Journal Européen des Systèmes Automatisés
Vol. 59, No. 6, June, 2026, pp. 1607-1617
Journal homepage: http://iieta.org/journals/jesa

Boost Converter Control Strategies for Photovoltaic: A Comprehensive Comparative Review and Design Perspective

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https://doi.org/10.18280/jesa.590608

Received: 7 April 2026
Revised: 27 May 2026
Accepted: 8 June 2026
Available online: 30 June 2026

Keywords:
solar photovoltaic, maximum power point tracking, boost converter, controller strategies, hybrid optimization

ABSTRACT

This paper aims to present the control strategies of boost converters that help improve the operational efficiency of solar photovoltaic (PV) systems in relation to the variation of the different operating conditions, such as solar irradiance, temperature, partial shading of the PV system, and load disturbances, in a structured and systematic manner. The methods that have been reviewed have been classified into three categories: (i) classical control (example: Proportional-Integral/Proportional-Integral-Derivative (PI/PID) with traditional maximum power point tracking (MPPT)), (ii) intelligent control (example: fuzzy logic, Artificial Neural Network (ANN), Adaptive Neuro-Fuzzy Inference System (ANFIS), and adaptive control), and (iii) hybrid and optimization-aided controllers (example: Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), and Model Predictive Control (MPC)-based methods). The purpose of this synthesis is to consolidate, for the various control methods in the three categories, the most relevant literature, and to compare, for each of the methods, the MPPT tracking efficiency, the convergence/response time, steady-state oscillations, output-voltage ripple, and the control methods' robustness and stability in a fast-changing environment. The synthesis concludes that although classical control methods are appealing because of their simplicity in control and low implementation cost, intelligent control and hybrid control methods tend to be superior as they can converge more quickly and lower the output ripple, especially for partial shading conditions and for highly dynamic irradiance conditions. The review also provides practical selection criteria and future research pertinent to the next generation PV power conditioning systems and further emphasizes the balance that must be made between the complexity of the control, the needed sensing and/ computing, and the performance that can be attained.

1. INTRODUCTION

One of the most innovative solutions to level off the oscillations is to deploy power electronic converters, most notably DC-DC boost converters, to raise the output voltage of the photovoltaic (PV) modules to the desired level for load or grid use. Boost converters are readily integrated into PV systems due to their high efficiency, ease of use, and overall simplicity of the device. Boost converters are operated by varying the duty cycle of the switching device using Pulse Width Modulation (PWM), enabling the PV to track the maximum power point tracking (MPPT) as closely as possible even under varying conditions [1]. In PV applications, the performance and effectiveness of the boost converter are directly linked to the control method and strategy used. Historically, control approaches focused on classical systems, relying on the use of Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers primarily because of their ease of use. However, they are sometimes ineffective under the rapidly changing conditions of the environment. In an attempt to optimize performance, enhancement of systems using MPPT, or maximum power point tracking, using the Perturb and Observe (P&O) and Incremental Conductance (INC) techniques was developed. While MPPT techniques work to improve energy capture, the number of oscillations around the point of maximum power, as well as the overall responsiveness, tends to remain [2]. Meanwhile, intelligent control methods have started to emerge, incorporating Artificial Intelligence and Soft Computing to tackle the nonlinear and time-varying dynamics of PV systems. Controllers like Model Reference Adaptive Control (MRAC), Fuzzy Logic Controller (FLC), and even Adaptive Neuro-Fuzzy Inference System (ANFIS) tend to outperform traditional methods, especially in terms of accuracy and response time during worst-case (partial shading) scenarios. In recent years, new optimization-based hybrid controllers have been combining traditional or intelligent algorithms with optimization methods, fine-tuning each control parameter for the best performance. Controllers such as Improved Grey Wolf Optimizer (IGWO), Particle Swarm Optimization (PSO), BFOA, and PID with PID-SMC (Sliding Mode Control) have shown outstanding performance in controlled simulations and real-life applications. For example, the hybrid GWO-P&O and the GWO-PO combined have displayed efficiencies exceeding 99.84%, impressive convergence rates, and minimal steady state ripple [3]. In almost all comparative studies, the intelligent methods, or hybrid, are shown to be superior than traditional methods with, or more, faster convergence and lower or suppressed ripple. steady-state control, and more robustness to environmental changes. This adds to the reliability, increased energy generation, and longevity for next-generation PV systems, making them essential [4]. With the complexity control systems have, the lack of in-depth analysis on them makes it crucial to perform a systematic comparative review of the performance. This study should not only meet the requirements but also analyse other essential qualities, such as overall efficiency, the time needed for convergence, the stability of the system, the control needed with varying systems in place, and adaptability. This work targets these goals and provides the necessary information to aid researchers, engineers, and system designers to optimize the performance, complexity, and cost control methods be derived or designed [5]. This study focuses on providing a systematic comparative analysis of control strategies pertaining to boost converters within PV systems. Special consideration is given to the operational, implementation, and adaptability aspects of the control strategies with respect to changing environmental conditions. A primary objective of this work is the analysis of traditional, intelligent, and hybrid control strategies and the development of empirical findings, with a view to guiding researchers and system developers, derived from the analysis of performance metrics, including, but not limited to, tracking efficiency, response time, voltage ripple, robustness, and implementation complexity.

1.1 Research gap and novelty

The literature on maximum power point tracking (MPPT) algorithms of PV shows that significant innovations have been made, and the literature on boost converters shows that some innovations have been made as well. Nonetheless, there are still gaps, and the literature shows the following. Most of the available literature uniquely focuses on a few techniques of MPPT and/or a few classes of control techniques and lists the efficiency of the tracking systems as the main measure of performance. However, in the case of a PV boost converter, a multi-faceted control performance is warranted, rather than efficiency, such as, but not limited to, the speed of the system response to the disturbance, the system's output voltage steadiness, the system's response to changes in the environment, destabilizing and fluctuating, the system's ability to adapt to a changing environment, including the phenomenon of partial shading, the system's control performance, and last but not least, the difficulty of implementing the control system. Also, most publications tend to examine, in isolation, the conventional control, the intelligent control, and the optimization-based control, which makes the direct comparison needed for the control selection in a practical system quite complex for researchers and system designers. This review offers a solution to the problem by providing a comprehensive comparative review of control techniques for boost converters used in PV systems, covering conventional, intelligent, and hybrid optimization-based control techniques.

This review contains:

- A systematic comparative review of control techniques for boost converters in PV systems,
- A multi-criteria assessment of control techniques based on tracking efficiency, system response time, output voltage steadiness, system robustness, and ease of control implementation,
- Implementation of control strategies in various operating environments of PV systems, particularly those that are highly dynamic and experience varying degrees of shading,
- An overview of the contemporary constraints, and a guide for future research, in advanced control strategies for PV boost converters.

2. REVIEW METHODOLOGY

This review will be organized to show the relevant studies on control strategies for boost converters within PV systems and how the control strategies have been published and organized on a timeline. Studies published between the years 2000 and 2025 are reviewed from the databases of IEEE Xplore, ScienceDirect, SpringerLink, MDPI, and Google Scholar. The inclusion or exclusion of a study goes through a selection process comprised of three main stages.

2.1 Identification stage

Study publications were located using the following keywords: 'boost converter', 'MPPT control', 'PV control strategies', 'intelligent MPPT', and 'hybrid optimization controllers'.

2.2 Screening stage

Any articles that did not relate to control of the DC-DC boost converter, or articles that did not include metrics for evaluating the performance of converters, were neglected for review.

2.3 Eligibility and selection

Of the preliminary review of over 120 studies, 47 were deemed to be most relevant based on the following criteria.

- Relevance to boost converter control,
- Presentation of performance metrics,
- Validation through experiment or simulation,
- Advancement to MPPT or control optimization.

The focus studies were divided into three primary categories:

- Control strategies that are considered classical,
- Control strategies that include Intelligent methodologies, and
- Control strategies that include Hybrid and/or Optimization-based methodologies.

The studies were evaluated according to the most common Key Performance Indicators (KPIs) of the studies, which include tracking efficiency, time to convergence, voltage ripple, stability, and overall performance when subjected to dynamic changes within the environment. The accepted review methodology sets the parameters for identifying, categorizing, and assessing studies. Using this sort of methodology, the next sections provide a rationale for advanced boost converter control in PV systems, as well as describe the main control strategies found in the literature. Essentially, the current research is a comparative review of published literature as opposed to an empirical study. Consequently, the method is based on systematic collection, description, and comparison of previously reported control strategies and assessment of their reported performance, implementation, and applicability in different conditions of operation.

3. MOTIVATION

The accelerating shift towards renewable energy has facilitated the growth of solar PV technologies as a leading sustainable option for electricity generation. While having its advantages, PV output is susceptible to environmental situational conditions such as irradiance and temperature, which vary constantly, and can cause drastic changes to the output power [6]. Energy harvesting efficiency is low due to the variability of power conditioning, or advanced control solutions not being exercised. The power output of PV cells and the ability to track the MPPT can be tracked using DC-DC boost converters, which are among the most efficacious controller solutions on the market. The focus is not on the device within the PV module. Converters can be optimized, and the control strategy can be tuned for the environment. Simplistic controllers, for example, PID or PI controllers, can be implemented. Such dispreferred solutions are of low relevance to actual market conditions. It lacks sophisticated control functionalities and therefore suffers from high convergence times, excessive voltage ripples, and subsequently low efficiency for rapidly changing conditions [7]. To overcome the cited disadvantages, various MPPT algorithms have been implemented, including INC and P&O, as well as its more sophisticated iterations, M-P&O and MINC, all of which are designed with the aforementioned disadvantages in mind. While there is no disputing the benefit of enhancement in tracking precision, oftentimes these solutions lack the requisite level of responsiveness for rapidly changing atmospheric conditions or partial shading [8]. Systems of control are therefore lacking, which sustains the paradigm of swift action in the field of accuracy with optimal stability. The most recent technical advancements have developed intelligent and hybrid controllers, including MRAC, FLC, and optimization techniques like IGWO with PID-SMC. The results have been astonishing, like with the Hybrid GWO-PO, which achieved 99.84% optimum efficiency, and MRAC with a stunning 0.0032-second convergence time with minimum voltage ripple [9]. The techniques, however, lack a cohesive comparison, which makes it difficult for engineers and researchers to easily find the right option for a particular PV application. To fill this void, the present research offers an in-depth boost converter-based control technique and juxtaposes the techniques on the basis of convergence time, efficiency, voltage ripple, and stability. Synthesizing various studies, this work offers practical design approaches for the control of PV systems, targeting enhanced reliability and energy yield in the field [10].

4. CONCEPT OF MAXIMUM POWER POINT

The definition of MPPT comes from the electrical circuit principle of merging the output and load impedances for the maximum power transfer from the PV cell. With this setup, the system achieves the highest power output. Control techniques—MPPT—try to keep the system working at this "most optimal" level. These algorithms automate the modification of system variables to consider things like temperature and solar irradiance, which greatly impact the location of the maximum power point. The current-voltage (I-V) characteristic of a PV module, as in Figure 1, is non-linear, and the MPPT is the point on the curve at which the power is at its highest.

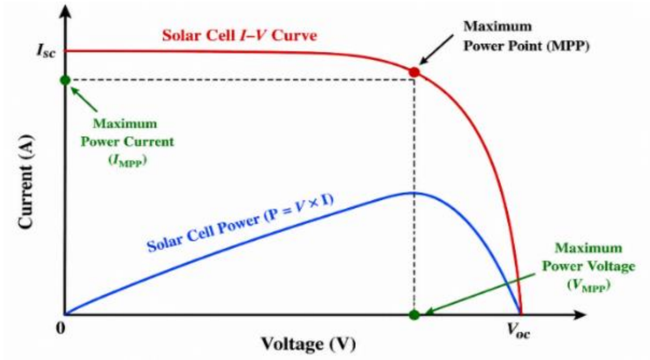

Figure 1. Typical current–voltage (I–V) characteristic of a photovoltaic (PV) cell illustrating the maximum power point operating region

While the theory seems simple, issues such as the presence of multiple local maxima as well as oscillations around the true maximum power point prove troubling in practice. This is a consequence of the PV array voltage power characteristics´ non-linearity and time variation because of changing atmospheric and load conditions. The primary goal of MPPT is to change thePWM controlling the power converter to the duty cycles of the load.

5. PHYSICAL MODEL OF BOOST CONVERTER

5.1 System overview

Figure 2 shows the diagram of a booster converter system's basic model. It consists of a boost converter PV cell functioning as the source, stationed at the DC input voltage level V_{in}, a controllable MOSFET switch, an inductor L, a capacitor C, a load resistor R, and a PWM block. The output voltage across the capacitor is termed V_o, while IL is the current flowing through the inductor. The PWM block controls the converter's functionality by changing the duty cycle on the switch D. When the MOSFET is in the ON state, the diode $D1$ is reverse-biased, permitting the inductor to derive the power that will later be used as a boost input. The power is then released to the resistor R, where the switch is ideal, and the losses in the inductor and capacitor are ignored. The MOSFET is turned OFF, allowing the diode to conduct. This form of analysis is known as the inductor's energy dump. The relation of input voltage to output voltage in a boost converter is expressed mathematically in the following way.

$$\frac{V_O}{V_{in}} = \frac{1}{(1 - D)} \tag{1}$$

6. ALGORITHMS DESCRIBED

The primary objective of control algorithms for boost converters is to ensure reliable output-voltage regulation in the presence of input or load disturbances. These boost converters provide efficient power conversion and control rapid dynamic response by regulating the switching duty cycle. Performance improvement, accuracy, and system stability can be achieved using algorithms based on conventional, intelligent, and optimization approaches.

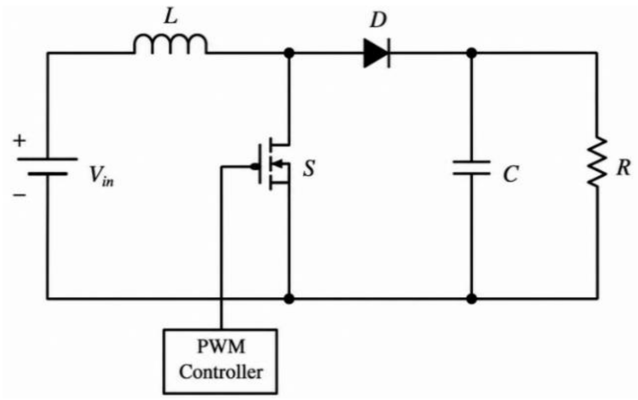

Figure 2. Simplified configuration of the DC-DC boost converter used in photovoltaic (PV) power conditioning systems

The examined control strategies represent a wide spectrum of operational principles and computational and implementation complexities. Traditional methods are usually grounded in straightforward control laws and direct perturbative decision methods. In contrast, intelligent methods apply adaptive inference or learning-based methods for nonlinear response behaviour. The hybrid optimization methods combine heuristic optimization and either traditional or intelligent control system methods. They offer enhancements for parameter adjustment, convergence, and system stability under varying operating environments.

6.1 Particle Swarm Optimization

The PSO Strategy draws parallels with the behaviours of birds flying in a flock and fish swimming in a school. Think of PSO in the context of optimizing the position of a particle in a multidimensional space. PSO derives its intelligence from the imitation of the social governing movements of animal groups. The swarm collaborates by virtue of its position within the particle cloud, and the entire swarm sifts 'intelligently' through the solutions of a given problem to approximate an optimal answer [11].

6.2 Genetic Algorithm

Complex and nonlinear issues utilize heuristic systems known as Genetic Algorithms (GAs), based on selection and reproduction. There might be multiple hypotheses, but the most optimal is used for further enhancement. There is, as a rule, a gradual increase and improvement in performance and adaptation in subsequent generations. GAs, which are part of a broad class of algorithms known as evolutionary algorithms (EAs), work with selection, crossover or recombination, and genetic mutations, and inheritance to produce actual results from perceived non-solutions over a period [12].

6.3 Fuzzy logic framework

Fuzzy logic is a sophistication within mathematics that attempts to cope with inadequate information and wider-than-usual reasoning. This allows logical systems to operate even when confronted with information that is vague or imprecise. In the 1960s, Lotfi Zadeh proposed fuzzy logic to be incorporated in classical logic, which integrated binary systems with true or false states. In fuzzy logic, systems and functions of logic do not work with only binary states of zero and one. There is the potential of considering the two extreme values 0 and 1, which now represent different ranges of truth or falsity. Fuzzy logic is thus more useful in systems with multidimensionality and complex structuring [13].

6.4 Perturb and Observe

In the case of the P&O method, the system reconfigures the PV unit's working voltage at tiny steps and cascade actions, noting the power variation for each change. When power increases, the algorithm continues perturbing in the same direction. If power decreases, the algorithm changes direction. This process iteratively draws power to the maximum power point. Directly correlating perturbed power and MPPT responds to rapidly changing sunlight and can result in power tracking errors that oscillate instead of stabilizing [14].

6.5 Adaptive Neuro-Fuzzy Inference System

ANFIS is an Adaptive Neuro-Fuzzy Inference System that utilizes artificial intelligence in the interface of a neural net and fuzzy logic. This is about the duality of the two technologies, and ANFIS is a testimony of the profound relationships between the two. The self-learning neural attributes of a neural network and the logic of fuzzy logic are consolidated for the purpose of structuring ANFIS. Nonlinear systems are particularly difficult to work with because of the nature of the relationships involved and the unpredictability of the behaviour of the system. Fuzzy logic has the unique ability to reason within a sufficiently complex system, which neural logic is unable to do. And fuzzy logic is used to enhance the reasoning level of the system [15].

6.6 Adaptive reference Proportional-Integral controller

Consider the word adaptive reference PI controller as a more sophisticated version of a standard PI controller descriptor. Like the latter, the former also attempts to change the reference parameters that are used to set the current contextual conditions of the system. Such is the value of the adaptive reference PI controller that it enables the use of a PI controller in modular systems in power electronics, renewable energy systems, and grid-connected PV systems, which all need to improve control, stability, and flexibility [16].

6.7 Grey Wolf Optimize

The GWO is a metaheuristic algorithm inspired by the leadership hierarchy and the hunting style of grey wolves. It uses the motivational steps of prey encirclement and hunting, followed by attacking the prey. It refines the search with the best solutions. GWO exhibits excellent global optimization capabilities and has outperformed other methods in MPPT applications under partial shading [17].

6.7.1 Comparative performance analysis

Table 1 summarizes the performance metrics of various boost converter control strategies applied to PV systems found in the research literature. Based on the information provided, there are notable differences in the operational behavior of techniques classified as conventional, intelligent, and hybrid optimization-based approaches. The use of PI, P&O, and INC techniques is classified as 'conventional' control techniques. These techniques tend to exhibit a tolerable performance level when systems are operating in a stable environment. This is primarily due to the simplicity and ease of use of these techniques. At the same time, these techniques tend to demonstrate poorer performance in terms of speed of response, the level of voltage ripple, and the robustness of the control system in environments where inputs to the system are rapidly changing. Compared to conventional control techniques, intelligent control techniques historically outperform in the areas of control system response time, control system level performance, ease of control, and reduction of control system output oscillation. These approaches account for the dynamic and unpredictable behavior of a nonlinear PV system and/or surrounding external disturbances. Hybrid optimization-based control techniques tend to have the best performance of all control techniques reviewed. The use of flexible control techniques along with the use of adaptive parameter optimization tends to improve system performance in terms of control system-level output, reduction of control system output oscillation, and improvement of control system output convergence behavior. At the same time, these techniques tend to be complex in terms of implementation and require intensive computational efforts. The information provided tends to indicate that when choosing control strategies, it is important to consider the environment control is operating, the level of control robustness necessary, and the level of control complexity acceptable, in addition to the peak control performance.

To facilitate a quantitative evaluation of the reviewed control strategies, Table 1 summarizes their reported performance in terms of voltage ripple, response time, and efficiency based on the referenced studies. To provide a clearer understanding of the characteristics of the reviewed control strategies, Table 2 presents a qualitative comparison of their strengths, limitations, dynamic robustness, implementation complexity, and typical PV applications.

Table 1. Performance evolution of various advanced methods for boost converter

Research	Controller Techniques	Performance Metric	Results
[18]	Proposed MRAC	1- Voltage ripple 2- Overall Efficiency (%)	1- 0.02 V 2- 98.5%
	INC	1 - Voltage ripple 2- Overall Efficiency (%)	1- 3.5 V 2- 95.5%
	P&O	1 - Voltage ripple 2- Overall Efficiency (%)	1- 4.0 V 2- 95.1%
[19]	P&O	1 - Voltage ripple 2- Overall Efficiency (%)	1- 1.2 V 2- 94.5%
	INC	1 - Voltage ripple 2- Overall Efficiency (%)	1- 1.1 V 2- 95.1%
	FLC	1 - Voltage ripple 2- Overall Efficiency (%)	1- 0.6 V 2- 97.5%
	ANN	1- Voltage ripple 2- Overall Efficiency (%)	1- 0.5 V 2- 98.2%
[20]	FLC	1- Efficiency	1- 94.8%
[21]	FLC	1- Voltage Ripple 2- Response Time 3- Efficiency	1- 0.8 V 2- 0.02–0.03 S 3- 98–99.2%
	P&O	1- Voltage Ripple 2- Response Time 3- Efficiency	1- 2.0 V 2- 0.06–0.08 S 3- 94–96%
[22]	FLC	1- Voltage Ripple 2- Response Time 3- Efficiency	1- 0.4 V 2- 0.03% 3- 98.7%
[23]	PI	1- Voltage Ripple 2- Response Time 3- Efficiency	1- 1.2 V 2- 0.45 S 3- 94%
	FLC	1- Voltage Ripple 2- Response Time 3- Efficiency	1- 0.6 V 2- 0.23 S 3- 97%
	ANN	1- Voltage Ripple 2- Response Time 3- Efficiency	1- 0.5 V 2- 0.17 S 3- 98.5%
[24]	PI – P&O	1- Efficiency 2- Voltage Ripple	1- 96% 2- 0.15 V
[25]	Classical Methods	1- Efficiency 2- Voltage Ripple	1- 92–94% 2- 1.1 V
	Intelligent Method (Fuzzy, ANN, GA)	1- Efficiency 2- Voltage Ripple	1- 95–98% 2- 0.6 V
[26]	P&O	1- Response Time 2- Efficiency	1- 0.06 S 2- 92%

	INC	1- Response Time 2- Efficiency	1- 0.035 S 2- 95%
	FLC	1- Response Time 2- Efficiency	1- 0.02 S 2- 97–98%
[27]	FLC	1- Voltage Ripple 2- Efficiency	1- 0.3 V 2- 97.3%
	P&O	1- Voltage Ripple 2- Efficiency	1- 1.2 V 2- 96.8%
[28]	INC	1- Voltage Ripple 2- Efficiency	1- 0.7 V 2- 97.2%
	ANN	1- Voltage Ripple 2- Efficiency	1- 0.4 V 2- 97.55%
	Hybrid GWO-P&O	1- Voltage Ripple 2- Efficiency % 3- Response Time	1- 0.2 V 2- 99.84% 3- 0.12 S
[29]	GWO	1- Voltage Ripple 2- Efficiency % 3- Response Time	1- 0.4 V 2- 99.77% 3- 0.15 S
	PSO+P&O	1- Voltage Ripple 2- Efficiency % 3- Response Time	1- 0.6 V 2- 99.57% 3- 0.16 S
[30]	FLC	1- Voltage Ripple 2- Efficiency	1- 0.2 V 2- 93.1%
[31]	INC	1- Voltage Ripple 2- Efficiency	1- 2 V 2- 97%
[32]	MPC+ PSO	1- Voltage Ripple 2- Efficiency	1- 0.5 V 2- 98%
[33]	PI	1- Voltage Ripple 2- Efficiency	1- 0.9 V 2- 96.2%
[34]	PI	1- Efficiency	1- 96.5%
[35]	FLC	1- Efficiency 2- Time response	1- 98% 2- 0.1 S
[36]	IGWO	1- Efficiency 2- Time response	1- 98.54% 2- 0.24 S
[37]	GWO	1- Efficiency 2- Time response	1- 97% 2- 0.2 S
[38]	PI	1- Efficiency	1- 96%
[39]	INC	1- Efficiency 2- Time response	1- 98% 2- 0.2 S
[40]	PSO	1- Efficiency 2- Time Response	1- 99% 2- 0.15 S
[41]	MINC	1- Efficiency 2- Voltage Ripple 3- Response Time	1- 99% 2- 0.38 V 3- 0.022 S
[42]	P&O	1- Efficiency 2- Voltage Ripple 3- Response Time	1- 95.8% 2- 1.2 S 3- 0.018 S
[43]	P&O	1- Efficiency 2- Ripple Voltage 3- Response Time	1- 96% 2- 4 V 3- 0.3 S
[44]	PI-PSO	1- Voltage Ripple 2- Efficiency	1- 1.3 V 2- 96%
[45]	PSO	1- Voltage Ripple 2- Response Time 3- Efficiency	1- 0.6 V 2- < 0.06 S 3- 99.1%
[46]	EGWO	1- Voltage Ripple 2- Time Response 3- Efficiency	1- 0.1 V 2- 0.1 S 3- 99%
[47]	GA	1- Time Response 2- Efficiency	1- 0.25 S 2- 97%
[48]	PID-SMC	1- Voltage Ripple 2- Response Time 3- Efficiency	1- < 1.5 V 2- < 0.1 S 3- 96.1%
[49]	PSO-ANFIS	1- Voltage Ripple 2- Response Time 3- Efficiency	1- < 1.3 V 2- < 0.05 S 3- 96.43%
[50]	P&O - INC	1- Response Time 2- Efficiency	1- 0.5 S 2- 96%
[51]	GWO	1- Response Time 2- Efficiency	1- 0.4 S 2- 98.9%
	WOA	1- Response Time	1- 0.48 S

		2- Efficiency	2- 98.2%
[52]	P&O	1- Voltage Ripple 2- Response Time 3- Efficiency	1- 1.2 V 2- 0.36 S 3- 96.8%
	INC	1- Voltage Ripple 2- Response Time 3- Efficiency	1- 1.1 V 2- 0.3 S 3- 97.2%
	FLC	1- Voltage Ripple 2- Response Time 3- Efficiency	1- 0.6 V 2- 0.18 S 3- 99%
	ANN	1- Voltage Ripple 2- Response Time 3- Efficiency	1- 0.5 V 2- 0.15 S 3- 99.5%
[53]	INC	1- Voltage Ripple 2- Response Time 3- Efficiency	1- < 1.5 V 2- 0.04 S 3- 93.2%
[54]	FLC	1- Voltage Ripple 2- Response Time 3- Efficiency	1- 1.2 V 2- 0.045 S 3- 94.7%
[55]	PI	1- Voltage Ripple 2- Efficiency	1- 1.2 V 2- 95.4%
[56]	AFLC	1- Voltage Ripple 2- Response Time 3- Efficiency	1- < 1.5 V 2- 0.06 S 3- 98%

Note: MRAC = Model Reference Adaptive Control; INC = Incremental Conductance; P&O = Perturb and Observe; FLC = Fuzzy Logic Controller; ANN = Artificial Neural Network; PI = Proportional-Integral; PID = Proportional-Integral-Derivative; GA = Genetic Algorithm; GWO = Grey Wolf Optimizer; Hybrid GWO-P&O = Hybrid Grey Wolf Optimizer–Perturb and Observe; PSO = Particle Swarm Optimization; MPC = Model Predictive Control; IGWO = Improved Grey Wolf Optimizer; MINC = Modified Incremental Conductance; EGWO = Enhanced Grey Wolf Optimizer; SMC = Sliding Mode Control; ANFIS = Adaptive Neuro-Fuzzy Inference System; WOA = Whale Optimization Algorithm; AFLC = Adaptive Fuzzy Logic Controller.

Table 2. Qualitative comparison of boost converter control strategies for photovoltaic (PV) systems

Control Strategy	Strengths	Limitations	Dynamic Robustness	Implementation Complexity	Typical Applications
PI/PID	Simple implementation, low computational demand	Limited adaptability, slower response	Low	Low	Small PV systems
P&O	Easy implementation, low cost	Oscillation around MPPT, slower under rapid changes	Low	Low	Residential PV
INC	Improved tracking over P&O	Complexity slightly higher than P&O	Moderate	Low–Moderate	Standard PV applications
FLC	Fast response, nonlinear adaptability	Requires tuning expertise	High	Moderate	Dynamic PV systems
ANN	High accuracy, adaptive learning capability	Training complexity, computational demand	High	High	Advanced intelligent PV control
ANFIS	Combines fuzzy reasoning and learning	Model complexity	High	High	Nonlinear PV environments
PSO / GWO	Strong optimization capability	Computational burden	High	High	Partial shading applications
MPC	Excellent dynamic control performance	Model dependency, high computation	High	High	Grid-connected advanced PV systems
Hybrid controllers	Superior efficiency and robustness	Highest implementation complexity	Very High	Very High	Large-scale advanced PV applications

Note: PI = Proportional-Integral; PID = Proportional-Integral-Derivative; P&O = Perturb and Observe; INC = Incremental Conductance; FLC = Fuzzy Logic Controller; ANN = Artificial Neural Network; ANFIS = Adaptive Neuro-Fuzzy Inference System; PSO = Particle Swarm Optimization; GWO = Grey Wolf Optimizer; MPC = Model Predictive Control.

6.7.2 Performance under dynamic environmental conditions

Rapidly changing environmental conditions, such as fluctuating irradiance and temperature, partial shading, and load disturbances, pose challenges for PV systems. Under such conditions, the responsiveness and stability of the control strategy become very important. Some traditional control methods, such as PI, P&O, and INC, can be deemed sufficient under relatively stable conditions. However, under rapidly changing conditions, the deterministic control of these methods may lead to slow adaptation, increased oscillations about the maximum power point, and decreased performance. The use of intelligent control methods, such as FLC controllers, ANN methods, and ANFIS methods, can improve adaptability to nonlinear conditions and reduce overall control response time. These aspects can improve system stability and enhance the tracking performance under environmental disturbances. Enhanced search and optimization capabilities of the Hybrid control methods make them the most adaptive and robust to rapidly changing operating conditions. In rapidly changing shading and irradiance environments, these methods can outperform traditional control methods, which may result in degraded performance. Based on the above considerations, the dynamic operating behavior of the boost converter control methodology must be considered for PV applications.

7. RESULTS

From an analysis of thirty-nine different reviewed control techniques of boost converter-based PV systems, it was noted that there was significant variation in performance, which was attributed to the design and execution of the algorithms.

Among all techniques, it was particularly noted that the use of intelligent and hybrid controllers substantially improved performance in all measures of efficiency, turnaround time, and reduction in voltage ripple when compared to the other, more traditional techniques. From recent studies, the ANN controller demonstrated superior overall performance due to its 99.5% efficiency, 0.5 V voltage ripple, and 0.15-second response time. Compared to traditional techniques such as INC and P&O, this is a significantly better performance, as their efficiencies range from 95% to 97.5%, and they considerably lag in dynamic response time. The other controller, the FLC, was also very competitive as it was demonstrated to have 99% efficiency, 0.6 V voltage ripple, and 0.18 second response time, showing that it is very robust and flexible with operating circumstances. Also, very rewarding were hybrid optimization techniques. The hybrid GWO-PO achieved 99.84% efficiency and very low voltage ripple, although response-time reporting was limited in some studies. Unlike other methodologies, PI and P&O were the oldest controllers, but still underperformed under dynamic and partially shaded environments. Such techniques feature more voltage ripple, slower response times, and less responsive tracking accuracy, which makes them poorer suited to top-of-the-range PV systems that sustain changes from the surrounding conditions. Based on the comparative analysis presented in this review, Table 3 summarizes the top three performing boost converter control techniques and highlights their response time, efficiency, and voltage ripple characteristics

Table 3. Summary of the top three performing techniques identified in this review

Technique	Response Time	Efficiency (%)	Voltage Ripple
Hybrid GWO-P&O	0.12 S	99.84%	0.2 V
E-GWO	0.1 S	99.00%	0.1 V
ANN	0.15 S	99.5%	0.5 V

The table lists the most appropriate technologies for use in boost converters, along with the needed degradation time and the respective voltage waveform. These advanced smart algorithms optimize performance with respect to converter size, variable-frequency drive, and voltage stability. This, in turn, boosts the control efficiency and operational reliability of the system.

Performance metrics are helpful for technical comparison, but when it comes to real-life applications, decisions are based on other factors. Some of these factors include operating costs, planting and equipment costs, time, and ambient conditions. This next section will supply guidelines for real-world control selection.

8. PRACTICAL DESIGN GUIDELINES FOR BOOST CONVERTER CONTROL SELECTION

Based on this review's analysis, practical recommendations for selecting control methodologies for boost-converter–based PV systems can be established.

1- Cost-sensitive Small-scale PV Solution:

For the case of small-scale, low-cost PV systems, the classical control paradigms of PI, P&O, and INC control retain relevance due to the low computation, ease of implementation, and low hardware needs. These control methods are suitable for small residential or standalone PV systems, under moderate, stable conditions, where the environmental variations can be stabilized.

2- Rapidly Changing Environmental Conditions:

For the rapidly evolving environmental conditions, where there are rapid variations of irradiance and temperature, control methods of these categories, ANFIS, FLC, and ANN, yield better performance. These methods substantially diminish steady-state oscillations and improve the accuracy of the control methods.

3- High Partial Shading and High Yield Applications:

For high-yielding PV plant applications, control methods of PSO, GWO, and MPC are hybrid optimization-based methods and offer better speed of convergence and associated robustness. These control methods are primarily recommended for grid-connected, large-scale PV plants.

4- Implementation Considerations:

Although intelligent and hybrid methods yield better performance, they offer heavy demand for computational power, calibration of parameters, control systems, and greater accuracy in modeling control systems. Thus, the selection of the control systems should reflect a compromise between the desired superior performance and the complexity of implementation.

5- Coming Innovations in PV Technology:

Research on newer PV systems is centered on developing controllers that are adaptive and/or learning so that they can perform/tasks such as real-time optimization, self-tuning, and compatible operation with other systems as well as Smart Grids.

9. CONCLUSIONS

The review provided a comparison of different strategies used for controlling boost converters in PV systems. Emphasis was given to control strategies such as Intelligent, Conventional, and Control strategies based on hybrid optimization. From the analysis, in most cases, Conventional control strategies may still be desirable as implementation and computational costs would be relatively low for most stable operating environments. However, these controls are likely to be less effective as environmental conditions and/or operating conditions change quickly due to rapidly changing irradiance and for scenarios involving partial shading. Intelligent control strategies provide better adaptability and improved characteristics for controlling and responding to non-linear conditions. Therefore, they would be appropriate for the dynamic operating conditions typically present in a PV system. Among the available control strategies, Control Hybrid Strategies provide better effectiveness in terms of tracking, faster convergence, and improved robustness. However, the costs of implementation would be relatively high for each of these strategies. Control strategies in systems should be designed not only for efficiency, but also for the practical side of implementation, the environmental operating conditions, and the specific requirements that the application demands. Developing adaptive and intelligent control strategies that would focus on reducing the demands on processing and control within a structured framework would be advantageous for highly changing environmental conditions and would also offer improved robustness and integration with the next generation of grid-connected PV systems.

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NOMENCLATURE

PV	Photovoltaic
MRAC	Model Reference Adaptive Control
INC	Incremental Conductance
M P&O	Modified Perturb and Observe
P&O	Perturb and Observe
E- GWO	Enhanced Grey Wolf Optimizer
PI	Proportional–Integral Controller
IGWO	Improved Grey Wolf Optimizer
MINC	Modified Incremental Conductance
PID-SMC	Proportional-Integral-Derivative combined with Sliding Mode Control
MPC	Model Predictive Control
PSO	Particle Swarm Optimization
GA	Genetic Algorithm
FLC	Fuzzy Logic Controller
ANFIS	Adaptive Neuro-Fuzzy Inference System
PWM	Pulse Width Modulation
BFOA	Bacterial Foraging Optimization Algorithm
GWO	Grey Wolf Optimizer
AFLC	Adaptive Fuzzy Logic Controller
ANN	Artificial Neural Network
WOH	Whale Optimization Algorithm