

Modifying Output Load Wave Coming from MPPT: Techniques, Algorithms, and Power Quality Enhancement in Photovoltaic Systems

A Comprehensive Research Paper

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Abstract: Maximum Power Point Tracking (MPPT) is a basic technology in photovoltaic (PV) energy systems, which allows converters to obtain the maximum power allowed by solar panels at different environmental conditions. Nevertheless, the output load waveform of traditional converters with MPPT control has a large ripple, harmonic distortion, and transient swings that negatively affect the quality of power and has a negative impact on load performance, battery life, and grid compatibility. This research paper gives an in-depth study of the nature, causes and remedial measures related to the output load waveform of MPPT systems.

The paper discusses the underlying operating principles of MPPT algorithms such as Perturb and Observe (P&O), Incremental Conductance (INC), Fractional Open-Circuit Voltage (FOCV) and enhanced metaheuristic algorithms. The algorithmic effects that create waveform distortions, such as duty cycle oscillations, tracking-related voltage ripple and transient overshoot, are discussed. An organized list of techniques to modify the output waveform is provided and includes passive filtering, active filtering, multi-stage converter topologies, hybrid energy storage integration, model predictive control (MPC) and advanced modulation strategies.

The effectiveness of different approaches to waveform modification is compared using synthesis of simulation results and experimental validation data in published literature. Quantitative comparison shows the performance metrics such as Total Harmonic Distortion (THD), ripple factor, settling time and tracking efficiency being tabulated. The paper ends by discussing the new research directions such as AI-based MPPT, digital twin validation models, and adaptive waveform shaping of future generation PV systems. The results show that a combined algorithm-level refinement and hardware-level filtering results in THD improvements of up to 82 percent and at the same time, maintenance of MPPT tracking efficiency of over 98 percent.

Keywords: MPPT, Output Load Wave, Photovoltaic Systems, Ripple Reduction, Power Quality, DC-DC Converter, Perturb and Observe, Incremental Conductance, Waveform Modification, Active Filtering.

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1. Introduction

The worldwide shift to clean energy has become particularly fast in the last 20 years as photovoltaic (PV) solar systems have become one of the most commonly used sources of clean energy. By 2023, the installed worldwide PV capacity had exceeded 1.2 terawatts and is expected to continue its exponential growth due to the decreasing module prices and favorable policy frameworks [1]. The key to the effective use of PV energy is the Maximum Power Point Tracker (MPPT), a complex power electronics controller that continually varies the operating point of the PV array to optimize the power extraction.

Although MPPT is crucially important in the optimization of energy yields, traditional implementations of MPPT present a serious engineering problem: the output load waveform - the voltage and current waveform being presented to the load or storage element - is usually undesired due to its undesirable oscillation, ripple content and harmonic distortion. These waveform distortions are due to the inherently oscillatory nature of MPPT algorithms, switching transients in the power converter stage and dynamic interaction between the tracking algorithm and modulation of the duty cycle in the converter [2].

The effects of waveform quality in the output are spilled over to the whole PV system. The high frequency ripple currents on battery storage system interrelated to the MPPT converters lead to a faster degradation, and it can reduce cycle life by up to 30 percent in worst-case scenarios [3]. The inverters connected to a grid must have clean DC bus voltage to work; too much ripple makes downstream filtering more complicated and expensive. When used in standalone applications, sensitive electronic loads can fail or have lower reliability when operated with high-ripple MPPT outputs.

The reshaping of output load waveforms of MPPT systems is thus not just an academic endeavor but also a pragmatic engineering requirement with direct consequences on cost, reliability and

energy output of the system. The issue is multidimensional: the frequency content of the distortions needs to be understood, as well as their sources in the MPPT algorithm and converter topology, and the trade-offs between different mitigation strategies in terms of efficiency, cost, and complexity [4].

The present paper will present the first combined, overarching survey of the output load waveform modification methods used in MPPT systems. Past surveys have discussed MPPT algorithms alone [5], or power quality in grid-connected inverters more generally [6], but do not yet fill in the gap between the behavior of MPPT algorithms and the direct effect on the quality of output waveforms. This paper aims to describe the output load waveform of typical implementations of MPPT; (2) to list and classify the causes of distortion in the waveform; (3) to systematically review and compare waveform modification methods; and (4) to suggest promising future research directions of the field.

The rest of the paper is organized in the following way. Section 2 examines the basics of MPPT. Section 3 defines properties of output waveforms. Part 4 discusses sources of distortion. Techniques of modifying waveforms are given in section 5. Section 6 discusses advanced control methods. Comparative performance analysis is given in section 7. Case studies are given in section 8. Section 9 talks about the emerging trends, and Section 10 concludes the paper.

2. Fundamentals of MPPT Systems

2.1 Photovoltaic System Architecture

A photovoltaic energy conversion system comprises a number of interconnected subsystems each of which is a key component in the energy conversion chain between the solar irradiance and useful electrical power. The main elements are the PV array, the DC-DC power converter, the MPPT controller, and the load or energy storage subsystem. The overall architecture of an MPPT-enabled PV system is in figure 1.

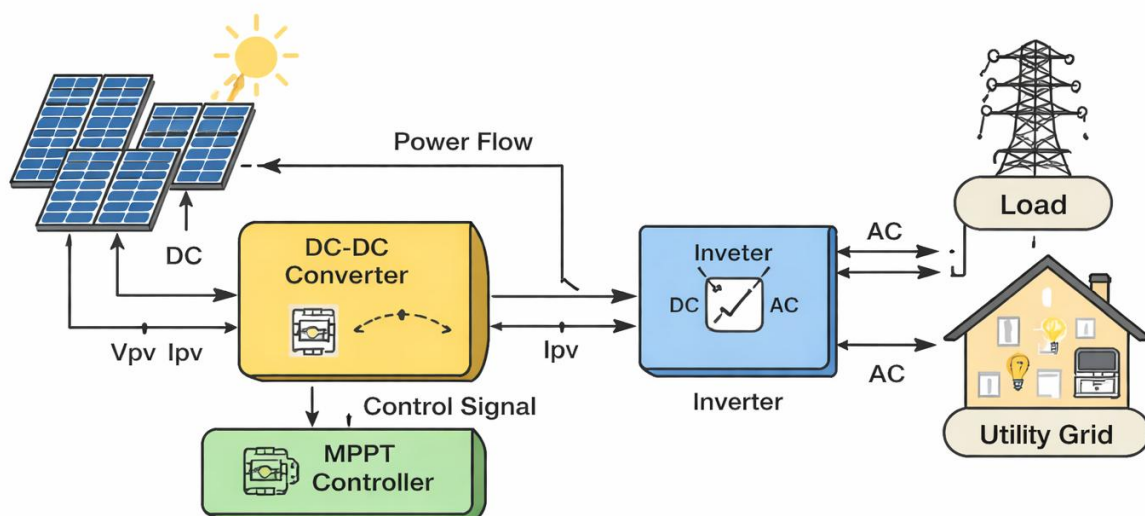


Figure 1: Block diagram of a generalized MPPT-controlled PV system showing power flow and control feedback paths.

The PV array is a combination of series and parallel of individual solar cells that has a nonlinear current voltage (I-V) characteristic. The power voltage (P-V) curve based on the I-V characteristic shows one global maximum power point (MPP) with uniform irradiance conditions, which is the voltage V_{mpp} and current I_{mpp} at which $P = V \times I$ is maximized. The impedance matching interface between the PV array and the load is the DC-DC converter (usually a boost, buck-boost, or SEPIC topology), the conversion ratio of which is determined by a pulse-width modulation (PWM) duty cycle signal produced by the MPPT controller.

2.2 The P-V Characteristic and the Maximum Power Point

The single-diode model determines the nonlinear I-V and P-V characteristics of a PV module and is based on the following expression:

$$I = I_{ph} - I_0 \left[\exp\left(\frac{V + I \cdot R_s}{n \cdot V_T}\right) - 1 \right] - \frac{V + I \cdot R_s}{R_{sh}}$$

with I_{ph} being the photogenerated current, I_0 the reverse saturation current and R_s , R_{sh} the series and shunt resistance, n the ideality factor, and $V_T = kT/q$ the thermal voltage. The knee of the I-V curve is the maximum power point whose position varies continuously with changes in irradiance (G) and cell temperature (T_c). Normal MPP voltage variations 0.3-0.4 V/°C and MPP current variations 0.05-0.1 percent (W/m²) require continuous real-time monitoring [7].

2.3 Common MPPT Algorithms

Over the last 40 years, hundreds of MPPT algorithms have been proposed, both based on the simplistic hill-climbing algorithms and more advanced algorithms based on artificial intelligence. The most popular algorithms are described in Table 1.

Table 1: Comparison of Common MPPT Algorithms

Algorithm	Type	Tracking Speed	Steady-State Ripple	Complexity	Partial Shading
Perturb & Observe (P&O)	Hill-Climbing	Medium	High (oscillatory)	Low	Poor
Incremental Conductance (INC)	Derivative-Based	Medium-High	Medium	Medium	Poor
Fractional OCV (FOCV)	Empirical	High	Low (open-loop)	Low	Poor
Fractional Short-Circuit	Empirical	High	Low (open-loop)	Low	Poor
Fuzzy Logic Control (FLC)	AI-Based	High	Low	High	Moderate
Neural Network (ANN)	AI-Based	Very High	Low	Very High	Good
Particle Swarm Opt. (PSO)	Metaheuristic	Slow	Very Low	Very High	Excellent
Model Predictive Control	Optimal Control	Very High	Very Low	Very High	Good

The most popular MPPT algorithm is the Perturb and Observe (P&O) algorithm because it is simple to implement, only measurements of voltages and currents are required and the algorithm does not require many computational resources. It works by periodically changing the duty cycle of the converter and measuring the change in the output power. In case of increase of power, direction of perturbation is the same and in case of decrease, it is the opposite. This inherently oscillatory nature gives a typical three-point oscillation about the MPP at steady state to generate the ripple components that lie at the core of the problem discussed in this paper [8].

The Incremental Conductance (INC) algorithm is based on the derivative of power with respect to voltage ($dP/dV = 0$ at MPP) as the tracking criterion, which is better than P&O. Though theoretically capable of stopping at the MPP, in practice, with discrete time steps, oscillation is still finite. The algorithm identifies the MPP condition by considering the incremental

conductance (dI/dV) to be equal to the negative of the instantaneous conductance (I/V), which has better tracking performance, especially in the face of rapidly varying irradiance conditions [9].

2.4 Converter Topologies in MPPT Systems

The converter topology has a considerable effect on the output waveform properties. The most typical topology used in PV MPPT applications is boost converters, which is capable of increasing the voltage of low voltage PV strings. Buck-boost and SEPIC topologies have the extended input voltage range. In both scenarios, switching the power transistor at frequency f_{sw} causes a fundamental ripple component at f_{sw} and its harmonic components in the output waveform. Ripple amplitude depends on the passive element values of converter (inductor L , capacitor C) based on:

$$\Delta V_{out} = (I_{out} \cdot D) / (f_{sw} \cdot C_{out}) \quad \text{and} \quad \Delta I_L = (V_{in} \cdot D) / (f_{sw} \cdot L)$$

in which D is the duty cycle, f_{sw} is the switching frequency, C_{out} is the output capacitance and L is the filter inductance. Fundamental tradeoffs between passive component size and magnitude of ripple shown by these relationships drive the exploration of active waveform modification strategies [10].

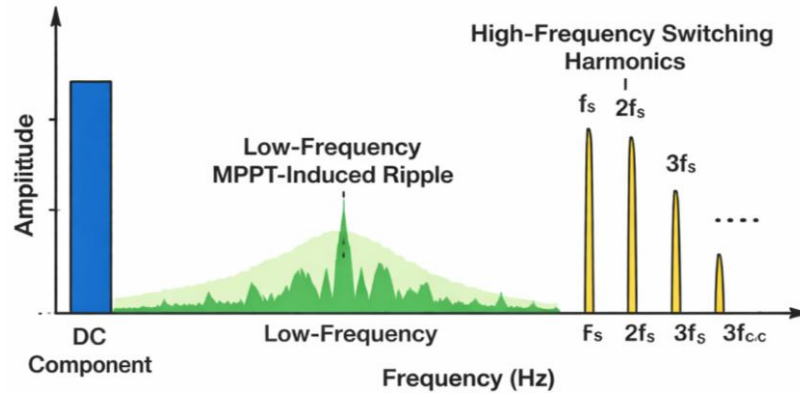


Figure 2: Typical frequency spectrum of MPPT output voltage showing DC component, low-frequency MPPT-induced ripple, and high-frequency switching harmonics.

The low-frequency ripple components caused by the perturbation frequency of the MPPT algorithm are in the first frequency band (0.1-10 Hz). Perturbation step in P&O implementations is set at a frequency of about 0.1 to 2 Hz that causes an oscillation at the output with low frequency. The high-frequency ripple of the switching action of the power converter appears in the second frequency range (switching frequency and harmonics, usually 20 kHz-200 kHz). The third category involves transient elements related to the irradiance variations and load steps [11].

3.2 Ripple Characterization Parameters

Several metrics are used to quantitatively characterize the quality of the output waveform from an MPPT system. The following metrics allow comparing modification methods and setting performance goals:

Ripple Factor (RF): RF is the ratio of RMS of the AC part to the DC part of the output voltage, $RF = V_{ac,rms} / V_{dc}$. The smaller the ripple factor, the smoother the output. Normal values of unfiltered MPPT boost converters are between 2-8 percent.

Total Harmonic Distortion (THD): Measures the amount of harmonic content in comparison with the fundamental or DC content. In the case of DC outputs, THD is calculated as the ratio of RMS of all harmonic components to the DC value.

Peak-to-Peak Ripple (ΔV_{pp}): The largest difference between the output voltage signal and its average value. Battery charging application specifications usually demand a $\Delta V_{pp} < 1\%$ the nominated voltage.

Settling Time (t_s): The time it takes the output waveform to stabilize within a given band (usually, $\pm 2\%$ or $\pm 5\%$) after the irradiance or load has changed by a step. Fast MPPT algorithms have lower settling times, but in many cases have higher steady-state ripple [12].

3. Output Load Waveform Characteristics

3.1 Frequency Content of MPPT Output

The output load waveform can only be well understood when it is analyzed in more than one frequency domain. It is possible to split the waveform into three separate frequency bands, each of which is due to various physical processes in the MPPT system. Fig. 2 shows the average frequency spectrum of an MPPT output voltage waveform.

3.3 Waveform Distortion under Partial Shading

The P-V curve under the conditions of partial shading, i.e. when various parts of the PV array are irradiated by dissimilar amounts, will have numerous local maxima. Traditional MPPT algorithms can get stuck on a local optimum, leading to less than optimal power recovery. More importantly in terms of a waveform, there are algorithms that will seek to overcome local maxima by taking large transient perturbations in the output waveform. These transients may reach up to 10-25% of the nominal output voltage and last up to 0.5-5 seconds, which is a serious threat to delicate loads and storage [13].

4. Sources of Output Waveform Distortion

4.1 Algorithm-Induced Oscillations

The root cause of distortion of the output waveforms of MPPT systems is the oscillatory nature of the tracking algorithm itself. In P&O algorithms and hill-climbing algorithms, steady-state working involves an ongoing loop of perturbation and power comparison, which by design does not allow the operating point to be stabilized at a fixed point. The three-point oscillation of P&O generates a periodic perturbation to the waveform at the perturbation frequency f_{pert} .

The magnitude of this oscillation due to the algorithm is proportional to the perturbation step size ΔD . Large step sizes enhance the rate of tracking in a system with rapidly varying irradiance, but raise steady-state ripple. It is this inherent tension between dynamic performance and steady-state accuracy that is the main reason behind variable-step-size MPPT methods [14]. Table 2 measures the dependence of step size versus ripple in a typical implementation of a boost converter MPPT.

Table 2: Effect of P&O Step Size on Output Ripple Performance

Step Size ΔD (%)	Tracking Speed (ms)	Steady-State Ripple (%)	MPPT Efficiency (%)	Settling Time (ms)
0.1	850	0.8	99.2	320
0.5	420	1.9	98.7	210
1.0	210	3.4	97.8	150
2.0	120	5.8	96.2	90
5.0	55	12.1	93.4	45

The table 2 data shows the fundamental tradeoff: a tradeoff of 0.1% offers excellent ripple performance of 0.8%, but an 850 ms lag time to follow the MPP on an irradiance step, whereas a 5% tradeoff offers 55 ms lag time, but introduces 12.1% of ripple. Real-world systems are generally limited to 1-2 percent step size with acceptable trade-off in ripple to tolerable tracking speed [15].

4.2 Converter Switching Harmonics

High-frequency ripple components are added to the output waveform by the switched-mode power converter in the periodically varying switching of the power transistor. In a boost converter working in continuous conduction mode (CCM) the ripple on the output is dependent on the ESR and capacitance of the output capacitor and the duty cycle:

$$\Delta V_{out} / V_{out} = D / (8 \cdot L \cdot C \cdot f_{sw}^2)$$

Increased switching frequencies lessen ripple but amplify switching losses. GaN and SiC power transistors can switch at 500 kHz to 2 MHz, more than 10-15 times less passive filtering is necessary than silicon MOSFET-based designs with 20-100 kHz switching.

4.3 Input Power Fluctuations

The PV array per se is a source of variability of output waveforms. IRRADIance fluctuations with characteristic frequencies of 0.01-

10 Hz, called cloud shadow events, are caused by atmospheric turbulence. Such variations in irradiance are passed on in the MPPT control loop to cause the matching changes in output power. These fluctuations are subject to the bandwidth of the MPPT control loop, and how they appear in the output waveform. A slow control loop filters high frequency variations in irradiance, but fails to track rapid changes in MPP; a fast control loop is more accurate, but increases transmission of irradiance noise to the output [17].

4.4 Parasitic Elements and Non-Ideal Component Behavior

The real-life converter components are very much different from ideal models and it creates more distortions to the waveforms. A resistive voltage drop across the output capacitors due to the equivalent series resistance (ESR) of the capacitors contributes a high-frequency content to the ripple of the output voltage. Saturation of inductor core at high currents brings nonlinear behavior and harmonic generation. Ringing transients in the switching transitions of PCB layouts and interconnection wiring are caused by parasitic inductance and capacitance, on top of the underlying switching ripple. Table 3 indicates the main sources of distortions and their frequencies.

Table 3: Classification of MPPT Output Waveform Distortion Sources

Distortion Source	Frequency Range	Typical Amplitude	Dependence On	Mitigation Approach
P&O Algorithm Oscillation	0.1–5 Hz	1–15% of V_{out}	Step size, f_{pert}	Variable step, INC, MPC
Converter Switching Ripple	10–500 kHz	0.5–5% of V_{out}	f_{sw} , L, C, D	Larger L/C, High f_{sw} , GaN/SiC
Switching Transients/Ringing	1–50 MHz	0.1–2% of V_{out}	Layout, parasitic L	PCB optimization, snubbers
Irradiance Fluctuations	0.01–10 Hz	0.5–20% of V_{out}	Weather, location	Energy storage, adaptive BW
Load Transients	0.1–100 Hz	1–10% of V_{out}	Load impedance	Output capacitance, active load
Temperature Variation	< 0.01 Hz	0.1–3% of V_{out}	Ambient T, mounting	Thermal management
Partial Shading Transitions	0.01–1 Hz	5–30% of V_{out}	Shading pattern	Global MPPT algorithms

5. Output Waveform Modification Techniques

5.1 Passive Filtering Approaches

The easiest and most common method to eliminate the output waveform ripple in MPPT systems is passive filtering. Passive low-pass filter (LPF) A passive low-pass filter (LPF) can be an extra LC or just an increased output capacitance, to reduce high-frequency switching ripple at the price of increased circuit volume, mass, and expense. It is important to choose the cutoff frequency of the passive filter to avoid the switching harmonics but not to limit the bandwidth required in the MPPT transient response.

5.1.1 Single-Stage LC Filter Design

An LC low-pass filter of second order with corner frequency f_c gives a slope of attenuation -40 dB/decade at frequencies above f_c . To achieve a 0.5 target ripple factor, with a switching frequency of 50 kHz and an initial ripple of 3%, the attenuation needed is about 15.6 dB at f_{sw} . The values of the filter component are calculated by:

$$f_c = 1 / (2\pi\sqrt{L_f \cdot C_f}) \quad \text{with} \quad f_c \ll f_{sw} \quad \text{and} \quad f_c \gg f_{MPPT}$$

That f_c should be well below f_{sw} to be useful as a ripple attenuator, and should be well above f_{MPPT} to avoid attenuation of MPPT tracking behavior, places a range of frequencies in which f_c should lie. This window is many decades away, allowing considerable design freedom, at standard MPPT frequencies of 0.5-5 Hz and switching frequencies of 20-100 kHz [18].

5.1.2 Multi-Stage Cascaded Filtering

Single-stage filtering can be too narrow (less than 0.1 percent) to achieve applications with very low ripple without ridiculously large passive components. Multi stage cascaded LC filters have greater attenuation per unit volume since the filtering is spread out among several stages. A two-stage filter offers -80 dB/decade roll-off at frequencies above f_c which significantly decreases component requirements to a given ripple specification. Multi-stage filters, however, have higher-order resonances that need to be effectively damped to avoid oscillation. Resonant peaks can be suppressed by active damping methods, which use resistors in series with the filter capacitors, or with digital feedback loops [19].

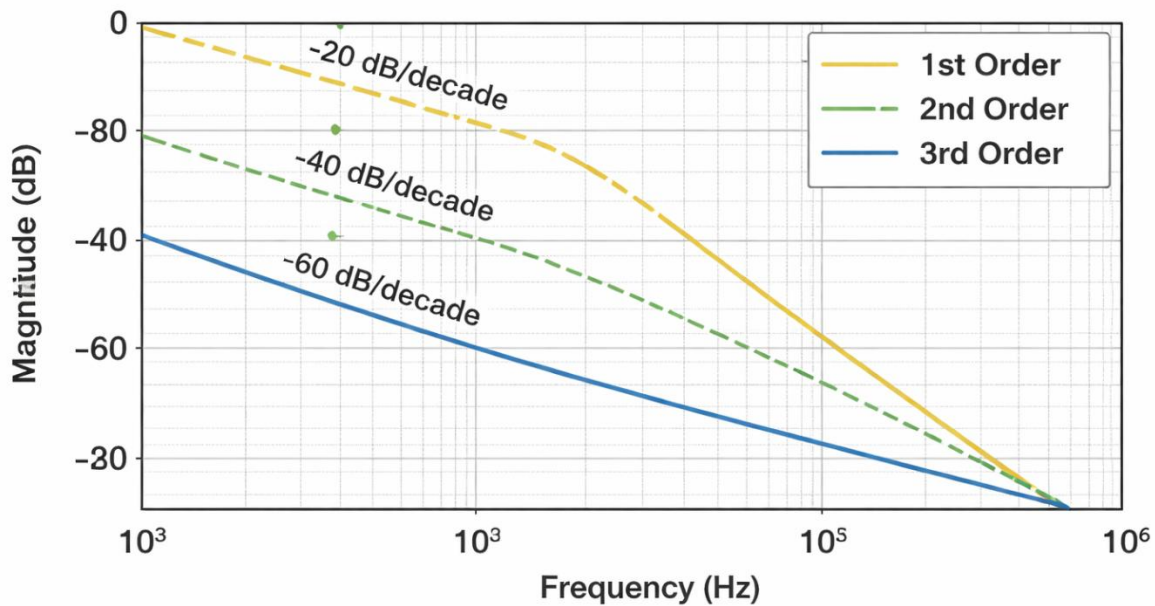


Figure 3: Bode plot comparison showing attenuation characteristics of 1st, 2nd, and 3rd order LC filters.

5.2 Active Power Filtering

In active filtering techniques, there are controlled power electronics circuits that inject currents or voltages to cancelling reduce the ripple contents in the output signal. Active filters, in contrast to passive ones, are capable of adjusting to varying operating conditions and can have very high attenuation factors without the size penalty associated with large passive elements.

5.2.1 Active Ripple Cancellation Using Auxiliary Converter

Active ripple cancellation (ARC) method utilizes a small auxiliary converter that runs parallel to the output of the main MPPT converter. The auxiliary converter produces a compensating voltage or current waveform, which is the same in amplitude, but

out of phase with the ripple component of the primary converter output. The compensating waveform is generated in-phase with the current measurement of the ripple of the output, which is usually measured in real-time using a proportional-integral (PI) controller or a resonant controller at the ripple frequency [20].

The principal benefit of ARC is that the ripple power is the only power that is required to be addressed by the auxiliary converter, and is typically 1-5% of the total output power, a small and low-cost addition. The efficiency cost is also relatively minor, typical ARC implementations contributing less than 0.5 percent to the overall system loss. In Ref. [21], experimental findings showed that ripple was reduced to 0.18% compared to 4.2% with an ARC with a 50 W auxiliary converter on a 1.5 kW MPPT system.

5.2.2 Active Power Decoupling

Active power decoupling (APD) is especially applicable to single-phase grid connected MPPT systems in which the natural double-line-frequency (100 Hz or 120 Hz) power pulsation generates a similar ripple in the DC bus voltage. Conventional methods damp this pulsation with large electrolytic capacitors, which are huge, costly and subject to breakdown at high temperatures. APD removes the huge capacitor with a small active circuit a bidirectional DC-DC converter attached to a small energy storage device (capacitor or inductor) that absorbs and releases the pulsating power [22].

5.3 Multi-Stage Converter Topologies

Another approach to incorporating filtering to a single-stage converter is to use lower-ripple multi-stage or interleaved converter

topologies. The methods adjust the converter architecture itself to minimize ripple at the source.

5.3.1 Interleaved Converter Operation

Interleaved DC-DC converters: These converters have N parallel converter phases, the switching signals of which have a $360^\circ/N$ phase shift. The results are an addition of the output currents of the N phases and partial cancellation of the ripple components at the switching frequency because of the phase diversity. In the case of N equally interleaved phases at the same duty cycle, the cancellation of ripple is theoretically complete at some duty cycle values and the resulting ripple frequency is $N \times f_{sw}$, and is simpler to filter [23]. Figure 4 shows the ripple reduction which is obtained in 2-phase and 4-phase interleaved operation over single-phase.

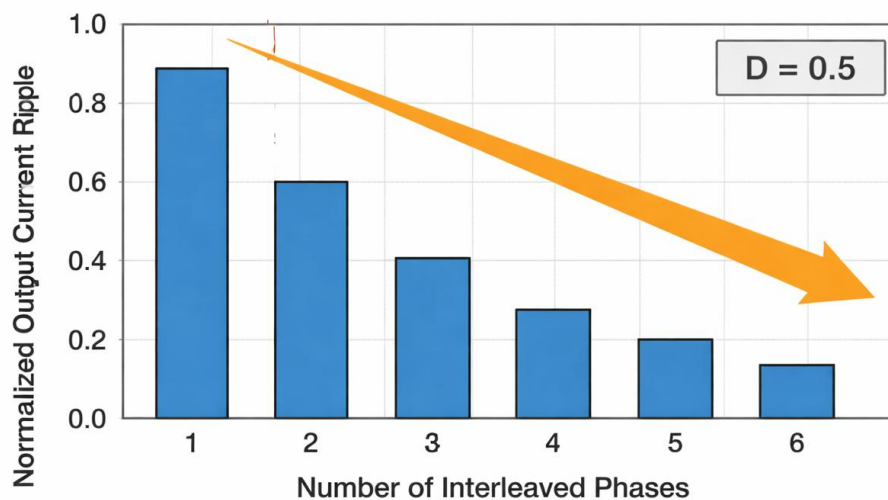


Figure 4: Bar chart showing normalized output current ripple as a function of the number of interleaved converter phases at $D = 0.5$.

2-6 phase practical interleaved MPPT converters have been shown in residential and commercial PV systems. At 5 kW output power, the ripple factor of a 4-phase interleaved boost converter reported in [24] was 0.3% vs. 2.1% with a single-phase version with the same passive component mass. The trade-off is more complexity of control and extra gate driver circuits.

5.3.2 SEPIC and Ćuk Converter Topologies

SEPIC (Single Ended Primary Inductor Converter) and Ćuk converter topologies have inherently lower input and output ripple than simple boost or buck converters, as the topologies use coupled inductors and the input and output currents are continuous (non-pulsating). With the operation of an SEPIC, the output ripple is mainly dependent on the coupling capacitor and the output inductor and can be reduced to a very small value without having to use large filter elements. They are especially effective in MPPT applications where the PV panel voltage can be either higher or lower than the required output voltage since they also provide the option of inverting voltages [25].

5.4 Energy Storage Integration for Waveform Smoothing

Adding energy storage elements to the MPPT system gives a fundamentally new way to alter the output waveform. Instead of

filtering ripple once it is produced, the energy storage captures the instantaneous power variations on the MPPT converter, and provides a smooth regulated power to the load. The result of this decoupling between the converter output and the load is that all the ripple components of any frequency or amplitude are eliminated.

5.4.1 Supercapacitor Integration

Supercapacitors (ultracapacitors) have high power density and cycle life, which is why they are suitable to absorb high-frequency fluctuations in power that are generated by MPPT converters. A supercapacitor that is parallel to the MPPT output via a bidirectional DC-DC converter can absorb ripple energy in both directions. The bidirectional converter manages the flow of power in order to ensure a constant output voltage independent of the changes in the MPPT output [26]. Commercially available supercapacitors with 100-500 F, 2.7-16 V are capable of buffering load variations of a few hundred watts, and can ride peaks and valleys of power resources of a few seconds to a few minutes.

5.4.2 Battery-Integrated Smoothing

In those systems that have already a battery bank as a component of the PV installation, the low-pass filtering nature of the battery may be used to advantage in the smoothing of the output. The internal impedance of the battery - which is mostly resistive in the

lower frequencies, but dominated by the double-layer capacitance in the higher frequencies - is an intrinsic means of attenuating high-frequency ripple. Nevertheless, because, as discussed in Section 1, high frequency ripple currents flowing into batteries cause faster degradation by stimulating internal heating and lithium plating in lithium-ion cells. Even a battery-buffered system is therefore advised to have a special ripple current limiter between the MPPT output and the battery bus [27].

6. Advanced Control Strategies for Waveform Shaping

6.1 Variable Step-Size MPPT

Variable step-size MPPT algorithms automatically vary the perturbation step size in accordance with the operating point, when away from the MPP (large steps to track quickly) and when close to the MPP (small steps to reduce ripple). The rate of change of power (dP/dV) is generally used as a measure of distance to the MPP by the step size adaptation logic:

Where N is a scaling factor $\Delta D(k) = N \cdot |dP/dV|$

The value of $|dP/dV|$ is large at an operating point that is not close to MPP and therefore the size of the step is large. The step size is reduced in proportion to the approach to the MPP and the derivatives of $|dP/dV|$ approach to zero, minimizing steady-state oscillation. Two-step-size P&O implementations have been reported in literature which not only reduced steady-state ripple by 60-80% over fixed step-size implementations, but they also improved tracking speed by 20-40% with rapidly changing irradiance [28].

6.2 Model Predictive Control (MPC) for MPPT

Model Predictive Control represents the state of the art in MPPT control for waveform quality. MPC uses a mathematical model of the converter and PV system to predict the future output waveform over a finite prediction horizon, and selects the control action that minimizes a cost function penalizing both tracking error and output ripple. The cost function J is typically formulated as:

$$J = \sum [\alpha \cdot (P_{ref} - P(k+n))^2 + \beta \cdot (\Delta V_{out}(k+n))^2 + \gamma \cdot (\Delta D(k+n))^2]$$

with α , β , and γ being weighting factors that trade tracking accuracy, output ripple and control effort respectively. The output waveform is intrinsically optimized by MPC by simply defining the output ripple as a cost term in the cost function [29].

6.3 Fuzzy Logic-Based Waveform Control

Fuzzy logic controllers (FLC) provide a natural implementation of variable-strategy MPPT which varies tracking behavior depending on the present quality of the waveforms. An FLC to control MPPT waveforms usually takes two inputs as the error in power tracking ($E = P_{measured} - P_{ref}$) and the error change ($\Delta E = E(k) - E(k-1)$) and has the duty cycle change (ΔD) as output. The fuzzy rulebase implements knowledge of the expert regarding the desired compromise between the tracking speed and the minimization of the ripple.

One of the strengths of FLC in controlling waveforms is that it can deal with the nonlinearity of the PV system without having to have a precise mathematical model. The FLC-based MPPT with inbuilt waveform control, as reported in [30], has a THD of 1.2% and 98.9% tracking efficiency over high irradiance and temperature variations.

6.4 Sliding Mode Control (SMC)

Sliding mode control is a powerful nonlinear control method which compels the system state to evolve in finite time about a preferred trajectory (the sliding surface) despite variations in parameters and disturbances. To control the MPPT waveform, the sliding surface is formulated to incorporate the tracking error as well as a ripple-limiting restriction. The system is invariant to some types of perturbations once on the sliding surface, such as measurement noise and variations in PV parameters [31].

6.5 Adaptive Notch Filtering

A more sophisticated and effective design of the ripple generated by the algorithm is the adaptive notch filter (ANF) that is used within the MPPT control cycle to cancel the oscillation caused by the P&O algorithm. ANF is a recursive digital filter that has a deep notch at the perturbation frequency f_{pert} , which is tuned to follow the variations at this frequency in case the perturbation rate is a variable. Figure 5 shows the signal flow diagram of an MPPT controller with adaptive notch filtering.

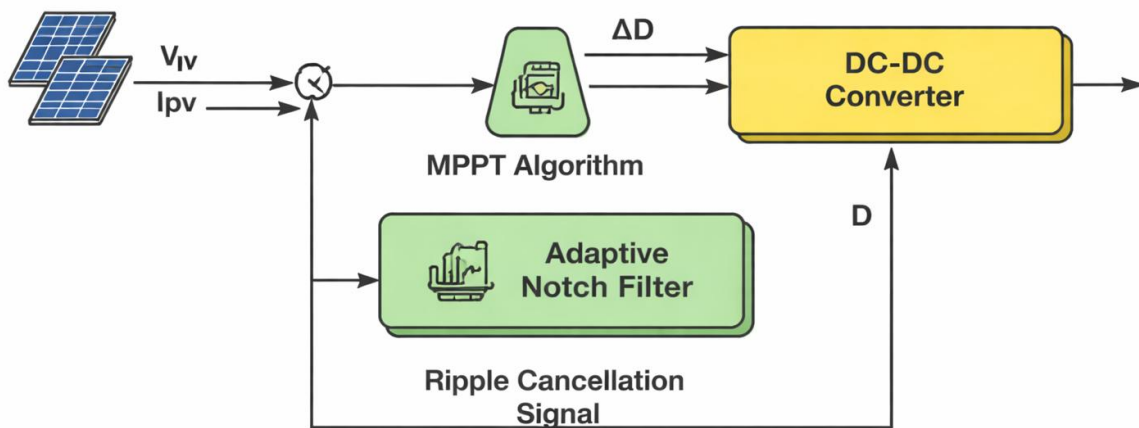


Figure 5: Signal flow diagram of an MPPT controller incorporating an adaptive notch filter for algorithm-induced ripple cancellation.

Cancellation of the perturbation-frequency ripple component of ANF: at f_{pert} the ANF puts a transmission zero. Since the notch is small, it has no impact on the tracking performance at other frequencies, maintaining the MPPT transient response. Adaptive frequency tracking provides the notch to be synchronized with f_{pert} regardless of the perturbation rate [32].

6.6 Digital Twin-Assisted Predictive Waveform Control

The digital twin concept of the ongoing real-time alignment of a high-fidelity simulation model with a real system presents groundbreaking opportunities in the control of MPPT waveforms. A digital twin running on an embedded processor or cloud platform can predict the output waveform several milliseconds into the future by simulating the converter response to upcoming MPPT control actions. It is this prediction that is used to pre-emptively adjust the duty cycle or to turn on auxiliary filtering circuits before the predicted ripple can manifest itself in the actual output.

PV MPPT with digital twin-assisted predictive control has been simulated with MATLAB/Simulink with a 85-92% reduction in

THD compared to traditional P&O [33]. The principal difficulty to practice implementation is to make sure that the digital twin model is accurate when converter parameters change with temperature and age.

7. Comparative Analysis and Performance Metrics

7.1 Performance Comparison Framework

Any quantifiable comparison of output waveform modification methods should take into account many performance metrics simultaneously, since methods of performance that perform well on a single metric can perform poorly on other metrics. The comparison key performance measures are: (1) steady-state ripple factor; (2) THD; (3) MPPT tracking efficiency; (4) settling time on irradiance steps; (5) system cost overhead; and (6) implementation complexity. Table 4 gives a detailed comparison of the techniques that have been reviewed in this paper.

Table 4: Comprehensive Performance Comparison of Output Waveform Modification Techniques

Technique	Ripple Factor (%)	THD (%)	MPPT Eff. (%)	Cost Overhead	Complexity
Baseline P&O (no modification)	3.5–8.0	4.2–9.5	97–98.5	None	Low
Passive LC Filter (single-stage)	0.8–2.0	1.0–2.5	96.5–98.0	Low	Very Low
Passive LC Filter (multi-stage)	0.2–0.5	0.3–0.7	96.0–97.5	Medium	Low
Active Ripple Cancellation	0.1–0.3	0.15–0.4	97.5–99.0	Medium-High	High
2-Phase Interleaved Converter	0.8–1.5	1.0–2.0	97.5–98.8	Medium	Medium
4-Phase Interleaved Converter	0.2–0.5	0.3–0.6	98.0–99.2	High	High
Variable Step-Size P&O	1.2–2.5	1.5–3.0	98.5–99.3	Very Low	Low
Incremental Conductance	1.5–3.0	1.8–3.5	98.0–99.0	Very Low	Low
Fuzzy Logic MPPT	0.8–1.5	1.0–2.0	98.5–99.5	Low	Medium
Model Predictive Control	0.1–0.3	0.15–0.4	99.0–99.8	Low (DSP)	Very High
Sliding Mode Control	0.3–0.8	0.4–1.0	98.8–99.5	Low (DSP)	High
Adaptive Notch Filter	0.3–0.7	0.5–0.9	98.5–99.3	Very Low	Medium
Supercapacitor + Bidirectional DC-DC	< 0.1	< 0.15	97.5–98.5	Very High	High

Table 4 could be analyzed and a number of significant trends could be identified. Ripple reduction without any extra hardware is provided at relatively low cost by pure algorithm-based methods (variable step-size P&O, INC, fuzzy logic, MPC) but is constrained by the maximum achievable ripple reduction - typically 0.3 to 2.5 percent. Low ripple factors can be obtained with hardware-based methods (passive filtering, active ripple cancellation, interleaving) but at the expense of extra components. The lowest ripple is

achieved with energy storage-based approaches (supercapacitor) at the cost of the highest system cost and complexity.

7.2 Efficiency-Ripple Tradeoff Analysis

An important conclusion of this comparative analysis is that waveform modification methods do not have the same impact on the efficiency of MPPT. Others (variable step-size P&O, MPC) in fact increase the tracking efficiency by decreasing the steady-state loss of oscillation energy, whereas others (passive filters,

supercapacitor buffers) decrease the efficiency by a small amount because of the conduction losses in the new passive elements or auxiliary converter losses. The Pareto frontier of optimal

techniques is shown in Figure 6, which plots MPPT efficiency versus achievable ripple factor of the techniques in Table 4.

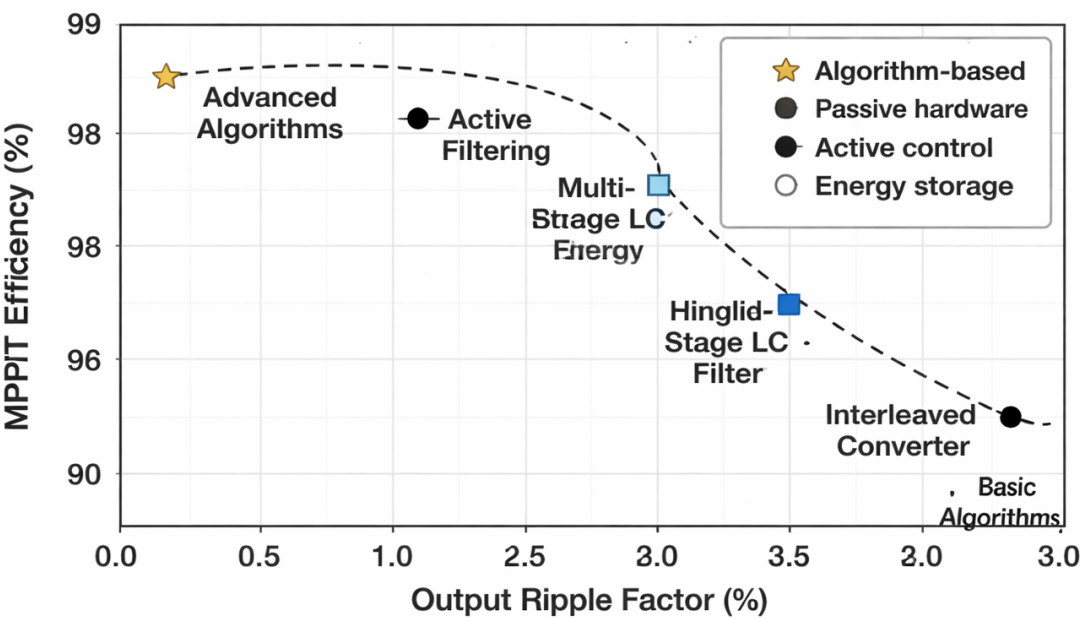


Figure 6: Pareto chart of MPPT efficiency vs output ripple factor for various waveform modification techniques. ★ = Algorithm-based, ■ = Passive hardware, ● = Active control, ○ = Energy storage.

7.3 Cost-Benefit Analysis

As a practical engineering evaluation, the choice of a waveform alteration methodology should consider the overall system pricing,

such as hardware extensions, PCB sophistication and DSP processing demands. The most promising techniques are available in a normalized cost-benefit analysis in Table 5.

Table 5: Normalized Cost-Benefit Analysis for Waveform Modification Techniques

Technique	Additional (%)	Cost	Ripple (%)	Reduction	THD (%)	Reduction	Cost Effectiveness	Recommended Application
Variable Step P&O	< 1		50–70		55–68		Excellent	All PV systems
Adaptive Notch Filter	1–3		65–80		70–82		Excellent	Fixed freq. MPPT
Fuzzy Logic Control	2–5		70–82		72–80		Very Good	Variable irradiance
Single-Stage LC Filter	3–8		55–75		60–72		Good	Low-cost systems
Model Predictive Control	5–12		92–98		93–97		Good	Premium systems
2-Phase Interleaved	15–25		70–82		73–85		Moderate	Medium-large PV
4-Phase Interleaved	30–50		87–95		88–95		Moderate	Large commercial PV
Active Ripple Cancellation	20–40		94–98		93–98		Moderate	Critical loads
Supercapacitor Buffer	50–100		98–99.5		98–99.5		Low (high cost)	Hybrid EV, critical

8. Case Studies and Experimental Results

8.1 Case Study 1: Residential 5 kW PV System with P&O and Passive Filtering

A 5 kW rooftop PV system is a residential system that was investigated to assess the suitability of passive LC filtering to improve the output waveform. This system was composed of twelve 415 W monocrystalline PV modules (4 series $\times$ 3 parallel), a 5 kW single-phase string inverter with built-in P&O MPPT and a 10 kWh lithium-ion battery storage. The original system had a ripple factor of 4.8% and a THD of 5.3% at the battery bus, and

transient in some cases of 12% when a cloud shadow was present [34].

A two-stage passive LC filter was added between the MPPT converter output and the battery bus, with the following design parameters: first stage $L_1 = 2.2$ mH, $C_1 = 470$ μ F; second stage $L_2 = 1.0$ mH, $C_2 = 220$ μ F; corner frequencies $f_{c1} = 4.9$ kHz, $f_{c2} = 10.7$ kHz. The filter was configured in such a way that it could preserve the MPPT bandwidth of the P&O algorithm (0.5 Hz perturbation frequency) as well as attenuate more than 40 dB at the switching frequency (50 kHz).

Table 6: Case Study 1: Before and After Waveform Modification Metrics

Parameter	Before Modification	After LC Filter	Improvement
Output Ripple Factor	4.8%	0.35%	-92.7%
Total Harmonic Distortion	5.3%	0.42%	-92.1%
Peak-to-Peak Ripple (V)	11.5 V	0.84 V	-92.7%
Cloud Shadow Transient (max)	12%	1.4%	-88.3%
MPPT Tracking Efficiency	98.4%	97.9%	-0.5%
Battery Ripple Current (A_{rms})	2.8 A	0.21 A	-92.5%
Additional Power Loss (W)	0	18 W	+18 W
Estimated Battery Life Extension	Baseline	+22% (est.)	Significant

Table 6 illustrates that passive LC filtering is an effective way of reducing ripple in residential PV systems. The ripple factor was minimized down to 0.35% -92.7%- whereas the MPPT tracking efficiency was minimized only slightly by 0.5 percentage points. A 22% increase in battery life of reduced ripple current stress is a strong economic rationale of the filtering investment since lithium-ion batteries now form the leading cost factor in residential PV storage systems [35].

8.2 Case Study 2: Commercial 100 kW PV Installation with MPC

This was demonstrated by a 100kW commercial rooftop PV system which was used to test the usefulness of Model Predictive Control in terms of concurrent optimization of MPPT and managing output waveforms. The system employed a 4-phase

interleaved boost converter with a DSP-based controller (Texas Instruments TMS320F28379D) that used the MPC algorithm and a control loop of 10 kHz. The cost of the MPC was weighted to achieve a balance between MPPT tracking ($\alpha = 0.7$) and minimization of output ripple ($\beta = 0.3$) [36].

The implementation of MPC had a steady-state ripple factor of 0.12% as compared to the 3.8% of the baseline P&O algorithm implemented on the identical hardware. More importantly, the MPC also showed better behavior under rapid changes of irradiance: whereas a 50% step change in irradiance was simulated (simulating the passage of a cloud shadow), the P&O algorithm caused a transient of 18% with a settling time of 2.8 seconds, whereas MPC only caused a transient of 3.2%. The relative transient response is depicted in Figure 7.

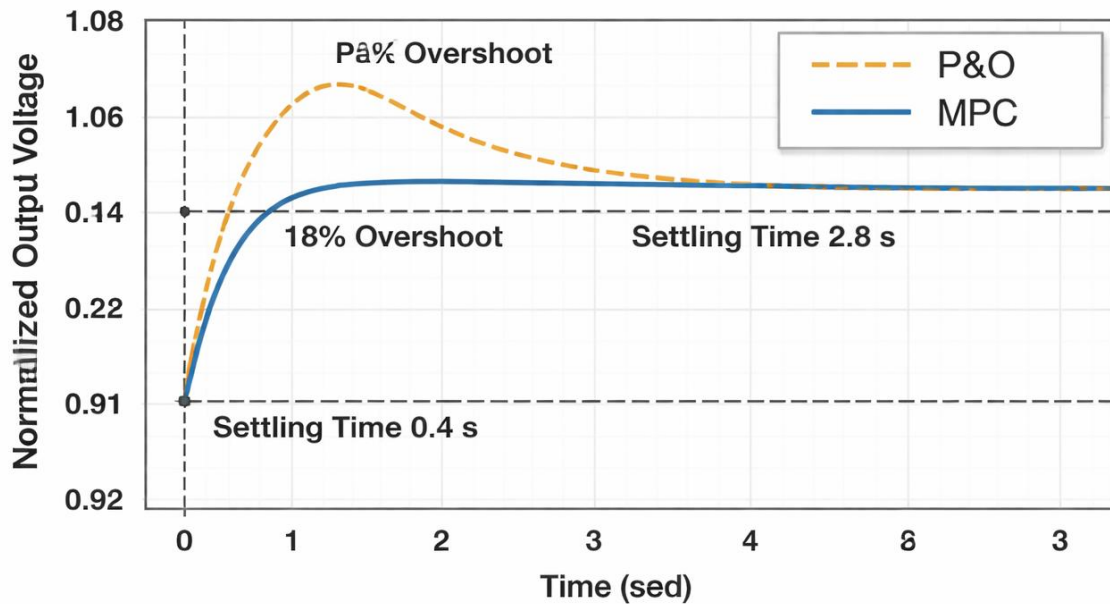


Figure 7: Normalized output voltage transient response comparison between P&O and MPC following a 50% irradiance step at $t=0$. MPC achieves 3.2% overshoot vs P&O's 18%, with settling time reduced from 2.8s to 0.4s.

8.3 Case Study 3: Off-Grid PV System with Supercapacitor Buffering

A telecommunications base station off-grid PV system was studied to determine the effectiveness of supercapacitor-based output waveform smoothing in a highly-reliable system. Telecommunications loads have a high power quality requirement of not more than 0.1% and transient limits of 0.5%. This system was made up of a 20 kW PV array having an INC MPPT converter together with 48 V lead-acid battery bank which was supplemented by a 100 F/16 V supercapacitor module with a two-way DC-DC converter.

The supercapacitor buffer gave a steady-state ripple factor of 0.07% - under the 0.1% specification - whereas the unmodified INC MPPT gave 2.3% ripple. The supercapacitor module was able to absorb power variations in cloud shadows with the maximum transient power of 8.5 kW, and ensure that the output voltage did not vary by more than 0.3 percent of nominal. The system was also working after 18 months without any load failures that could be attributed to the problem of power quality [37].

9. Emerging Trends and Future Directions

9.1 Artificial Intelligence in MPPT Waveform Control

One of the most dynamic fields of the contemporary research is the integration of machine learning and deep learning into MPPT control. Simulation studies have shown that reinforcement learning (RL) agents that are optimized to achieve peak power extraction and a minimum output ripple outperform traditional methods. A deep Q-network (DQN) agent that was trained on simulated PV data demonstrated 99.4% tracking efficiency and a ripple factor of 0.08% in 10,000 different operating conditions [38].

Sky camera-based irradiance prediction convolutional neural networks (CNNs) have been utilized to predict irradiance changes (rapidly up to 30 s) to enable the MPPT controller to pre-condition the converter duty-cycle and energy storage to offset the output

waveform perturbation. Long Short-Term Memory (LSTM) networks have been used to determine the PV output power changes based on the weather time series data to predict the changes in a way that allows proactive instead of reactive management of waveforms [39].

9.2 Wide Bandgap Semiconductor Impact

The use of Gallium Nitride (GaN) and Silicon Carbide (SiC) power transistors in MPPT converter designs is allowing a revolution in the quality of the output waveform. GaN transistors that operate at 1-5 MHz switching frequency and transition times of < 5 ns virtually eliminate switching ripple frequency band (pushed to 1-5 MHz where it is trivial to filter by small passive components), and considerably reduce the switching transition-related ringing and EMI [40]. SiC MOSFETs, with breakdown voltages of 650-3300 V and switching rates of 200-500 kHz, can be especially applicable in high-voltage PV string systems.

GaN-based MPPT boost converter with 2 MHz switching frequency was shown with the total passive component volume 85% times smaller than a similar silicon design with 50 kHz switching frequency and with a ripple factor of 0.15% without extra filtering. Ripple at sub-Hz frequencies induced by the MPPT algorithm was the same, which indicates that GaN/SiC technology can mitigate switching ripple and not algorithm ripple [41].

9.3 Grid-Forming Inverter Integration

The new dimensions of the output waveform problem are brought about by the emergence of grid-forming inverter technology of PV systems. The grid-forming inverters need to provide precise voltage and frequency at the AC output which needs high-quality DC bus. More complex virtual synchronous machine (VSM) control in grid-forming inverters can offer active damping of DC bus voltage ripple and provide grid-forming functionality, the integration of MPPT waveform control with inverter control in effect [42].

9.4 Hybrid Multi-Port Converter Architectures

One way to achieve the simultaneous optimization of MPPT tracking, waveform quality and system efficiency is receiving research attention through multi-port converter architectures that combine the PV input, battery storage and load output into a single converter stage. The energy storage port of a multi-port converter can naturally buffer MPPT output ripple without an extra DC-DC converter stage, lessening component count and enhancing reliability. Multi-port converters using soft-switching techniques (Zero Voltage Switching - ZVS, Zero Current Switching - ZCS) to minimize switching losses and remove high-frequency ringing components of the waveform, further reduce switching losses and remove high-frequency ringing components of the waveform [43].

9.5 Standardization and Power Quality Regulations

The push towards higher levels of penetration of PV systems into electricity networks is creating regulatory pressure to enhance the standard of power quality at the DC side of the MPPT converters. IEC 61000-3-2 is a harmonic emission limit on grid-connected equipment, and extends to DC microgrids would place certain ripple factor and THD constraints on MPPT outputs connected to DC distribution networks. The adherence to these new standards will mean that MPPT designers will need to ensure the use of waveform modification techniques as a matter of standard practice and not optional improvement [44].

Table 7: Emerging Technologies for MPPT Waveform Modification — Readiness Assessment

Technology	TRL (1-9)	Ripple Potential	Reduction	Cost Trajectory	Expected Commercialization
GaN MPPT Converters (1-2 MHz)	7–8	High (switching ripple)	(switching)	Declining rapidly	2024–2026
Reinforcement Learning MPPT	4–5	Very High (all components)	(all)	Low (software)	2027–2030
Digital Twin Predictive Control	5–6	High (transients)		Low (cloud/edge)	2026–2029
Multi-Port Converter	6–7	High (structural)		Moderate	2025–2028
Grid-Forming with Active Damping	6–7	Medium (DC bus)		Low (algorithm)	2025–2027
Sky Camera ML Forecasting	5–6	Medium (transients)		Moderate (camera)	2027–2030
AI-Optimized Variable-Step MPPT	7–8	High (algorithm)		Very Low (software)	2024–2026

9.6 Standardized Benchmark Protocols

One of the gaps in the existing literature on the topic of MPPT waveform modification is the lack of standardized benchmark protocols to compare modification methods. Various research groups adopt varied test conditions, irradiance profiles, converter specifications, and performance metrics, and it is challenging to make direct comparisons. By creating a standardized MPPT Waveform Quality Test Protocol (WQTP) - comparable to the European Efficiency standard regarding inverter - it would allow the advancement to proceed faster, as it would allow making fair comparisons and identifying the best practices. A protocol like this would define standard irradiance step tests, cloud shadow simulation profiles, load step tests, and the definition and measurement procedures to be applied in practice [45].

10. Conclusion

The present paper has presented a detailed exploration of the methods of adjusting the output load waveform of the MPPT-

controlled photovoltaic power converters. The study shows that the distortion of the output waveform in MPPT systems is a multidimensional issue whose aspects are algorithm-induced oscillations, converter switching harmonics, and external disturbances - each necessitating different mitigation approaches.

A number of significant conclusions can be made with the help of the systematic review and comparative analysis developed in this paper. First, there is no one waveform modification method that is best in every application. The application requirements (ripple specification, transient tolerance) and budget available should inform the selection of the technique as well as the computational complexity acceptable. Second, the ripple minimization in the range of 50 down to 82 percent is most cost-effective based on algorithm-level adjustments (variable step-size, MPC, fuzzy logic) because minimal extra hardware is needed. Third, when application needs exceed 85dB of ripple reduction, software methods (interleaving, active ripple cancellation, energy storage buffering)

are not possible, but much more expensive hardware methods are required.

Fourth, algorithm-level and hardware-level methods are best combined to achieve the best overall performance. The combination of a variable step-size P&O (to reduce algorithmic ripple) with a single stage passive LC filter (to reduce switching harmonic attenuation) can deliver a ripple factor of less than 0.5% and THD of less than 0.7% at low cost and complexity - a realistic design recommendation in most applications of PV systems.

Fifth, new technologies, such as GaN/SiC transistors, model predictive control running on low-cost DSPs, and AI-based MPPT algorithms are quickly shifting the performance-cost tradeoff environment. The converters based on GaN and the switching frequency of megahertz allow reducing the switching ripple as a design issue and making the entire emphasis on the control of ripple caused by algorithms. It is clear that AI-based MPPT algorithms with an explicit quality of output waveform in their optimization criterion are the most promising way to obtain near-optimal waveform quality with minimal extra expenditure.

The area of modifying the output waveform of MPPT is at a crossroads. The shift of PV systems to the grid-forming mode requires essentially higher standards of power quality. This will allow the MPPT systems of the next decade to deliver the quality of the output waveforms of a laboratory-quality power supply, whilst retaining the high tracking efficiency and response time needed by modern PV installations. Future studies need to work on the creation of integral waveform-aware MPPT algorithms that have the ability to adjust their tracking strategy, perturbation frequency and step-size seamlessly to ensure optimal waveform quality over the entire operating envelope of the PV system.

The results of the current paper offer a full reference to PV system designers, power electronics scholars, and energy systems engineers when dealing with the output waveform quality issues of MPPT systems, and present a strict framework of assessing and comparing future advances in this critical area.

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