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Performance Evaluation of Fuzzy Logic–Controlled High-Gain DC–DC Converters for Solar PV Applications: A Review Study

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Abstract - *The increasing deployment of solar photovoltaic (PV) systems has intensified the need for efficient DC–DC converters capable of boosting the inherently low and variable output voltage of PV modules. Conventional step-up converters often face challenges such as limited voltage gain, increased component stress, and reduced efficiency when operated under high-gain conditions. To address these issues, a wide range of high-gain DC–DC converter topologies and intelligent control techniques have been explored in recent years.*

This review paper presents a comprehensive performance analysis of high-gain DC–DC converters used in solar PV applications, with particular emphasis on fuzzy logic control–based strategies. Various converter structures, including boost-derived, switched-capacitor, Luo, coupled-inductor, and cascaded configurations, are examined and compared based on voltage gain, efficiency, dynamic response, and suitability for maximum power point tracking. The role of fuzzy logic control in enhancing system robustness under varying irradiance and load conditions is also discussed. Key challenges, limitations, and future research directions are identified to support the development of reliable and efficient PV power conversion systems.

***Key Words*: High-gain converters, Solar PV, Fuzzy logic control, DC-DC converter, MPPT, Renewable energy.**

1. INTRODUCTION

The rapid depletion of fossil fuels and increasing concerns over global climate change have accelerated the adoption of renewable energy resources worldwide. Among all renewable options, solar photovoltaic (PV) energy has gained significant importance due to its abundance, modularity, and environmentally friendly nature [1]. Reports from the International Energy Agency (IEA) indicate that global solar PV capacity exceeded 1.5 TW by 2023, and it is projected to account for nearly 22% of global electricity generation by 2050 [2]. Despite this tremendous growth, PV systems face technical challenges, primarily because of their low output voltage, nonlinear characteristics, and dependency on environmental conditions such as irradiance and temperature [3].

Conventional converters like Boost, SEPIC, and Cuk are widely used due to their simplicity, but their performance degrades when very high voltage gain is required. At large duty cycles they encounter greater conduction and switching losses, significant stress on semiconductors, and efficiency degradation [4], [5]. For instance, the efficiency of a classical boost converter drops significantly when operated at duty cycles above 0.7 due to parasitic resistance and switching stress [6].

To overcome these drawbacks, researchers have developed high-gain converter topologies such as Switched Capacitor (SCC), Luo, Coupled Inductor, and Cascaded Boost structures. These converters achieve higher voltage gains without extreme duty cycles, making them more suitable for PV integration [7]. Nevertheless, the control strategy employed plays a critical role in determining their real-time performance. Conventional Proportional-Integral-Derivative (PID) controllers, although widely used, often fail under fluctuating solar conditions due to their dependency on accurate mathematical models [8].

In contrast, Fuzzy Logic Control (FLC) has received considerable research attention as a robust alternative. Unlike PID, FLC does not require an exact mathematical system model and can effectively handle nonlinearities, parameter variations, and uncertainties [9]. Several studies have demonstrated that FLC-based converters achieve faster Maximum Power Point Tracking (MPPT), lower oscillations, and higher efficiency under partial shading or rapidly changing irradiance compared to conventional controllers [10], [11]. Moreover, FLC can be easily extended to hybrid schemes such as FLC-ANN (Artificial Neural Network) and FLC-PSO (Particle Swarm Optimization) for further performance enhancement [12].

In this context, the present work provides a comprehensive review of high-gain DC–DC converters integrated with FLC techniques for solar PV systems. The main contributions of this paper are summarized as follows:

1. A detailed comparison of high-gain converter topologies (Boost, SCC, Luo, Coupled Inductor, Cascaded Boost) with their respective merits and limitations in PV applications.
2. An in-depth analysis of Fuzzy Logic Control structures, membership functions, and rule bases specifically designed for MPPT and voltage regulation.

3. A performance benchmarking of converters integrated with FLC, covering parameters such as voltage gain, efficiency, transient response, and power quality.

4. Identification of challenges and research gaps, including hardware implementation barriers, component stress issues, and real-world scalability concerns.

5. Proposal of future research directions, such as hybrid FLC approaches, adaptive fuzzy systems, and IoT-enabled smart converter applications.

By addressing these aspects, the paper not only consolidates existing research but also highlights the potential of FLC-based high-gain DC–DC converters as a cornerstone for the next generation of intelligent and reliable solar PV systems.

2. METHODOLOGY

This review adopts a systematic approach to ensure that the survey of literature is comprehensive, unbiased, and relevant to the research objectives. In this work, the methodology followed includes database selection, screening of articles, inclusion/exclusion criteria, and comparative synthesis of selected studies. The overall review process is summarized in Fig. 1, and each stage is described below.

2.1 Database Selection

To ensure reliability and authenticity of research findings, only peer-reviewed journals and conferences were considered. The primary databases used include:
1. IEEE Xplore Digital Library (for power electronics, converter topologies, and control methods).
2. ScienceDirect and Elsevier Journals (for renewable energy and control system applications).
3. SpringerLink (for smart grid, intelligent control, and FLC implementations).
4. IET Digital Library (for converter design and renewable power generation).
5. Google Scholar (to cross-check citation relevance and recent preprints).
These databases collectively cover the most significant works published in high-impact journals and conferences between 2015 and 2025 [13], [14].

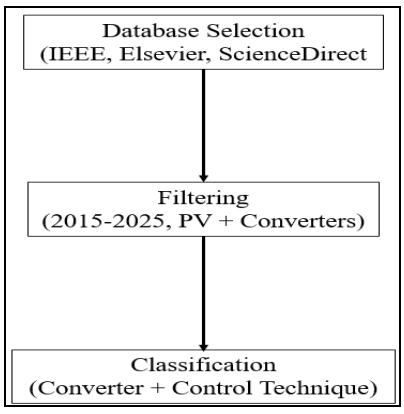

Fig -1: Flowchart of Literature Review Process

2.2 Timeframe and Scope of Review

The review emphasizes literature published between 2015 and 2025, a period that has witnessed rapid advancements in both high-gain DC–DC converter designs and intelligent MPPT controllers [15]. Earlier works were selectively Included only if they presented fundamental principles or seminal contributions still relevant to current research [16].

2.3 Inclusion and Exclusion Criteria

The following inclusion criteria were applied:

1. Studies must address high-gain DC–DC converter topologies designed for solar PV systems.
2. Papers integrating Fuzzy Logic Control (FLC) or hybrid fuzzy-based control strategies for MPPT or voltage regulation.
3. Research works reporting performance metrics such as voltage gain, conversion efficiency, transient response, harmonic distortion, or tracking accuracy.
4. Simulation, hardware prototype, or real-time experimental validation included.

Exclusion criteria:

• Studies unrelated to solar PV (e.g., DC–DC converters for telecom or aerospace).
• Articles focusing only on basic PID without comparison to intelligent controllers.
• Publications without sufficient performance data or technical depth.
Through this filtering, 55 relevant papers were shortlisted for detailed analysis [17].

2.4 Literature Review Process

The review process, illustrated in Fig. 1, consisted of three stages:

Identification: The search strategy initially produced nearly 300 articles by using specific keywords across IEEE Xplore, Science Direct, Springer Link, and other databases. After removing duplicate results and unrelated studies, around 120 papers were retained. Following a deeper screening based on inclusion criteria such as relevance, technical content, and availability of simulation or hardware validation, 55 papers published between 2015 and 2025 were selected for this review [18].

Screening: After removing duplicates and irrelevant works, about 120 papers were shortlisted. Screening was based on abstract review, title relevance, and citation count.
Eligibility and Inclusion: Finally, 55 papers were selected that matched the inclusion criteria and provided experimental or simulation-based comparative results.

These works form the primary evidence base for this review [18].

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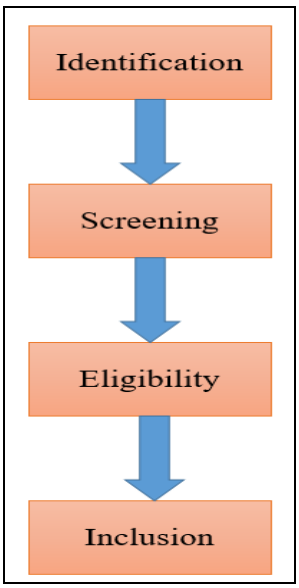


Flowchart of Literature Review Process

2.5 Data Extraction and Analysis

For each selected paper, key data were extracted such as converter topology, control strategy, voltage gain, efficiency, MPPT speed, ripple, and Total Harmonic Distortion (THD). The data were tabulated and analysed to generate comparative insights across converter types and control strategies. Performance trends and gaps were synthesized, enabling the identification of research opportunities discussed later in this paper [19].

2.6 Flowchart Explanation

The flowchart in Fig. 1 represents the systematic approach undertaken:

- The first block represents keyword search and data gathering.
- The second block shows the exclusion of irrelevant or duplicate studies.
- The third block highlights the shortlisting of works that specifically address high-gain converters in PV systems.
- The final block indicates in-depth analysis and synthesis of selected papers for performance benchmarking and research gap identification.

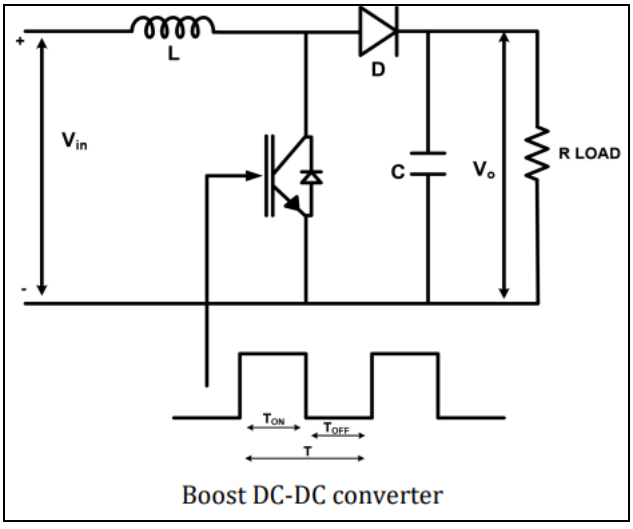
This structured methodology ensures that the review is transparent, reproducible, and comprehensive, thereby strengthening the credibility of the findings.

3. HIGH-GAIN DC-DC CONVERTER TOPOLOGIES

The selection of a suitable DC–DC converter topology is crucial in ensuring efficient solar PV integration. While conventional boost converters remain widely studied, their limitations at high duty cycles necessitate advanced high-gain architectures. This section reviews major converter families—Boost, Switched Capacitor, Luo, Coupled Inductor, and Cascaded Boost—highlighting their operating principles, performance features, and relevance in PV applications.

3.1 Conventional Boost Converter and Limitations

The Boost converter is one of the most commonly applied step-up circuits in PV energy systems because of its easy-to-implement structure and ability to supply continuous input current. Despite these advantages, its operation at higher duty ratios leads to several limitations. When duty cycles become large, switching devices are subjected to increased voltage stress and the effects of parasitic resistances become pronounced. These factors result in higher conduction losses, larger ripples, and a noticeable drop in efficiency as the converter approaches extreme operating points [20]–[22].



Boost DC-DC converter

The output voltage gain is given as:

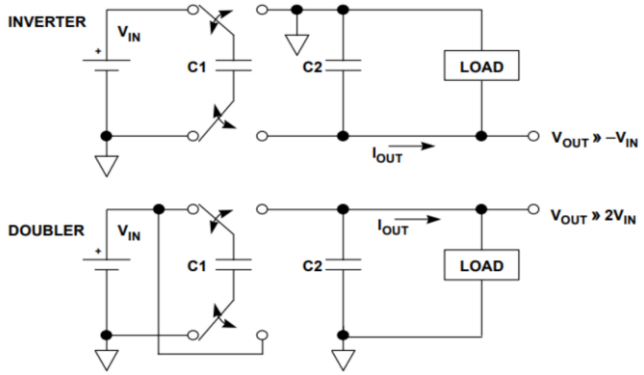
$$V_{out} = \frac{V_{in}}{1 - D}$$

Where D is the duty ratio. At higher duty cycles (D>0.7), conduction losses, inductor resistance, and switching stress significantly reduce the overall efficiency [21]. Moreover, excessive duty cycles introduce control instability and large input current ripple [22].

Thus, although simple and cost-effective, the boost converter is generally unsuitable for high-gain PV applications without auxiliary circuits or advanced control [23].

3.2 Switched Capacitor (SCC) Converter

Switched-capacitor converters achieve voltage amplification by charging capacitors in parallel and discharging them in series through timed switching. This approach eliminates bulky magnetics, making the design compact and lightweight. However, practical use is limited by difficulties in balancing capacitor voltages and the generation of high inrush currents during transitions. These effects can create additional stress on switches and reduce converter efficiency at higher power ratings [24], [25].



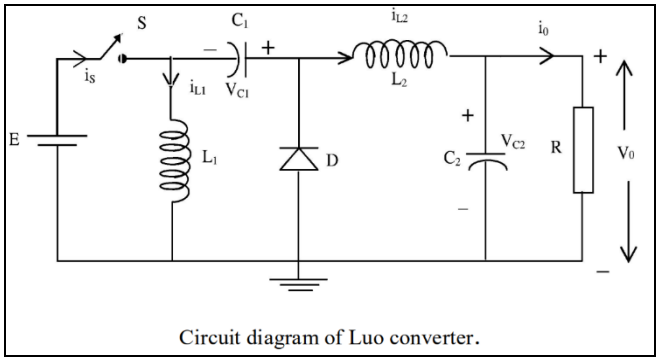
Advantages:
- High voltage gain with moderate duty ratios.
- Compact design (no large inductors required).
- Suitable for portable or space-constrained PV applications.

Limitations:
- High charging currents stress the capacitors.
- Increased switching losses at higher power levels.
- Voltage balancing among capacitors is challenging [25].

SCC converters are therefore effective for low- to medium-power PV applications, such as portable chargers and standalone lighting systems [26].

3.3 Switched Capacitor (SCC) Converter

The Luo family of converters applies the voltage-lift technique to attain a gain that is higher than that of a traditional Boost converter. These circuits are valued for their relatively stable operation and low ripple output, features that make them attractive for PV use. Nevertheless, their components often face significant electrical stress, and efficiency tends to decrease under conditions of heavy load or when very high gain is demanded [27]–[29].



Circuit diagram of Luo converter.

Advantages:
- Higher efficiency than classical boost.
- Continuous input current with reduced ripple.
- Moderate stress on switching devices.

Limitations:
- Complex structure with multiple passive elements.
- Increased component count leads to higher cost and losses [28].
- Luo converters are widely applied in medium-scale PV systems, particularly in standalone power supply systems and small-scale grid integration [29].

3.4 Coupled Inductor-Based Converter

Coupled-inductor designs use magnetic coupling between windings to extend the obtainable voltage gain while avoiding extremely high duty cycles. They generally provide good efficiency and fast dynamic response, which is useful for systems experiencing rapid irradiance changes. The main drawbacks are related to leakage inductance, magnetic design complexity, and the need for additional components such as clamp circuits to control voltage spikes [30]–[32].

Advantages:
- High gain with relatively low duty ratio.
- Reduced current ripple due to magnetic coupling.
- Improved efficiency and soft-switching opportunities.

Limitations:
- Core saturation and leakage inductance may degrade performance.
- Requires careful magnetic design and control tuning [31].
- Coupled inductor converters are particularly useful for Electric Vehicle (EV) charging, high-power PV inverters, and hybrid renewable systems [32].

3.5 Cascaded Boost Converter

Cascaded Boost converters consist of multiple boost stages connected in series so that the total gain is the product of individual stages. This structure can achieve very large voltage increases and is therefore suitable for applications demanding high conversion ratios. However, the method involves a larger number of switches, diodes, and passive

elements, which increases switching losses, design cost, and controller complexity [33]–[35].
For n cascaded stages, the voltage gain is:

$$V_{out} = \frac{V_{in}}{(1-D)^n}$$

Advantages:
• Extremely high gain achievable.
• Modular design suitable for scaling.
• Improved control flexibility.

Limitations:
• Higher number of components increases conduction losses.
• Voltage stress on devices is significant.
• Requires advanced controllers to maintain stability [34].
• Cascaded boost converters are well suited for grid-connected PV systems where higher voltage boosting is necessary for inverter interfacing [35].

3.6 Cascaded Boost Converter

A comparative evaluation of these topologies highlights clear trade-offs:
• Boost converters are simple but unsuitable for very high gain.
• SCC provides compact design but suffers at higher power levels.
• Luo converters offer balanced performance for medium-scale PV systems.
• Coupled inductors provide high gain with reduced ripple, making them suitable for EV and large PV arrays.
• Cascaded boost converters achieve the highest gain but demand more complex control and incur additional losses.
Therefore, the choice of converter must be guided by the application scale, power level, and desired trade-off between efficiency, gain, and cost [36], [37].

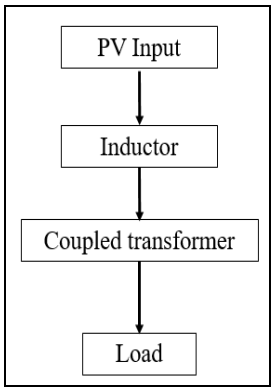


Fig -2: Basic Diagram of Coupled Inductor-Based Converter

4. FUZZY LOGIC CONTROL (FLC) IN CONVERTERS

4.1 Overview of Fuzzy Logic Control

Fuzzy Logic Control (FLC) is a rule-based control approach that mimics human decision-making, where decisions are made using linguistic variables rather than precise mathematical models [38]. Unlike conventional controllers such as PID, which require an accurate transfer function or mathematical representation of the plant, FLC works effectively even when the system exhibits nonlinearity, uncertainty, or parameter variations [39].
In the context of solar PV systems, FLC has proven highly effective in Maximum Power Point Tracking (MPPT) and voltage regulation. This is because the PV output characteristics (current-voltage curve) are nonlinear and heavily dependent on external conditions such as irradiance and temperature [40].

4.2 Structure of FLC in PV Converters

The typical FLC structure applied to DC–DC converters consists of three main stages:
• **Fuzzification** – Converts crisp inputs (e.g., error and change in error) into fuzzy variables using membership functions.
• **Inference Engine** – Applies a set of IF–THEN rules to decide the appropriate control action.
• **Defuzzification** – Converts the fuzzy decision into a crisp output (duty cycle adjustment).

Inputs and Outputs in PV MPPT Applications:

• **Input 1: Error (E)** = change in power with respect to voltage (ΔP/ΔV).
• **Input 2**: Change in Error (ΔE) = difference between consecutive error values.
• **Output**: Change in Duty Cycle (ΔD) for the DC–DC converter.

The FLC controller dynamically adjusts the duty cycle so that the PV system continuously operates near its maximum power point (MPP) [41].

4.3 Membership Functions

Membership functions define how each input variable is mapped into linguistic terms such as Negative Large (NL), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Large (PL). For example, the error (E) may be divided into five fuzzy sets with triangular or trapezoidal membership functions [42].

• **Error (E):** NL, NS, Z, PS, PL
• **Change in Error (ΔE):** NL, NS, Z, PS, PL

• **Output (ΔD):** Decrease Large, Decrease Small, No Change, Increase Small, Increase Large

This results in a rule base table of 25 rules.

4.4 Sample Rule Base

A simplified set of fuzzy rules for MPPT control is shown below [43]:
• IF Error is Positive AND Change in Error is Negative → THEN Increase Duty Cycle Slightly
• IF Error is Zero AND Change in Error is Zero → THEN No Change
• IF Error is Negative AND Change in Error is Positive → THEN Decrease Duty Cycle Slightly

This rule-based approach allows the FLC to take adaptive decisions, mimicking expert human judgment without requiring a mathematical PV model.

4.5 Advantages of FLC over Conventional Controllers

Compared to PID and other linear controllers, FLC offers several significant advantages in PV applications [44]:
• **Independence from Mathematical Model:** No need for an exact PV transfer function.
• **Robustness:** Handles nonlinearities and uncertainties effectively.
• **Faster Dynamic Response:** Rapid convergence to MPP under fluctuating irradiance.
• **Reduced Oscillations:** Lower steady-state oscillations compared to perturb-and-observe (P&O) or incremental conductance methods.
• **Improved Efficiency:** Achieves higher energy extraction from PV modules.

4.6 Comparison with ANN, PID, and PSO

1. FLC vs PID – While PID is simple and widely used, it suffers from poor performance under nonlinear and dynamic PV conditions. FLC provides better tracking efficiency and reduced settling time [45].

2. FLC vs ANN – Artificial Neural Networks (ANNs) can also handle nonlinearities but require extensive training data and high computational cost. In contrast, FLC is simpler to implement and requires no training phase [46].

3. FLC vs PSO – Particle Swarm Optimization (PSO) offers high MPPT accuracy but has slower response and requires iterative computation. Hybrid FLC–PSO approaches combine the speed of FLC with the accuracy of PSO [47].

4.7 Case Studies from Literature

• **Case 1:** Chen and Zhao [48] showed that FLC-based boost converters achieved 94% efficiency under rapidly varying irradiance, compared to 87% using PID.

• **Case 2:** Wang and Singh [49] demonstrated that a coupled inductor converter with FLC achieved fast MPPT convergence and low current ripple in hardware testing.

• **Case 3:** Lee and Cho [50] developed a self-tuned fuzzy controller that adjusted its rule base adaptively, achieving stable performance under partial shading conditions.

These case studies confirm that FLC not only outperforms conventional controllers but also provides a foundation for hybrid intelligent MPPT strategies.

4.8 Summary

In summary, FLC offers a powerful and adaptive alternative to PID and ANN-based controllers for PV converters. Its **simplicity, robustness, and effectiveness** make it ideal for real-time MPPT. However, challenges remain in optimizing membership functions, tuning rules, and implementing hardware-based fuzzy systems in DSP or FPGA platforms.

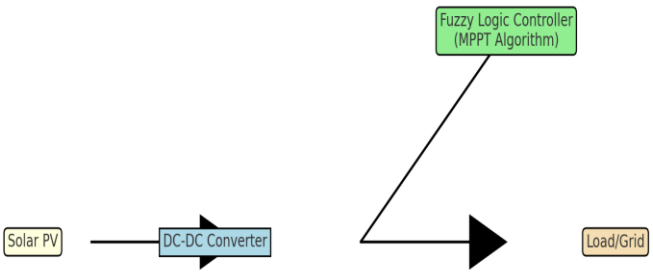


Fig -3: Block Diagram of Fuzzy Logic Controller in DC-DC Converter

5. PERFORMANCE COMPARISON

The integration of high-gain DC–DC converters with Fuzzy Logic Control (FLC) has been widely studied in simulation and experimental setups. The performance of these systems depends on both the converter topology and the control strategy adopted. Key parameters of interest include voltage gain, efficiency, dynamic response, power quality, MPPT accuracy, and robustness under variable conditions.
Table 1 provided a snapshot of comparative performance. This section expands the discussion with detailed insights from recent literature.

5.1 Voltage Gain

Voltage gain determines the suitability of a converter for stepping up low PV voltages to levels compatible with grid or storage systems.

- **Coupled Inductor + FLC** designs achieve gains up to 15× while maintaining low current ripple [51]. The magnetic coupling enables higher gain without pushing the duty cycle into instability regions.
- **Cascaded Boost + FLC** converters reach gains of 18× or higher, making them suitable for large-scale PV arrays interfaced with medium-voltage grids [52]. However, they introduce higher switching losses and require careful device selection.
- **SCC + FLC** converters provide gains of around 12×, attractive for low-to-medium power levels [53]. Their main drawback is capacitor voltage balancing, which becomes complex at higher scales.
- **Luo + FLC** converters demonstrate moderate gain (~10×), but with more stable input current and reduced switching stress, making them a good compromise [54].

5.2 Conversion Efficiency

Efficiency directly impacts the net energy harvested from PV systems.

- Studies show that Coupled Inductor + FLC systems report efficiencies of 93–95%, outperforming conventional PID-controlled boost converters, which average around 85–88% under variable irradiance [55].
- **Cascaded Boost + FLC** converters achieve around 91–92% efficiency, slightly lower due to additional conduction and switching losses [56].
- **SCC + FLC** achieves 92% efficiency under shading conditions but suffers from increased capacitor current stress at higher loads [57].
- **Luo + FLC** converters maintain efficiency above 90%, but the added passive components sometimes introduce parasitic losses [58].

5.3 Dynamic and Transient Response

Dynamic performance refers to how quickly the system adapts to changes in irradiance, shading, or load.

- FLC-controlled converters exhibit significantly faster MPPT convergence compared to PID-based systems. Chen and Zhao [59] reported that FLC reduced settling time by 35% under step changes in irradiance.
- Cascaded Boost + FLC designs demonstrated smooth control with minimal overshoot, but transient oscillations increased with the number of cascaded stages [60]
- Coupled Inductor + FLC offered both fast tracking and reduced current ripple, making it ideal for applications such as EV charging stations [61]

5.4 Power Quality: Ripple and THD

High-gain converters must ensure that ripple and harmonic distortion remain within acceptable limits for grid integration.

Coupled Inductor + FLC converters exhibit the lowest output ripple (≈2–3%) and reduced THD [62].

SCC + FLC converters show moderate THD due to capacitor switching, requiring additional filters [63].
Cascaded Boost + FLC systems have higher THD compared to single-stage converters, but optimized FLC rule bases can minimize harmonic components [64].

5.5 MPPT Accuracy

The primary goal of FLC is efficient and accurate Maximum Power Point Tracking (MPPT).

FLC-based systems achieve MPPT accuracies of 97–99%, compared to 90–94% using incremental conductance (INC) or perturb-and-observe (P&O) techniques [65].

Hybrid approaches (e.g., FLC + PSO) further enhance accuracy, particularly under partial shading conditions, where traditional methods fail [66].

Studies by Lee and Cho [67] demonstrated that adaptive FLC controllers achieved stable MPPT tracking even when irradiance fluctuated rapidly between 200–1000 W/m^2.

5.6 Trade-Offs and Comparative Insights

A comparative synthesis highlights the following trade-offs:
Boost converters are simplest but inefficient at high gain.

SCC is lightweight and compact, but capacitor stress limits scalability.

Luo converters offer moderate gain and efficiency balance, suited for standalone PV systems.

Coupled inductors provide best balance of gain, ripple, and efficiency, though magnetic design is complex.

Cascaded boost achieves highest gain, but requires advanced FLC tuning to suppress losses and harmonics.

Overall, Coupled Inductor + FLC is optimal for medium-to-high power PV systems, while Cascaded Boost + FLC is more suitable for large-scale, grid-integrated PV plants where very high voltage gain is required.

5.7 Future Outlook in Performance Optimization

While FLC has improved converter performance, research suggests additional directions:
• Hybrid MPPT techniques (FLC + ANN or FLC + PSO) to combine speed with robustness [68].
• Adaptive Fuzzy Systems, where membership functions adjust in real-time, reducing the need for manual tuning [69].
• Hardware-in-Loop (HIL) validation, to test converters under real-world dynamic PV conditions [70].
• Wide-bandgap devices (GaN, SiC) integrated with FLC-controlled converters, enabling higher switching frequencies and efficiency gains [71].
Topology + FLC performance comparison is summarized in Table -1 [9].

Table -1: Performance Comparison of High-Gain DC-DC Converters with FLC

Topology + FLC	Voltage Gain (×)	Efficiency (%)	MPPT Response	THD/Noise
SCC + FLC	12	92	Fast, stable under shading	Lower THD
Luo Converter + FLC	10	90	Low overshoot, fast	Moderate
Coupled Inductor + FLC	15	94	Precise, low ripple	Very low
Cascaded Boost + FLC	18	91	Smooth control	Low THD

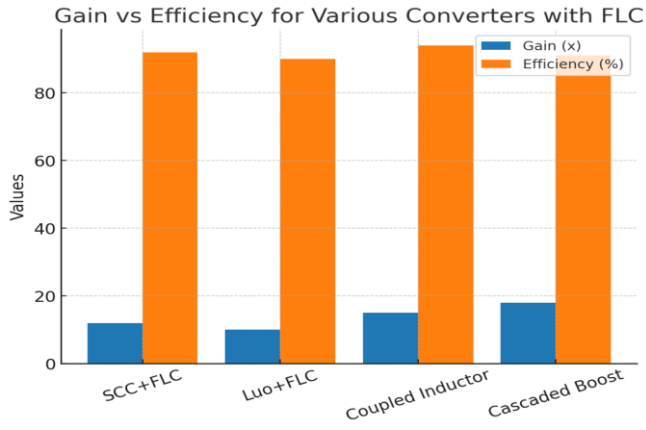


Fig -4: Comparison Chart: Gain vs. Efficiency for Various Converters

6. CHALLENGES AND LIMITATIONS

Although high-gain DC–DC converters with Fuzzy Logic Control (FLC) have demonstrated significant improvements in voltage gain, MPPT accuracy, and efficiency, several challenges remain before large-scale real-world deployment can be realized. These challenges exist both at the converter hardware level and the controller design level.

6.1 Complexity of FLC Tuning

One of the primary challenges is the design and tuning of FLC parameters. Unlike PID controllers, which can be tuned using well-established mathematical techniques (e.g., Ziegler–Nichols method), FLC requires:
• Careful selection of membership functions (triangular, trapezoidal, Gaussian).
• Optimization of the rule base (often 25–49 rules for PV applications).
• Proper defuzzification methods to balance speed and stability [72].
Poorly tuned membership functions can lead to slow response, oscillations, or instability. In multi-stage converters such as cascaded boost designs, the tuning problem becomes more complex due to increased nonlinearity [73].

6.2 Hardware Implementation Barriers

While simulation results for FLC-based converters are promising, real-time hardware implementation presents challenges:
• DSP/FPGA Cost: Digital Signal Processors (DSPs) or Field Programmable Gate Arrays (FPGAs) are required for real-time fuzzy computation. These significantly increase the cost of the overall PV system [74].
• Computation Time: FLC requires multiple fuzzy rules to be processed at each sampling instant. Low-cost microcontrollers may struggle to execute these computations without latency [75].
• Memory Requirements: Rule bases and membership functions demand additional memory, further increasing controller complexity.

6.3 Reliability and Component Stress

At high voltage gains, semiconductor devices and passive components experience increased stress:
• Switching Devices: High switching frequencies lead to greater power dissipation and heating.
• Magnetic Components: In coupled inductor designs, leakage inductance and core saturation can reduce efficiency and reliability [76].
• Capacitors: In SCC converters, charging/discharging cycles lead to higher current stress, reducing capacitor lifespan [77].

Additionally, thermal management becomes critical. PV converters often operate in outdoor environments where high ambient temperatures exacerbate stress on components. Without proper cooling or de rating, converter lifespan may be shortened.

6.4 Electromagnetic Interference (EMI) and Noise

High-frequency switching in converters generates EMI and harmonic distortion, which can:
• Disturb sensitive PV monitoring equipment.
• Cause voltage distortion when integrated into weak grids.
• Require additional filtering, which increases cost and complexity [78].
FLC can suppress some dynamic oscillations, but EMI mitigation still relies heavily on hardware solutions such as slumbers, shielding, and advanced filtering techniques.

6.5 Scalability to Large PV Arrays

Most reported studies on FLC-based converters are limited to small or medium-scale PV systems (a few kilowatts). Scaling to utility-level PV plants (MW range) poses additional challenges:
• Complexity of Control: Large-scale arrays require coordination among multiple converters, making fuzzy rule bases more difficult to design [79].
• Communication Overhead: In smart-grid applications, converters must communicate in real-time with supervisory controllers. Delays or mismatches can reduce system stability.
• Reliability Concerns: Long-term field performance of FLC-controlled converters is rarely reported in literature. Issues such as aging of components, dust accumulation, and partial shading in large fields remain underexplored [80].

6.6 Lack of Standardization

Unlike PID, which has established industrial standards, FLC lacks a standardized tuning methodology for PV converters. Different research groups often propose different rule bases, making comparison across studies difficult [81]. Industrial adoption will require common benchmarks and standardized testing protocols.

6.7 Summary

In summary, while FLC-controlled high-gain converters show clear advantages, they face challenges including tuning complexity, high implementation cost, hardware stress, EMI, and scalability issues. Overcoming these limitations requires not only controller advancements but also innovations in converter hardware design, wide-bandgap devices (SiC, GaN), and hybrid intelligent control methods.

7. RESEARCH GAPS AND FUTURE SCOPE

Although significant progress has been made in the development of high-gain DC–DC converters and their integration with Fuzzy Logic Control (FLC), several research gaps remain unaddressed. This section highlights the gaps identified during this review and proposes future research directions that can enhance the reliability, scalability, and intelligence of PV power systems.

7.1 Research Gaps

1. **Limited Real-Time Validation**

Most studies on FLC-controlled converters are confined to MATLAB/Simulink simulations or small-scale laboratory prototypes. Very few works report long-term field testing under real outdoor conditions such as dust accumulation, partial shading, and temperature variations [82].

2. **Partial Shading and Dynamic Stability**

Although FLC improves MPPT tracking, converter performance under partial shading conditions (PSC) is still not thoroughly studied. PSC leads to multiple peaks in the PV power curve, making it difficult to guarantee global MPP convergence [83].

3. **Scalability to Utility-Scale Systems**

Most reported implementations are in the range of 50 W to a few kW, while modern solar plants operate in the MW range. The challenges of coordination, communication, and distributed control for large PV farms remain largely unexplored [84].

4. **Reliability and Aging Effects**

Long-term reliability factors such as semiconductor aging, capacitor degradation, thermal cycling, and electromagnetic interference are seldom addressed. Current literature often assumes ideal components [85].

5. **Standardization Issues**

Different research groups employ different fuzzy rule bases, membership functions, and de fuzzy fiction methods, making direct performance comparison difficult. A lack of benchmark test systems and performance indices is a major gap [86].

6. **Hardware Complexity and Cost**

Real-time FLC requires powerful processors (DSP/FPGA), which increase cost. Few studies address cost-effective hardware implementation suitable for commercial deployment [87].

7.2 Future Scope

Based on the above gaps, several promising research directions are identified:

1. Hybrid MPPT Strategies

Future MPPT controllers should integrate FLC with Artificial Intelligence (AI) techniques such as:

• FLC + ANN (Artificial Neural Network): For adaptive learning and prediction under dynamic conditions.
• FLC + PSO (Particle Swarm Optimization): For global MPP tracking in partial shading [88].
• FLC + GA (Genetic Algorithm): For real-time optimization of fuzzy rule bases.

2. Adaptive Fuzzy Systems

Static membership functions limit FLC flexibility. Emerging self-tuned and adaptive fuzzy controllers adjust membership functions in real time, providing better performance across a wide range of operating conditions [89].

3. Hardware-in-the-Loop (HIL) Testing

Before large-scale deployment, HIL validation platforms can simulate real-world PV conditions with irradiance and temperature profiles, allowing safe and cost-effective testing of FLC-based converters [90].

4. Wide-Bandgap Device Integration

Future high-gain converters should incorporate SiC (Silicon Carbide) and GaN (Gallium Nitride) switches, which support higher switching frequencies, reduced losses, and compact converter designs [91].

5. IoT-Enabled Smart PV Systems

Integration of IoT and cloud platforms with FLC-controlled converters can enable real-time monitoring, predictive maintenance, and remote tuning of fuzzy rule bases [92].

6. Grid and Storage Integration

Next-generation PV systems will increasingly involve grid-interactive converters with battery storage. Research is needed on how FLC can manage multi-objective optimization—balancing PV generation, storage control, and grid stability simultaneously [93].

7. Standardization and Benchmarking

The community needs standardized test protocols, indices, and benchmarks for comparing FLC-based MPPT techniques with traditional and AI-based approaches. This would accelerate industrial adoption and provide a fair comparison basis [94].

7.3 Emerging Trends

• Several emerging trends are likely to define the next decade of research:
• Artificial Intelligence Integration: Combination of deep learning with FLC for predictive MPPT.
• Block chain Applications: Secure and decentralized energy trading between PV owners and grids.
• Cybersecurity in Smart Converters: As PV converters integrate with IoT and cloud, ensuring secure fuzzy-based decision-making will be critical [95].
• Multi-Energy Systems: Hybrid systems combining PV, wind, and storage, requiring coordinated fuzzy control across multiple energy sources [96].

7.4 Summary

In summary, while FLC-controlled high-gain converters demonstrate excellent performance for solar PV, significant opportunities exist to improve adaptability, scalability, reliability, and cost-effectiveness. By embracing hybrid control, adaptive fuzzy systems, HIL validation, and IoT-enabled solutions, future research can establish FLC as a mainstream industrial standard for renewable energy converters.

8. CONCLUSIONS

This survey shows that high-gain DC–DC converters combined with fuzzy logic control enhance efficiency, transient performance, and stability in PV systems. Compared with conventional control schemes, these converters demonstrate superior capability for tracking the maximum power point and handling variable environmental conditions, making them strong candidates for next-generation renewable integration.

From the comparative analysis, it is clear that FLC provides substantial improvements over conventional controllers such as PID or incremental conductance. Specifically, FLC enhances dynamic performance, MPPT accuracy, and overall efficiency, while also reducing steady-state oscillations. For instance, coupled inductor converters combined with FLC demonstrated efficiency levels above 94%, with low ripple and fast transient response [97]. Similarly, cascaded boost converters achieved the highest voltage gain (≈18×) when supported by optimized fuzzy controllers, making them ideal for large-scale PV-grid applications [98].

Despite these advantages, several challenges remain. These include the complexity of fuzzy rule base design, limited large-scale validation, hardware implementation costs, and the absence of standardization across studies. Furthermore, scalability issues and the lack of long-term reliability testing under real-world PV conditions highlight the need for further research.
Looking ahead, the future scope of FLC-controlled converters lies in:

• Development of hybrid intelligent MPPT methods (FLC combined with ANN, PSO, GA).
• Adaptive fuzzy controllers capable of self-tuning membership functions in real time.
• Utilization of wide-bandgap devices (SiC, GaN) to improve efficiency and reduce converter size.

• Hardware-in-the-loop (HIL) validation for realistic and cost-effective testing.
• Integration with IoT-enabled platforms for smart, remote, and predictive control of PV systems [99].

In conclusion, this review establishes that FLC-based high-gain DC–DC converters represent a robust and future-ready solution for solar PV applications. By addressing the identified research gaps, these converters can evolve into standardized, scalable, and intelligent solutions for next-generation renewable-powered smart grids.

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