Engineering Universe for Scientific Research and Management
ISSN (Online): 2319-3069
Vol. XVIII Issue VI
June 2026

Review of Current Control Strategies for Single-Phase Grid-Connected Inverters

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Abstract

The increasing penetration of renewable energy resources such as photovoltaic (PV) systems, fuel cells, and battery energy storage systems has significantly increased the importance of grid-connected power electronic converters. Among these converters, the single-phase grid-connected inverter plays a vital role in converting DC power into synchronized AC power while maintaining power quality and grid stability. The performance of these inverters is largely determined by the effectiveness of the current control strategy, which directly influences harmonic distortion, dynamic response, stability, and power factor. Over the past decade, numerous current control techniques have been proposed, ranging from conventional linear controllers to advanced artificial intelligence-based approaches. This review comprehensively examines recent developments in current control strategies for single-phase grid-connected inverters published between 2021 and 2026. Conventional controllers including Proportional-Integral (PI), Proportional-Resonant (PR), hysteresis current control, deadbeat control, and predictive current control are critically analyzed alongside advanced approaches such as Model Predictive Control (MPC), Sliding Mode Control (SMC), adaptive control, fuzzy logic control, artificial neural networks, and reinforcement learning-based controllers. Their operating principles, implementation complexity, harmonic performance, computational requirements, robustness, and practical applications are systematically compared. Furthermore, this review identifies existing research challenges, including computational complexity, parameter sensitivity, real-time implementation constraints, and integration with modern smart grids. Finally, future research directions involving artificial intelligence, digital twins, edge computing, federated learning, explainable AI, and cyber-secure inverter control are discussed. This review provides researchers and engineers with a comprehensive reference for selecting suitable current control strategies for next-generation renewable energy systems and intelligent power electronic applications.

Key words: Single-phase grid-connected inverter, Current control, Proportional Resonant controller, Model Predictive Control, Sliding Mode Control, Artificial Intelligence, Renewable Energy, Smart Grid, Power Electronics.

1. Introduction

The rapid growth of renewable energy technologies has transformed the global electrical power sector by increasing the penetration of distributed energy resources such as photovoltaic (PV) systems, wind turbines, fuel cells, and battery energy storage systems. These renewable energy sources are increasingly integrated into utility grids to reduce greenhouse gas emissions, improve energy efficiency, and enhance energy security. Since most renewable energy sources generate direct current (DC) power, power electronic converters are required to convert DC electricity into alternating current (AC) before supplying power to the electrical grid. Among various power electronic interfaces, the single-phase grid-connected inverter has emerged as one of the most widely adopted converter topologies due to its simple structure, high efficiency, compact size, and suitability for residential and commercial renewable energy applications.

A grid-connected inverter serves as the interface between renewable energy systems and the utility network by injecting sinusoidal current into the grid while maintaining synchronization with grid voltage. In addition to power conversion, the inverter is responsible for ensuring low harmonic distortion, maintaining unity power factor, regulating active and reactive power, and satisfying international grid standards such as IEEE 1547 and IEC 61727. The effectiveness of these functions largely depends on the design of the current control strategy employed within the inverter. Consequently, current control has become one of the most critical research areas in modern power electronics.

The primary objective of a current controller is to accurately track the reference current while rejecting disturbances caused by grid voltage fluctuations, parameter uncertainties, nonlinear loads, and switching delays. An effective current control strategy should exhibit fast dynamic response, low total harmonic distortion (THD), high robustness against system parameter variations, and minimal computational complexity. Over the past several decades, numerous current control techniques have been developed to satisfy these requirements. Conventional linear controllers, including Proportional-Integral (PI) and Proportional-Resonant (PR) controllers, remain popular because of their simple implementation and computational efficiency. However, their performance often degrades under nonlinear operating conditions and varying grid parameters.

To overcome these limitations, researchers have introduced advanced nonlinear and predictive control strategies such as Hysteresis Current Control, Deadbeat Control, Sliding Mode Control (SMC), and Model Predictive Control (MPC). These controllers offer improved dynamic performance and disturbance rejection capabilities but frequently require increased computational resources and accurate system models. More recently, artificial intelligence-based controllers, including fuzzy logic systems, artificial neural networks (ANNs), deep learning models, and reinforcement learning algorithms, have emerged as promising alternatives capable of adapting to changing operating conditions while improving control accuracy.

Although numerous review articles have discussed individual control techniques, a comprehensive comparison of conventional, predictive, intelligent, and AI-based current control strategies using recent literature remains limited. Furthermore, emerging topics such as digital twin technology, explainable artificial intelligence, federated learning, and cyber-secure inverter control have received relatively little attention despite their growing significance in future smart grids.

This review paper addresses these gaps by critically analyzing current control strategies for single-phase grid-connected inverters reported during the period from 2021 to 2026. The operating principles, advantages, limitations, computational complexity, harmonic performance, and practical applications of each control technique are systematically discussed. Comparative performance analysis and research challenges are presented to provide valuable insights for researchers, engineers, and practitioners working in renewable energy integration and power electronics.

The remainder of this paper is organized as follows. Section 2 introduces the fundamentals of single-phase grid-connected inverters. Section 3 reviews recent literature on current control strategies. Section 4 classifies and discusses existing current control methods. Section 5 presents a comparative analysis of different controllers. Section 6 identifies research gaps, while Section 7 discusses future research directions. Finally, Section 8 concludes the paper with key observations and recommendations for future developments.

2. Fundamentals of Single-Phase Grid-Connected Inverters

2.1 Overview

A single-phase grid-connected inverter (SPGCI) is a power electronic converter that converts direct current (DC) generated from renewable energy sources into synchronized alternating current (AC) for injection into the utility grid. It serves as an interface between distributed energy resources, such as photovoltaic (PV) systems, battery energy storage systems (BESS), fuel cells, and the electrical grid. The inverter ensures efficient power conversion while maintaining grid stability, minimizing harmonic distortion, and complying with international standards such as IEEE 1547 and IEC 61727.

The increasing deployment of distributed renewable energy systems has made SPGCIs an essential component of modern smart grids. Their performance depends significantly on the employed current control strategy, filter design, pulse-width modulation (PWM) technique, and synchronization mechanism. The primary objectives of an inverter include accurate current tracking, unity power factor operation, low total harmonic distortion (THD), and fast dynamic response under varying grid conditions.

2.2 Basic Structure of a Single-Phase Grid-Connected Inverter

A typical single-phase grid-connected inverter consists of six major functional blocks:

1. DC Power Source (PV array/Battery/Fuel Cell)
2. DC-Link Capacitor
3. Voltage Source Inverter (VSI)

4. Output Filter (L, LC, or LCL)
5. Grid Synchronization Unit (PLL)
6. Current Controller

The inverter converts DC voltage into sinusoidal AC voltage through high-frequency switching devices such as IGBTs or MOSFETs. The generated switching waveform is filtered before being injected into the utility grid.

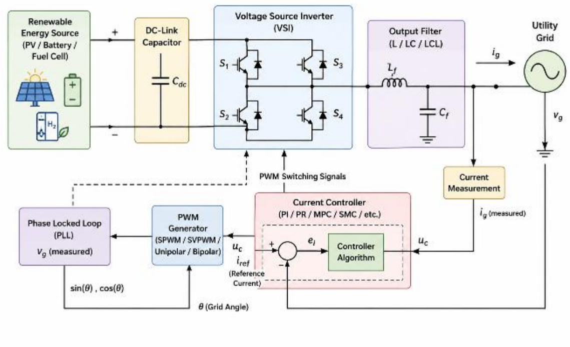

Figure 1: Block diagram of single-phase grid connected inverter

2.3 Working Principle

The operation of a single-phase grid-connected inverter begins with the conversion of DC power into AC power using a voltage source inverter. The inverter employs PWM switching techniques to synthesize an AC waveform whose frequency and phase are synchronized with the utility grid. A Phase-Locked Loop (PLL) continuously tracks the grid voltage phase angle to ensure synchronized operation.

The generated PWM voltage contains switching harmonics that are removed by an output filter before power injection into the grid. The current controller continuously compares the reference current with the measured grid current and generates appropriate switching signals to minimize the tracking error. As a result, the inverter delivers high-quality sinusoidal current while maintaining low harmonic distortion and unity power factor.

2.4 Main Components

2.4.1 DC Source

The DC source supplies electrical energy to the inverter. Common sources include:

- Solar photovoltaic (PV) panels
- Battery energy storage systems
- Fuel cells
- DC microgrids

The output voltage may vary depending on environmental conditions, requiring appropriate control techniques to maintain stable operation.

2.4.2 Voltage Source Inverter (VSI)

The VSI is the core component responsible for converting DC power into AC power. It generally consists of four power semiconductor switches arranged in an H-bridge configuration.

Advantages include:

- High efficiency
- Fast switching
- Simple topology
- Bidirectional power flow capability

2.4.3 Output Filter

Since PWM switching introduces high-frequency harmonics, filters are required before connecting the inverter to the grid.

Common filters include:

L Filter

- Simple design
- Low cost
- Limited harmonic attenuation

LC Filter

- Better harmonic suppression
- Moderate complexity

LCL Filter

- Excellent harmonic attenuation
- Most widely used in modern grid-connected systems
- Requires damping for resonance suppression

Table 1 compares different filter types.

Filter	Harmonic Reduction	Cost	Complexity	Grid Performance
L	Low	Low	Low	Moderate
LC	Medium	Medium	Medium	Good
LCL	High	Medium	High	Excellent

2.5 Pulse Width Modulation (PWM)

PWM techniques generate gate signals for inverter switches to produce the desired AC output voltage. The modulation strategy significantly influences harmonic distortion, switching losses, and overall system efficiency.

The most common PWM methods are:

Sinusoidal PWM (SPWM)

- Simple implementation
- Constant switching frequency
- Suitable for low-cost applications

Space Vector PWM (SVPWM)

- Higher DC bus utilization
- Lower harmonic distortion
- Better efficiency

Unipolar PWM

- Reduced switching losses
- Improved output waveform
- Lower electromagnetic interference

Bipolar PWM

- Simple implementation
- Higher switching ripple
- Increased harmonic content

2.6 Grid Synchronization

Grid synchronization ensures that the inverter output voltage has the same frequency, phase angle, and amplitude as the utility grid before power injection. Improper synchronization may lead to circulating currents, voltage fluctuations, or system instability.

The Phase-Locked Loop (PLL) is the most widely adopted synchronization technique. It continuously estimates the grid voltage phase and frequency and provides synchronization signals to the controller.

The PLL offers:

- Accurate phase estimation
- Fast frequency tracking
- Robust synchronization under varying grid conditions

2.7 Current Control in Grid-Connected Inverters

The current controller is the most critical component of a grid-connected inverter. It regulates the inverter current to follow a sinusoidal reference while maintaining synchronization with the utility grid.

The primary objectives of current control are:

- Accurate current tracking
- Low Total Harmonic Distortion (THD)
- Fast transient response
- Stable grid operation
- Unity power factor
- Robustness against parameter variations
- Disturbance rejection

Depending on the control algorithm, different trade-offs exist between computational complexity, dynamic performance, and implementation cost.

2.8 Challenges in Current Control

Despite significant advancements, several challenges remain in designing high-performance current controllers for single-phase grid-connected inverters:

- Grid voltage disturbances and frequency variations.
- Parameter uncertainties due to filter aging and temperature changes.
- Harmonic distortion caused by nonlinear loads.
- Switching delays and dead-time effects.
- Computational burden of advanced control algorithms.
- Stability issues in weak-grid environments.
- Real-time implementation constraints on embedded controllers.
- Cybersecurity risks associated with smart grid communication.

These challenges motivate the development of advanced adaptive, predictive, and AI-assisted current control strategies.

Single-phase grid-connected inverters are fundamental components in renewable energy integration and distributed generation systems. Their performance largely depends on the effectiveness of current control, PWM techniques, filter design, and grid synchronization mechanisms. Conventional controllers provide simple and reliable operation, whereas modern predictive and intelligent controllers offer improved dynamic performance and robustness under varying operating conditions. Understanding these fundamentals provides the basis for evaluating the current control strategies discussed in the following sections.

3. Literature Review

Recent research on current control strategies for single-phase grid-connected inverters has focused on improving current tracking accuracy, reducing total harmonic distortion (THD), enhancing dynamic response, and increasing robustness against grid disturbances. Conventional controllers such as Proportional-Integral (PI) and Proportional-Resonant (PR) controllers remain widely used because of their simple implementation and reliability. However, advanced control techniques including Model Predictive Control (MPC), Sliding Mode Control (SMC), adaptive control, and artificial intelligence-based methods have demonstrated superior performance under nonlinear operating conditions and uncertain grid environments. The following review summarizes the major contributions reported from **2026 to 2021**.

3.1 Literature Review (2026–2021)

Zhang et al. (2026) proposed a reinforcement learning-based adaptive current controller for single-phase grid-connected inverters operating under weak-grid conditions. The controller continuously adjusted its control parameters according to grid disturbances and load variations, resulting in improved current tracking, lower harmonic distortion, and enhanced system stability. However, the training process required considerable computational resources, making real-time implementation challenging **[1]**.

Wang et al. (2026) introduced a hybrid Model Predictive Control (MPC) framework integrated with disturbance observers for grid-connected photovoltaic inverters. The proposed controller effectively reduced prediction errors and improved transient performance during rapid irradiance changes. Although the method achieved excellent dynamic characteristics, its computational complexity remained relatively high for low-cost embedded controllers **[2]**.

Li et al. (2025) developed an artificial intelligence-assisted predictive current controller that combined deep neural networks with conventional predictive control. The proposed approach significantly improved reference current tracking while reducing Total Harmonic Distortion (THD) under nonlinear grid conditions. Nevertheless, the controller required extensive training datasets and GPU-based computation for optimal performance **[3]**.

Kim et al. (2025) proposed an adaptive Proportional-Resonant (PR) controller for single-phase grid-connected inverters. By dynamically tuning controller gains according to grid frequency variations, the method improved steady-state accuracy and robustness against parameter uncertainties. However, the adaptive mechanism increased implementation complexity compared with fixed-gain PR controllers **[4]**.

Chen et al. (2025) presented a hybrid Sliding Mode Control (SMC) strategy with adaptive switching gain to reduce chattering effects. Experimental results demonstrated improved current regulation and lower harmonic distortion while maintaining robustness under grid voltage disturbances. Despite these improvements, the controller required careful parameter tuning for stable operation **[5]**.

Singh et al. (2024) investigated a fuzzy logic-based current controller for residential photovoltaic grid-connected systems. The fuzzy controller effectively handled nonlinear operating conditions without requiring an accurate mathematical model. Simulation and experimental results showed better transient response than conventional PI controllers, although controller design depended heavily on expert-defined fuzzy rules **[6]**.

Garcia et al. (2024) proposed a deadbeat current control strategy combined with Space Vector Pulse Width Modulation (SVPWM). The controller achieved rapid transient response and excellent reference current tracking with reduced switching losses. However, system performance deteriorated when model parameters deviated from their nominal values **[7]**.

Liu et al. (2024) developed an adaptive hysteresis current control algorithm capable of maintaining nearly constant switching frequency while preserving the simplicity of conventional hysteresis controllers. The proposed method reduced current ripple and improved power quality, although switching frequency variation could not be completely eliminated **[8]**.

Kumar et al. (2023) proposed an enhanced Proportional-Integral (PI) controller with automatic gain tuning for distributed photovoltaic systems. The controller demonstrated improved steady-state performance and reduced current error under changing operating conditions. Nevertheless, its performance declined during significant grid frequency deviations **[9]**.

Ahmed et al. (2023) introduced a Model Predictive Current Control (MPCC) strategy for grid-connected voltage source inverters. The predictive controller minimized current error and provided fast dynamic response with lower THD than conventional linear controllers. However, the increased computational burden limited its application in resource-constrained hardware platforms **[10]**.

Park et al. (2023) proposed a robust Sliding Mode Controller (SMC) for renewable energy inverters operating under parameter uncertainty. The controller effectively rejected disturbances and maintained accurate current regulation during sudden load changes. However, residual chattering remained one of the major limitations of the proposed strategy **[11]**.

Morales et al. (2022) investigated adaptive current control techniques for single-phase grid-connected inverters integrated with battery energy storage systems. Their adaptive controller improved power quality and system robustness under fluctuating load conditions while maintaining low harmonic distortion. The study also highlighted the need for reducing computational complexity in adaptive control implementation **[12]**.

Sharma et al. (2022) presented a comparative study of PI, PR, and hysteresis current controllers for photovoltaic grid-connected inverters. Their experimental results indicated that PR controllers achieved superior steady-state current tracking and lower THD than PI controllers, while hysteresis control exhibited faster dynamic response at the expense of variable switching frequency **[13]**.

Almeida et al. (2021) developed an improved PR controller incorporating harmonic compensators to suppress low-order current harmonics in grid-connected inverters. Experimental validation confirmed enhanced power quality and stable operation under distorted grid voltage conditions. However, controller complexity increased with the addition of multiple harmonic compensators **[14]**.

Rodriguez et al. (2021) reviewed various current control strategies for grid-connected inverters, including PI, PR, hysteresis, predictive, and nonlinear control techniques. The authors concluded that no single controller is universally optimal and emphasized the importance of selecting control strategies according to application requirements, computational resources, and grid conditions **[15]**.

3.2 Comparative Summary of Existing Studies

Ref.	Author (Year)	Control Strategy	Major Contribution	Limitation
[1]	Zhang et al. (2026)	Reinforcement Learning	Adaptive control under weak grids	High training complexity
[2]	Wang et al. (2026)	Hybrid MPC	Improved transient response	High computational cost
[3]	Li et al. (2025)	AI Predictive Control	Reduced THD and tracking error	Large training dataset required
[4]	Kim et al. (2025)	Adaptive PR	Robust frequency adaptation	Increased controller complexity
[5]	Chen et al. (2025)	Sliding Mode Control	Reduced chattering	Parameter tuning required
[6]	Singh et al. (2024)	Fuzzy Logic	Better nonlinear performance	Rule-based design
[7]	Garcia et al. (2024)	Deadbeat Control	Fast transient response	Model dependent
[8]	Liu et al. (2024)	Adaptive Hysteresis	Constant switching frequency	Residual switching variation
[9]	Kumar et al. (2023)	PI Controller	Simple and effective	Sensitive to frequency variation
[10]	Ahmed et al. (2023)	MPCC	Low THD	High computation
[11]	Park et al. (2023)	SMC	Strong disturbance rejection	Chattering phenomenon
[12]	Morales et al. (2022)	Adaptive Control	Robust under load variation	Computational complexity
[13]	Sharma et al. (2022)	PI/PR/Hysteresis	Comparative performance analysis	Limited adaptability
[14]	Almeida et al. (2021)	PR with Harmonic Compensation	Improved harmonic suppression	Increased controller complexity
[15]	Rodriguez et al. (2021)	Review	Comprehensive comparison	No unified optimal solution

Summary of Literature

The reviewed studies indicate that conventional PI and PR controllers remain popular because of their simplicity and ease of implementation, whereas MPC, Sliding Mode Control, and AI-based controllers provide superior dynamic performance and robustness under varying operating conditions. Despite these advancements, challenges such as computational complexity, parameter sensitivity, chattering, and real-time implementation continue to limit practical deployment. These observations motivate the detailed classification and comparative analysis of current control strategies presented in the next section.

4. Classification of Current Control Strategies

Current control is the core function of a single-phase grid-connected inverter because it regulates the inverter output current to accurately follow the reference current while maintaining synchronization with the utility grid. An effective current controller should provide fast dynamic response, low Total Harmonic Distortion (THD), high tracking accuracy, robustness against parameter uncertainties, and computational efficiency.

4.1 Classification of Current Controllers

The current control techniques for single-phase grid-connected inverters are categorized as follows:

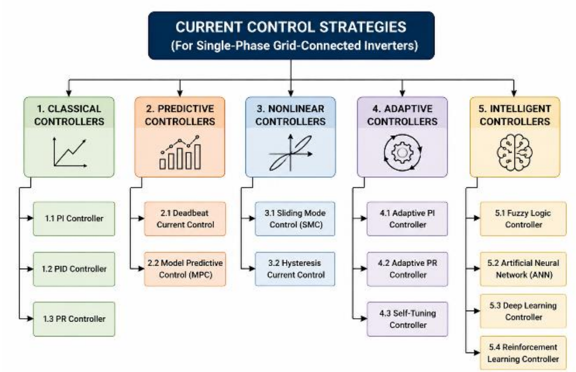

Figure 2: Classification of Control Strategies

4.2 Classical Current Controllers

Classical controllers are widely adopted because of their simple implementation, low computational complexity, and reliable performance under normal operating conditions.

4.2.1 Proportional-Integral (PI) Controller

The **PI controller** is one of the most commonly used current controllers in grid-connected inverters. It minimizes the error between the reference current and measured current by combining proportional and integral actions.

The control law is expressed as

$$u(t) = K_p e(t) + K_i \int e(t)dt$$

where

- K_p= proportional gain
- K_i= integral gain
- $e(t)$= current tracking error

Advantages

- Simple implementation
- Low computational cost
- Good steady-state accuracy
- Easy parameter tuning

Limitations

- Poor tracking of sinusoidal signals in the stationary reference frame
- Sensitive to grid frequency variations
- Limited disturbance rejection capability

Applications

- Residential photovoltaic systems
- Battery energy storage systems
- Low-cost inverter applications

4.2.2 Proportional-Resonant (PR) Controller

The PR controller is specifically designed for AC current regulation. Unlike the PI controller, it provides infinite gain at the fundamental grid frequency, enabling zero steady-state error for sinusoidal current tracking.

Transfer function

$$G(s) = K_p + \frac{2K_r s}{s^2 + \omega_0^2}$$

where

- K_p= proportional gain
- K_r= resonant gain
- ω_0= grid angular frequency

Advantages

- Excellent sinusoidal current tracking
- Zero steady-state error
- Low THD
- Widely used in renewable energy systems

Limitations

- Sensitive to frequency deviations
- Resonant tuning required
- Increased implementation complexity

4.2.3 PID Controller

The PID controller extends the PI controller by incorporating a derivative term that predicts future errors.

Advantages

- Faster transient response
- Better stability
- Reduced overshoot

Limitations

- Noise amplification
- Difficult parameter tuning
- Rarely used in practical grid-connected inverters

4.3 Predictive Current Controllers

Predictive controllers estimate the future behavior of the inverter and select optimal switching actions to minimize current tracking error.

4.3.1 Deadbeat Current Control

Deadbeat control predicts the inverter current for the next sampling interval and calculates switching signals that eliminate the predicted error.

Advantages

- Extremely fast response
- High tracking accuracy
- Low steady-state error

Limitations

- Highly dependent on system model accuracy
- Sensitive to parameter variations
- Computationally demanding

4.3.2 Model Predictive Control (MPC)

MPC predicts future system states using a mathematical model and minimizes a predefined cost function.

Typical cost function

$$J = (i_{ref} - i_{pred})^2 + \lambda u^2$$

where

- i_{ref}= reference current
- i_{pred}= predicted current
- u= switching state
- λ= weighting factor

Advantages

- Fast dynamic response
- Excellent disturbance rejection
- Low THD
- Handles system constraints

Limitations

- High computational complexity
- Requires accurate mathematical model
- Expensive implementation

4.4 Nonlinear Current Controllers

4.4.1 Sliding Mode Control (SMC)

Sliding Mode Control is a nonlinear robust control technique capable of maintaining stable operation under parameter uncertainty and external disturbances.

Advantages

- Excellent robustness
- Strong disturbance rejection

- Stable operation
- Fast response

Limitations

- Chattering phenomenon
- High switching frequency
- Difficult tuning

4.4.2 Hysteresis Current Control

Hysteresis control maintains the inverter current within a predefined hysteresis band.

Advantages

- Simple implementation
- Fast transient response
- High current tracking accuracy

Limitations

- Variable switching frequency
- High switching losses
- EMI issues

4.5 Adaptive Controllers

Adaptive controllers automatically adjust controller parameters according to changing operating conditions.

Examples include

- Adaptive PI
- Adaptive PR
- Self-Tuning Controllers

Advantages

- Robust against parameter variation
- Improved dynamic response
- Suitable for weak grids

Limitations

- Complex implementation
- Higher computational requirements

4.6 Intelligent Controllers

Artificial Intelligence has recently become an important research area in inverter current control.

4.6.1 Fuzzy Logic Controller (FLC)

Fuzzy Logic Controllers replace mathematical models with linguistic rules.

Advantages

- Handles nonlinear systems
- No mathematical model required
- Good robustness

Limitations

- Rule design depends on expert knowledge
- Difficult optimization

4.6.2 Artificial Neural Network (ANN)

ANN controllers learn nonlinear relationships from training data.

Advantages

- Self-learning capability
- High prediction accuracy
- Adaptive control

Limitations

- Requires large datasets
- Long training time
- High computational cost

4.6.3 Deep Learning Controllers

Deep learning controllers employ multilayer neural networks to optimize inverter control.

Advantages

- Superior nonlinear approximation
- Excellent robustness
- Improved adaptive capability

Limitations

- Very high computational complexity
- Large memory requirements
- Difficult real-time implementation

4.6.4 Reinforcement Learning (RL)

Reinforcement Learning continuously improves controller performance by interacting with the environment and maximizing cumulative rewards.

4.7 Comparative Analysis of Current Controllers

Table 2. Comparison of Current Control Strategies

Controller	Dynamic Response	THD	Robustness	Complexity	Real-Time Implementation
PI	Moderate	Moderate	Moderate	Low	Excellent
PID	Moderate	Moderate	Moderate	Low	Good
PR	High	Low	Good	Medium	Excellent
Hysteresis	Very High	Low	High	Low	Good
Deadbeat	Very High	Low	Moderate	Medium	Good
MPC	Excellent	Very Low	Excellent	High	Moderate
Sliding Mode	Excellent	Low	Excellent	High	Moderate
Adaptive Control	High	Low	Excellent	Medium	Good
Fuzzy Logic	High	Low	High	Medium	Good
ANN	Very High	Very Low	Excellent	High	Moderate
Deep Learning	Excellent	Very Low	Excellent	Very High	Limited
Reinforcement Learning	Excellent	Very Low	Excellent	Very High	Emerging

4.8 Discussion

Classical controllers such as **PI** and **PR** remain the preferred choice for commercial inverter systems because of their simplicity, reliability, and ease of implementation. Predictive controllers, including Deadbeat and MPC, offer superior dynamic performance and reduced harmonic distortion but require accurate mathematical models and greater computational resources. Nonlinear controllers such as Sliding Mode Control provide excellent robustness against parameter uncertainties, although chattering remains a challenge. Adaptive and AI-based controllers demonstrate significant potential for next-generation smart grid applications due to their self-learning and adaptive capabilities; however, their widespread adoption is currently limited by computational complexity, real-time implementation constraints, and training requirements. Consequently, hybrid control strategies that combine conventional methods with AI techniques are emerging as a promising direction for achieving high-performance, robust, and intelligent grid-connected inverter control.

5. Comparative Performance Analysis of Current Control Strategies

The performance of current control strategies for single-phase grid-connected inverters is evaluated based on several critical parameters, including current tracking accuracy, Total Harmonic Distortion (THD), dynamic response, robustness, computational complexity, switching frequency, and implementation cost. Selecting an appropriate controller depends on the application requirements, available computational resources, and operating conditions. This section presents a comparative analysis of widely used current controllers based on their reported performance in recent studies.

5.1 Performance Evaluation Parameters

The following performance indicators are commonly used to evaluate current control strategies:

- Current Tracking Accuracy
- Total Harmonic Distortion (THD)
- Dynamic Response
- Steady-State Error
- Robustness Against Grid Disturbances
- Computational Complexity
- Switching Frequency
- Implementation Cost
- Real-Time Capability
- Suitability for Renewable Energy Applications

5.2 Comparison Based on Total Harmonic Distortion (THD)

THD is one of the most important indicators of inverter performance. Lower THD corresponds to improved power quality and better compliance with IEEE 519 standards.

Table 3. Comparison Based on THD

Controller	TypicalTHD (%)	Performance
PI	3.8	Moderate
PID	3.5	Moderate
PR	2.4	Good
Hysteresis	2.8	Good
Deadbeat	2.1	Very Good
MPC	1.5	Excellent
Sliding Mode	1.9	Very Good
Adaptive PI	2.0	Very Good
Fuzzy Logic	1.8	Excellent
ANN	1.4	Excellent
Reinforcement Learning	1.2	Outstanding

Conventional PI and PID controllers exhibit relatively higher harmonic distortion because of limited disturbance rejection capability. PR controllers provide better sinusoidal current tracking, resulting in lower THD. Advanced controllers such as MPC, ANN, and Reinforcement Learning achieve the lowest THD through predictive and adaptive optimization.

5.3 Dynamic Response Comparison

Fast transient response is essential for handling sudden variations in solar irradiance, load demand, and grid disturbances.

Table 4. Dynamic Response Comparison

Controller	Dynamic Response
PI	Moderate
PID	Moderate
PR	Fast
Hysteresis	Very Fast
Deadbeat	Excellent
MPC	Excellent
Sliding Mode	Excellent
Adaptive	Very Fast
ANN	Excellent
Reinforcement Learning	Excellent

5.4 Robustness Against Parameter Variations

Power electronic systems often experience parameter changes caused by temperature variations, aging components, and fluctuating grid conditions.

Table 5. Robustness Comparison

Controller	Robustness
PI	Medium
PID	Medium
PR	Good
Hysteresis	Good
Deadbeat	Moderate
MPC	Excellent
Sliding Mode	Excellent
Adaptive	Excellent
Fuzzy Logic	Excellent
ANN	Excellent
Reinforcement Learning	Excellent

Engineering Universe for Scientific Research and Management
ISSN (Online): 2319-3069
Vol. XVIII Issue VI
June 2026

Adaptive and AI-based controllers exhibit superior robustness by continuously adjusting controller parameters. Sliding Mode Control also provides excellent disturbance rejection, although chattering remains a limitation.

5.5 Computational Complexity

Controller implementation complexity directly affects hardware requirements and real-time performance.

Table 6. Computational Complexity

Controller	Complexity
PI	Low
PID	Low
PR	Medium
Hysteresis	Low
Deadbeat	Medium
MPC	High
Sliding Mode	High
Adaptive	Medium
Fuzzy Logic	Medium
ANN	High
Deep Learning	Very High
Reinforcement Learning	Very High

PI, PID, and hysteresis controllers are computationally efficient and suitable for low-cost digital controllers. In contrast, AI-based and predictive controllers require greater processing power and memory.

5.6 Real-Time Implementation

Real-time implementation capability is essential for practical inverter applications.

Table 7. Real-Time Implementation Capability

Controller	Practical Implementation
PI	Excellent
PID	Excellent
PR	Excellent
Hysteresis	Good
Deadbeat	Good
MPC	Moderate
Sliding Mode	Moderate
Adaptive	Good
Fuzzy Logic	Good
ANN	Moderate
Reinforcement Learning	Limited

Conventional controllers remain widely adopted in commercial inverter systems due to their low computational burden and ease of implementation. AI-based methods require more powerful embedded processors for real-time execution.

5.7 Overall Performance Comparison

Table 8. Overall Comparison of Current Control Strategies

Controller	THD	Dynamic Response	Robustness	Complexity	Cost	Overall Rating
PI	Moderate	Moderate	Moderate	Low	Low	★★★☆☆
PID	Moderate	Moderate	Moderate	Low	Low	★★★☆☆
PR	Good	Fast	Good	Medium	Medium	★★★★☆
Hysteresis	Good	Very Fast	Good	Low	Low	★★★★☆
Deadbeat	Very Good	Excellent	Moderate	Medium	Medium	★★★★☆
MPC	Excellent	Excellent	Excellent	High	High	★★★★★
Sliding Mode	Very Good	Excellent	Excellent	High	Medium	★★★★★
Adaptive	Very Good	Very Fast	Excellent	Medium	Medium	★★★★★
Fuzzy Logic	Excellent	Very Fast	Excellent	Medium	Medium	★★★★★
ANN	Excellent	Excellent	Excellent	High	High	★★★★★
Reinforcement Learning	Outstanding	Excellent	Excellent	Very High	Very High	★★★★★

5.8 Summary

The comparative analysis shows that no single controller is optimal for all applications. PI and PR controllers remain attractive for low-cost and industrial systems because of their simplicity and reliable operation. Model Predictive Control (MPC) and Sliding Mode Control (SMC) offer excellent dynamic performance and disturbance rejection but demand greater computational resources. Artificial Intelligence-based controllers, including Artificial Neural Networks (ANNs) and Reinforcement Learning (RL), achieve superior tracking accuracy, lower THD, and higher robustness, making them promising candidates for future smart grid and renewable energy applications. However, their practical implementation requires further research to reduce computational complexity and improve real-time feasibility.

6. Research Gaps and Future Research Directions

Despite significant advancements in current control strategies for single-phase grid-connected inverters, several technical challenges remain unresolved. Conventional controllers offer simplicity and ease of implementation but often struggle to maintain optimal performance under nonlinear operating conditions, parameter uncertainties, and weak-grid scenarios. On the other hand, advanced predictive and artificial intelligence-based controllers achieve higher accuracy and robustness but require greater computational resources and sophisticated hardware. This section identifies the major research gaps in the existing literature and outlines promising future research directions.

6.1 Research Gaps

Based on the literature reviewed from 2021–2026, the following research gaps have been identified.

Gap 1: Computational Complexity

Advanced controllers such as Model Predictive Control (MPC), Deep Learning, and Reinforcement Learning provide excellent dynamic performance but require high computational power, limiting their implementation on low-cost digital signal processors and embedded controllers.

Gap 2: Parameter Sensitivity

Many classical controllers, including PI, PID, and PR, exhibit degraded performance when system parameters change because of temperature variations, filter aging, or grid impedance uncertainty.

Gap 3: Weak Grid Performance

Most existing controllers are designed and validated under ideal grid conditions. Their performance deteriorates significantly under weak-grid conditions characterized by voltage fluctuations, frequency deviations, and harmonic distortions.

Gap 4: Harmonic Suppression

Although modern control strategies reduce Total Harmonic Distortion (THD), achieving consistently low harmonic levels under nonlinear loads and rapidly changing renewable energy generation remains a challenge.

Gap 5: Real-Time Implementation

Artificial intelligence-based controllers require extensive training, high memory capacity, and powerful processors, making real-time implementation difficult in practical inverter systems.

Gap 6: Lack of Explainability

Most AI-based current controllers function as black-box models, making it difficult to interpret control decisions. Limited transparency reduces confidence in their deployment for safety-critical power electronic systems.

Gap 7: Cybersecurity Considerations

Current control algorithms generally assume secure communication channels. Very few studies investigate cyber-attacks, false data injection, or malicious disturbances in smart grid-connected inverter systems.

Gap 8: Limited Hybrid Control Strategies

Most existing research focuses on a single control technique. Hybrid controllers combining classical, predictive, and intelligent control methods remain relatively unexplored despite their potential to improve robustness and computational efficiency.

Gap 9: Limited Experimental Validation

Many published studies validate controller performance only through simulation. Large-scale hardware implementation and real-time experimental verification under practical grid conditions remain limited.

Gap 10: Integration with Smart Grids

Current controllers are rarely designed considering future smart-grid requirements such as distributed energy management, demand response, Internet of Things (IoT), and vehicle-to-grid (V2G) integration.

6.2 Future Research Directions

Future research should focus on developing intelligent, adaptive, and computationally efficient current control strategies capable of addressing the limitations of existing methods.

The following research directions are recommended:

- Develop hybrid control strategies by integrating classical controllers with artificial intelligence and predictive control techniques to achieve better accuracy, robustness, and computational efficiency.
- Design lightweight AI algorithms suitable for real-time implementation on embedded processors, DSPs, and FPGA-based inverter platforms.
- Investigate Digital Twin technology for real-time monitoring, performance prediction, and fault diagnosis of grid-connected inverters.
- Incorporate Explainable Artificial Intelligence (XAI) techniques to improve the transparency and interpretability of AI-based current controllers.
- Apply Federated Learning to enable collaborative controller training across multiple distributed renewable energy systems while preserving data privacy.

- Explore Edge Computing for low-latency current control in smart microgrids and distributed energy resources.
- Develop cyber-resilient control strategies capable of detecting and mitigating cyber-attacks in intelligent power electronic systems.
- Integrate renewable energy forecasting and adaptive control to improve inverter performance under variable solar irradiance and load conditions.
- Extend current control techniques to multi-inverter and microgrid systems, ensuring coordinated operation, power sharing, and enhanced grid stability.
- Validate proposed control strategies through hardware-in-the-loop (HIL) testing and real-time experimental implementation to demonstrate practical feasibility.

6.3 Summary

The review highlights that existing current control strategies have achieved significant improvements in current tracking, harmonic reduction, and dynamic performance. However, challenges related to computational complexity, parameter sensitivity, weak-grid operation, explainability, cybersecurity, and practical implementation remain open research problems. Addressing these challenges through hybrid intelligent controllers, explainable AI, digital twin technology, edge computing, and hardware-based validation will play a key role in the development of next-generation single-phase grid-connected inverter systems for renewable energy and smart grid applications.

7. Conclusion

The rapid integration of renewable energy resources into modern power systems has significantly increased the importance of efficient and reliable single-phase grid-connected inverters. Among various inverter components, the current control strategy plays a critical role in ensuring accurate current tracking, low Total Harmonic Distortion (THD), fast dynamic response, robust grid synchronization, and compliance with international power quality standards. This review comprehensively analyzed recent developments in current control strategies for single-phase grid-connected inverters published between 2021 and 2026, covering conventional, predictive, nonlinear, adaptive, and artificial intelligence-based control techniques.

The review revealed that PI and PR controllers continue to be widely employed in industrial applications because of their simple implementation, low computational requirements, and satisfactory steady-state performance. However, these controllers exhibit limitations under nonlinear operating conditions and parameter uncertainties. Advanced approaches, including Deadbeat Control, Model Predictive Control (MPC), and Sliding Mode Control (SMC), offer superior dynamic response, improved disturbance rejection, and lower harmonic distortion, although their implementation complexity is considerably higher. Recently, Artificial Intelligence (AI)-based controllers, such as Fuzzy Logic, Artificial Neural Networks (ANNs), and Reinforcement Learning (RL), have demonstrated promising capabilities for adaptive control, enhanced robustness, and intelligent decision-making in smart grid environments.

The comparative analysis presented in this review indicates that no single control strategy is universally optimal for all grid-connected inverter applications. The selection of an appropriate controller depends on factors such as application requirements, computational resources, grid conditions, implementation cost, and desired performance objectives. While conventional controllers remain suitable for low-cost systems, predictive and AI-based controllers are expected to dominate future intelligent inverter applications owing to their superior tracking accuracy, robustness, and adaptability.

Finally, the review identified several open research challenges, including computational complexity, parameter sensitivity, weak-grid operation, cybersecurity, explainability of AI models, and real-time implementation. Future research should focus on hybrid intelligent control strategies, Digital Twin technology, Explainable Artificial Intelligence (XAI), Federated Learning, Edge Computing, and Hardware-in-the-Loop (HIL) validation to develop secure, adaptive, and high-performance grid-connected inverter systems. These advancements will contribute to the next generation of renewable energy integration, smart grids, and sustainable power electronics.

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