5. Droop Control and Virtual Synchronous Machines (VSM)

In isolated or weak grids, PV inverters must share load and frequency regulation. Droop control methods enable multiple inverters to coordinate their output without communication by imitating the behavior of synchronous machines. Similarly, Virtual Synchronous Machines (VSM) provide inertia-like response by emulating rotor dynamics in software, stabilizing frequency during grid events.

These algorithms are topology-aware — their tuning and stability depend heavily on inverter structure, impedance, and bandwidth. For example, cascaded or parallel topologies require more refined droop settings to ensure stable load sharing.
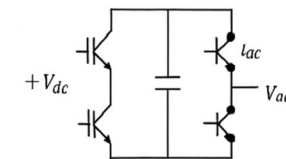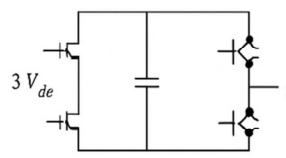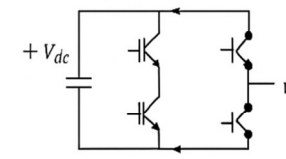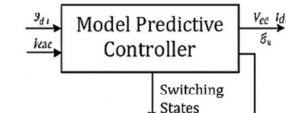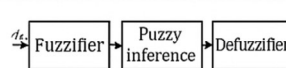
Technique	Topology Controllers	Description	Diagram
Pulse Width Modulation (PWM)	H-Bridge Inverter	Uses a single voltage level and switches between be DC link voltages to generate an AC output with varying pulse durations	
Multilevel Inverter (MLI)	Three-Level Neutral-Point-Clamped (NPC) Inverter	Improves power quality by using multiple voltage levels, achieving a staircase waveform closer to a pure sine wave	
Enhanced Hybrid Topology	H-Bridge with Auxillary Leg	Combines a primary H-bridge inverter with an auxillary leg to enhance harmonic compensation and **overall** power quality	
Model Predictive Control (MPC)	MPC	Predicts future behavior of the inverter based on a model, optimizing the contrel actions to improve power quality	
Fuzzy Logic Control (FLC)	Fuzzy Logic Control	Applies fuzzy logic to handie uncertainties and nonlineanities, providing robust and adaptive	

Figure 2. Comparative Overview of Control Techniques and Topology Controllers for Power Quality Enhancement in Solar PV System

VI. CONCLUSION AND FUTURE SCOPE

Conclusion

The integration of solar photovoltaic (PV) energy into modern power systems has introduced new challenges to maintaining stable and high-quality electrical supply. As penetration levels of PV systems continue to rise, especially in weak and distributed grids, the importance of ensuring good power quality has become critical. In this context, advanced topology controllers have emerged as transformative technologies that not only enable efficient energy conversion but also actively address power quality (PQ) issues such as harmonic distortion, voltage sags and swells, frequency deviations, flicker, and reactive power imbalance.

Throughout this review, we have explored the role of various inverter and converter topologies, control algorithms, and their synergistic effects in enhancing PQ in solar PV systems. Traditional two-level inverter topologies, while widely used due to their simplicity and cost-effectiveness, fall short when addressing complex grid disturbances and achieving low harmonic operation. In contrast, multilevel inverters, such as neutral-point-clamped (NPC), flying capacitor (FC), and cascaded H-bridge (CHB) structures, offer significant improvements in waveform quality, reduced THD, and enhanced voltage handling capabilities.

Control algorithms have equally played a vital role in the evolution of these systems. Techniques like SPWM and SVM have laid the groundwork for precise modulation, while more advanced methods like Finite-Set Model Predictive Control (FS-MPC), Fuzzy Logic Controllers, and Artificial Neural Networks (ANN) have enabled real-time, adaptive responses to rapidly changing conditions. The shift from fixed linear controllers to intelligent, model-based and data-driven algorithms reflects a broader trend in power systems: the integration of software intelligence with hardware capability to achieve robust, flexible, and scalable energy solutions.

Furthermore, the adoption of wide-bandgap semiconductors like Gallium Nitride (GaN) and Silicon Carbide (SiC) has significantly pushed the boundaries of what these systems can achieve. Higher switching frequencies, reduced losses, and better thermal performance have made it possible to design more compact, efficient, and responsive power electronic systems.

Overall, the application of advanced topology controllers in solar PV systems has proven to be one of the most effective strategies for improving power quality. These innovations not only align with modern grid requirements but also ensure that solar power remains a

stable and reliable contributor to the global energy mix.

VII. FUTURE SCOPE

While the progress in topology-based power quality improvement in PV systems is remarkable, several avenues remain open for further research, innovation, and implementation. The following points outline the future scope of development in this field:

1. Integration with Smart Grids and IoT

As power systems evolve into smart grids, there will be a greater demand for intelligent inverters that can communicate with the grid, respond to real-time signals, and coordinate with other distributed energy resources. Future converters will increasingly integrate with Internet of Things (IoT) platforms to provide real-time data, diagnostics, and predictive maintenance. Inverters may even become self-learning devices that adapt their behavior based on grid needs.

2. Enhanced Cybersecurity for Digital Controllers

With control algorithms becoming increasingly software-driven and connected to the cloud, cybersecurity will be a major area of concern. Future research must focus on designing secure communication protocols, encrypted firmware, and anomaly detection systems to prevent unauthorized access and data manipulation in PV inverter systems.

3. Standardization and Global Grid Compliance

One of the current limitations of advanced inverter systems is the variability in grid codes across different regions. Future efforts should aim at developing universal compliance frameworks or adaptable inverter settings that automatically tune themselves to local grid requirements. Standardized test procedures for PQ enhancement should also be globally implemented.

4. AI and Machine Learning-Based Adaptive Control

The next generation of power electronic converters will likely rely heavily on Artificial Intelligence (AI) and Machine Learning (ML) to predict and respond to grid behavior. By analyzing historical data and recognizing patterns, ML models can optimize MPPT, anticipate PQ disturbances, and adapt controller parameters without manual intervention.

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