

Grid-Connected 100 kW PV System with P&O-Based MPPT: A Simulation-Based Performance Assessment

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Abstract

This paper examines a 100 kW three-phase photovoltaic (PV) generating station that delivers power to the utility network through a two-level voltage-source inverter followed by an LCL filter. The array is kept at its maximum power point by a perturb-and-observe (P&O) tracker, which is realised in two forms: one with a constant voltage increment and one whose increment adapts to the size of the measured power change. The inverter is regulated in the synchronous reference frame, with a DC-link voltage loop feeding decoupled inner current loops. The investigation looks at how the two perturbation rules shape the transient path towards the new maximum power point, the ripple that remains around it, and the quality of the current injected into the grid when irradiance falls in discrete steps from 1000 to 400 W/m². Every plant, filter and controller setting is held identical between the two runs so that any observed difference can be attributed to the tracking rule alone. The study is confined to uniform irradiance and does not treat partial shading. All results are produced in MATLAB/Simulink.

Keywords: grid-connected photovoltaic system, LCL filter, MATLAB/Simulink, maximum power point tracking, perturb and observe, total harmonic distortion, variable step size.

1. Introduction

Electric power systems are moving away from a small number of large, dispatchable plants towards a mixture of central generation, distributed renewable sources and increasingly active consumers. Solar photovoltaics sit at the centre of this change, because module costs have fallen, installation is modular, and power-electronic interfaces make it possible to place capacity anywhere from a rooftop to a multi-megawatt field. The price of this flexibility is that PV output is not steady. It follows irradiance and cell temperature, and the converter that connects the array to the grid must therefore do two jobs at once: extract as much power as the weather allows, and deliver it to the network with acceptable current quality. The first job belongs to the maximum power point tracking (MPPT) algorithm; the second belongs to the inverter, its filter and its control loops.

Before turning to the converter level, it is useful to see where such plants sit in the wider smart-grid literature. On the demand side, Nan et al. [1] formulated an optimal scheduling problem for residential community demand response, showing how flexible household loads can be coordinated to follow

supply conditions. A similar concern with supply planning appears in the work of Ghorbel et al. [2], who proposed a long-term power procurement scheduling method for communication systems that draw energy from a smart grid. Both studies illustrate that scheduling decisions taken at the system level depend on a dependable picture of how much power generators can actually provide.

That picture is strongly influenced by renewable sources. Rehmani et al. [3] surveyed the way information and communication technologies help integrate renewable resources into the smart grid, and highlighted the difficulties created by their intermittent output. Bollen [4] approached the same subject from the power-quality side and discussed the concerns that arise when smart distribution-grid applications are put in place, including the disturbances that power-electronic equipment can introduce. At the consumer end, Chen et al. [5] described a communication-based appliance scheduling scheme for consumer-premise energy management systems, which again presumes that local generation and load can be planned with reasonable confidence.

Broader reviews confirm these observations. Moreno Escobar et al. [6] compiled the challenges and opportunities of smart grids, covering both technological and operational issues. More recently, a considerable body of work has focused on data-driven methods. Strielkowski et al. [7] discussed predictive demand analytics and machine learning as a route to greater resilience and efficiency in electric power systems, while Campana et al. [8] examined how digital technologies affect sustainability and the energy transition. Wang et al. [9] applied artificial intelligence to the prediction of smart-grid stability using the UCI stability dataset, and Jang et al. [10] improved load forecasting by combining feature selection based on explainable AI with expert-guided prompting. Rossi et al. [11] presented a reinforcement-learning tool for planning the optimal operation of future smart grids.

A further group of studies deals with digital twins, large models and storage. Antonesi et al. [12] reviewed transformers and large language models in the energy sector and pointed towards agentic digital twins. Costa and Del Papa [13] built a multi-physics electric-vehicle model inside a digital twin for AI-based energy management of vehicle-to-grid systems. Abonamah et al. [14] prepared a playbook that links artificial intelligence with environmental sustainability for leaders in the energy sector, and Machado et al. [15] studied how profits from a battery energy storage system can be shared through a blockchain solution within a virtual power plant, using intelligent techniques. Table I condenses the focus of these references and indicates why each is relevant to the present work.

TABLE I. Summary of Related Studies and Their Relevance

Ref.	Main focus	Relevance to this study
[1], [2], [5]	Demand-response scheduling, long-term power procurement and appliance scheduling in smart-grid settings.	These schedulers assume that generation is predictable; a well-behaved PV inverter with fast MPPT supports that assumption.
[3], [4]	Integration of renewable resources and the power-quality issues of smart distribution applications.	They motivate attention to both power extraction and the harmonic content of the injected current.
[6], [8]	Reviews of smart-grid challenges and of digital technologies in the energy transition.	They place PV converters within the wider modernisation of the network.

Ref.	Main focus	Relevance to this study
[7], [9]–[11]	Machine learning, stability prediction, load forecasting and reinforcement-learning-based operation planning.	Such tools consume measured or forecast PV output; the quality of that output depends on the converter-level tracking behaviour studied here.
[12], [13]	Large language models, agentic digital twins and multi-physics vehicle-to-grid models.	Digital twins need accurate component-level models, which is the role of the Simulink plant used in this paper.
[14], [15]	AI and sustainability in the energy sector; blockchain-based profit sharing for storage in virtual power plants.	They show the economic and environmental stakes attached to how effectively each PV kilowatt-hour is harvested.

The works cited so far mostly operate at the level of the power system, the market or the data layer. Underneath them lies the converter, and the literature on that layer is more specific. Reviews of MPPT techniques, such as the comparison by Efram and Chapman [16], show that P&O remains one of the most widely applied methods, since it needs only array voltage and current and no explicit knowledge of the array characteristics. Femia et al. [17] analysed how the perturbation amplitude and sampling period of P&O should be chosen, and made clear that a fixed step forces a compromise between tracking speed and steady-state oscillation. On the grid side, Blaabjerg et al. [18] gave an overview of control and synchronisation methods for distributed generation, including the synchronous-frame structure and phase-locked loops used here, while Liserre et al. [19] examined the design of LCL filters, which offer stronger switching-ripple attenuation than a single inductor at the price of a resonance that has to be handled. Harmonic limits for the resulting current are laid down in IEEE Std 519 [20]. The PV array itself is commonly represented by the single-diode equivalent circuit, whose simulation-oriented treatment by Villalva et al. [21] is followed in spirit in this work.

Two observations follow from this survey. First, system-level studies of scheduling, forecasting and optimisation rely on the PV plant behaving predictably when irradiance changes, yet the transient and steady-state properties of the tracker are rarely stated in those studies. Second, converter-level papers often examine the MPPT algorithm and the grid-current quality separately, so that the effect of a change in the tracking rule on the current delivered to the network is not always documented on a common model. The present paper addresses this gap in a limited and clearly bounded way.

The contributions are as follows:

1. A complete 100 kW grid-connected PV model is described, including a DC link, a two-level inverter, an LCL filter, a synchronous-frame PLL and cascaded voltage and current control.
2. Fixed-step and variable-step P&O trackers are implemented on that single model with all other settings frozen, which isolates the effect of the perturbation rule.
3. The response to a descending irradiance staircase is evaluated in terms of array power, settling behaviour, steady ripple and grid-current harmonic content.

The rest of the paper is arranged as follows. Section II describes the system and its controllers. Section III explains the two P&O schemes. Section IV gives the simulation set-up and the indices used for evaluation. Section V presents and discusses the results, Section VI states the limitations and possible extensions, and Section VII concludes.

2. System Description

A. Power Stage

The generating station consists of a 100 kW PV array, a DC link, a three-phase two-level voltage-source inverter (VSI), an LCL filter and a three-phase grid equivalent, arranged as in Fig. 1. The array feeds the DC-link capacitor, which decouples the slowly varying PV side from the pulsating power of the inverter. The inverter is switched at 10 kHz using sinusoidal PWM. Its output passes through the LCL filter, whose inverter-side and grid-side inductances are 4.495×10^{-4} H and 5.980×10^{-5} H, respectively, before reaching the point of connection at 400 V line-to-line and 50 Hz.

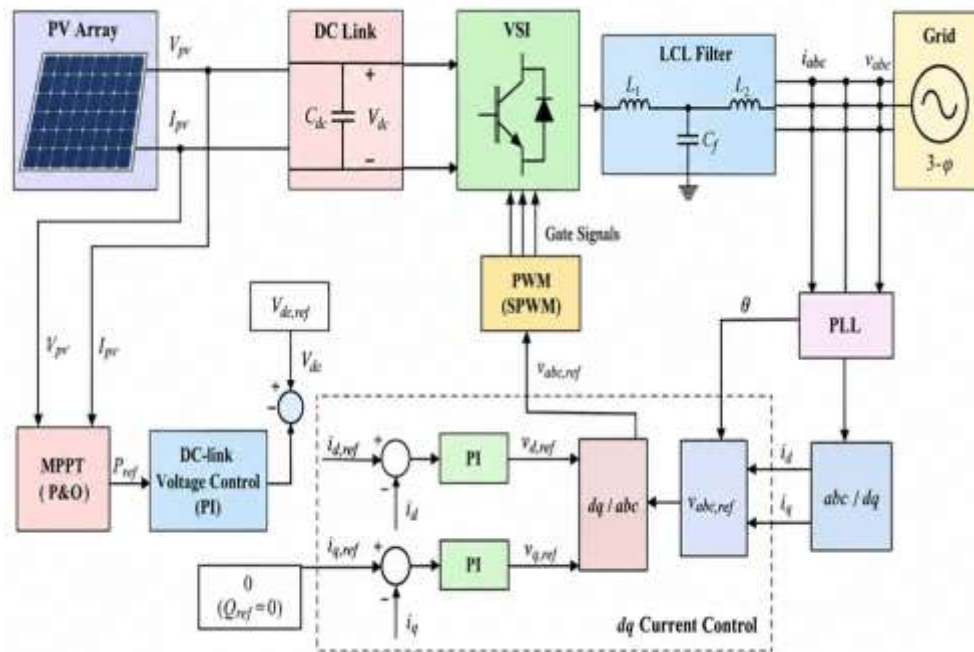


Fig. 1. Overall arrangement of the 100 kW grid-connected PV system.

B. PV Array Representation

The array is modelled with the single-diode equivalent circuit, in which the terminal current is written as

$$I = I_{ph} - I_0 \left[\exp \left(\frac{V + I R_s}{a V_t} \right) - 1 \right] - (V + I R_s) / R_{sh} \quad (1)$$

where I_{ph} is the photocurrent, which is roughly proportional to irradiance, I_0 is the diode saturation current, a is the ideality factor, V_t is the thermal voltage of the series-connected cells, and R_s and R_{sh} are the series and shunt resistances. Because I_{ph} scales with irradiance while the open-circuit voltage changes only logarithmically, the maximum power point moves mainly in current when irradiance changes and only slightly in voltage. This is why a tracker that operates on voltage perturbations can follow the peak without recomputing the array model.

C. LCL Filter

With inverter-side inductance L_1 , grid-side inductance L_2 and filter capacitance C_f , the filter has a resonance at

$$f_{res} = (1 / 2\pi) \sqrt{[(L_1 + L_2) / (L_1 L_2 C_f)]} \quad (2)$$

The resonance is normally placed well above the grid frequency and safely below half of the switching frequency, so that the filter attenuates switching harmonics without amplifying low-order content [19]. In the present model the same filter is used for every test, which means that any change in current distortion cannot be blamed on the filter.

D. Control Structure

The control system is organised in cascade, as shown in Fig. 2. Array voltage and current are measured and passed to the MPPT block, whose output serves as the reference for the DC-link regulation stage. A PI regulator compares the DC-link voltage with its reference and produces the d-axis current command i_d^* . The q-axis command i_q^* is set to zero, so the plant exchanges no reactive power with the grid in this study.

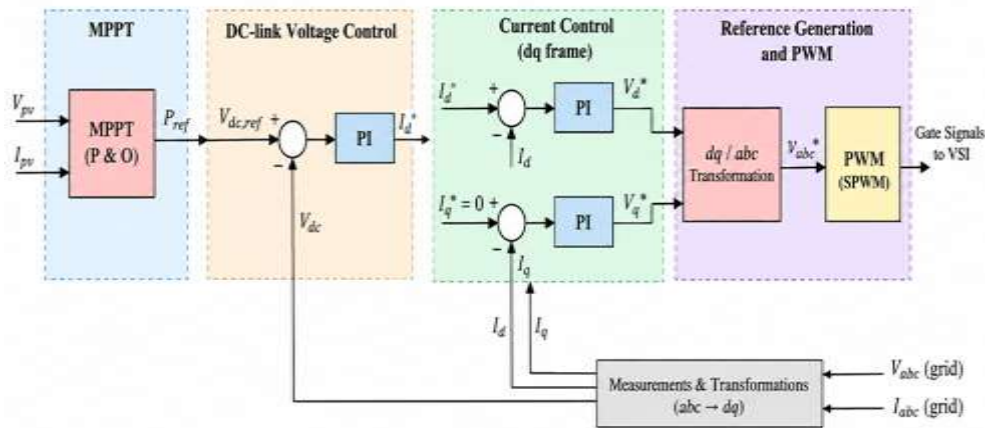


Fig. 2. Simplified control structure linking MPPT, voltage regulation and current control.

Grid voltages and currents are transformed to the dq frame with the angle supplied by a synchronous-reference-frame PLL. When the PLL aligns the d-axis with the grid voltage vector, the q-axis voltage is close to zero and the injected powers become

$$P = (3/2) e_d i_d, \quad Q = -(3/2) e_d i_q \quad (3)$$

so that i_d controls active power and i_q controls reactive power independently. The inner current loops are PI controllers with cross-coupling compensation. Taking L_t as the total series inductance seen by the current loop and ω as the grid angular frequency, the voltage commands sent to the PWM stage take the form

$$\begin{aligned} v_d^* &= e_d - \omega L_t i_q + u_d, \\ v_q^* &= e_q + \omega L_t i_d + u_q \end{aligned} \quad (4)$$

where u_d and u_q are the outputs of the two PI regulators acting on the current errors. The feed-forward and cross-coupling terms remove the mutual influence of the two axes, so that each PI loop behaves as a first-order system.

3. PERTURB-AND-OBSERVE MPPT

A. Operating Principle

P&O is a hill-climbing procedure. At each sampling instant k the tracker computes the array power $P(k) = V_{pv}(k) I_{pv}(k)$ and compares it with the previous sample. The changes in power and voltage are defined as

$$\begin{aligned} \Delta P &= P(k) - P(k-1), \\ \Delta V &= V_{pv}(k) - V_{pv}(k-1) \end{aligned} \quad (5)$$

If the last perturbation increased the power, the next perturbation continues in the same direction; if it decreased the power, the direction is reversed. Table II lists the four possible cases. Written compactly, the new reference is

$$V_{ref}(k+1) = V_{ref}(k) + \quad (6)$$

$$\text{sgn}(\Delta P) \cdot \text{sgn}(\Delta V) \cdot \Delta V_{\text{step}}$$

TABLE II. Decision Rule of the P&O Algorithm

ΔP	ΔV	Position on P-V curve	Action on V_{ref}
> 0	> 0	Left of the peak	Increase
> 0	< 0	Right of the peak	Decrease
< 0	> 0	Right of the peak	Decrease
< 0	< 0	Left of the peak	Increase

A well-known property of the method is that it never stops perturbing. Once the operating point reaches the peak it oscillates around it, and the amplitude of that oscillation is set by ΔV_{step} . This is the origin of the steady-state power ripple discussed later.

B. Fixed-Step Scheme

In the fixed-step scheme ΔV_{step} in (6) is a constant. The algorithm is trivial to implement, but one number has to satisfy two opposing requirements. A large increment lets the operating point cover the distance to a new peak in few samples after an irradiance change, yet it enlarges the oscillation once the peak is reached. A small increment reduces the oscillation but makes the search slow, and it can also make the tracker sluggish when the irradiance changes during the search [17].

C. Variable-Step Scheme

The variable-step scheme attempts to relax this compromise by making the increment depend on the observed power change,

$$\begin{aligned} \Delta V_{\text{step}} &= f(|\Delta P|), \text{ with} \\ \Delta V_{\text{step}} &= \Delta V_L \text{ for } |\Delta P| \geq P_{th}, \text{ and} \\ \Delta V_{\text{step}} &= \Delta V_S \text{ for } |\Delta P| < P_{th} \end{aligned} \quad (7)$$

with $\Delta V_L > \Delta V_S$. A large $|\Delta P|$ usually means that the operating point is still far from the peak, for example just after an irradiance change, so a large increment is used. A small $|\Delta P|$ suggests that the point is near the peak, and a fine increment keeps the oscillation small. The step levels and threshold were selected for the 100 kW array through preliminary runs on the same model; they were not optimised, and no claim of optimality is made. Only uniform irradiance is considered, so the multi-peak behaviour that appears under partial shading lies outside this study.

4. SIMULATION SET-UP AND EVALUATION INDICES

A. Test Conditions

Both trackers are run on the same MATLAB/Simulink model. Irradiance is applied as a descending staircase of 1000, 800, 600 and 400 W/m², with the cell temperature held at 25 °C. The MPPT sampling interval equals the control sampling time in both cases, and the inverter switching frequency, LCL

parameters, PLL and PI gains are not altered between runs. The principal parameters are listed in Table III.

TABLE III. Main Plant and Simulation Parameters (Common to Both MPPT Cases)

Parameter	Symbol	Value
PV array rated power	—	100 kW
Nominal DC-link voltage	V_{dc}	500 V
Inverter rating	—	100 kW
Inverter switching frequency	f_{sw}	10 kHz
LCL inverter-side inductance	L_1	4.495×10^{-4} H
LCL grid-side inductance	L_2	5.980×10^{-5} H
Grid line-to-line voltage (RMS)	V_g	400 V
Grid frequency	f_g	50 Hz
MPPT sampling time	T_{MPPT}	0.0005 s
Control sampling time	T_s	0.0005 s
Simulation step (powergui)	—	1×10^{-5} s
Cell temperature	T	25 °C
Irradiance profile (steps)	G	1000, 800, 600, 400 W/m ²

B. Performance Indices

Three aspects are examined. The first is the settling behaviour after each irradiance step, read from the waveforms as the time needed for the array power to enter and stay inside a narrow band around the new maximum. The second is the steady-state power ripple, taken as the peak-to-peak variation of array power over a short window once the transient has died out. The third is the quality of the grid current, which is expressed through the total harmonic distortion

$$THD_i = [\sqrt{(\sum_{h=2}^{50} I_h^2) / I_1}] \times 100 \% \quad (8)$$

where I_1 is the fundamental component and I_h is the RMS value of the h -th harmonic. The spectrum is obtained with the FFT tool of the powergui block for a 50 Hz fundamental and harmonic orders up to the 50th, over a short steady-state window after the initial transients have decayed. The result can be compared with the harmonic limits recommended in IEEE Std 519 [20].

V. RESULTS AND DISCUSSION

A. Array Power and Voltage Behaviour

For every irradiance step the array power moves to a new level that is consistent with the maximum power available at that irradiance. With the fixed step, the approach to the new operating region is orderly, but a residual ripple in power is visible after settling, and its amplitude does not depend on how close the operating point is to the peak. With the variable step, large corrections appear mainly during the transient. As soon as the power change becomes small the increment falls to its fine level, and the steady ripple is reduced. Fig. 3 shows the power response over the full test duration.

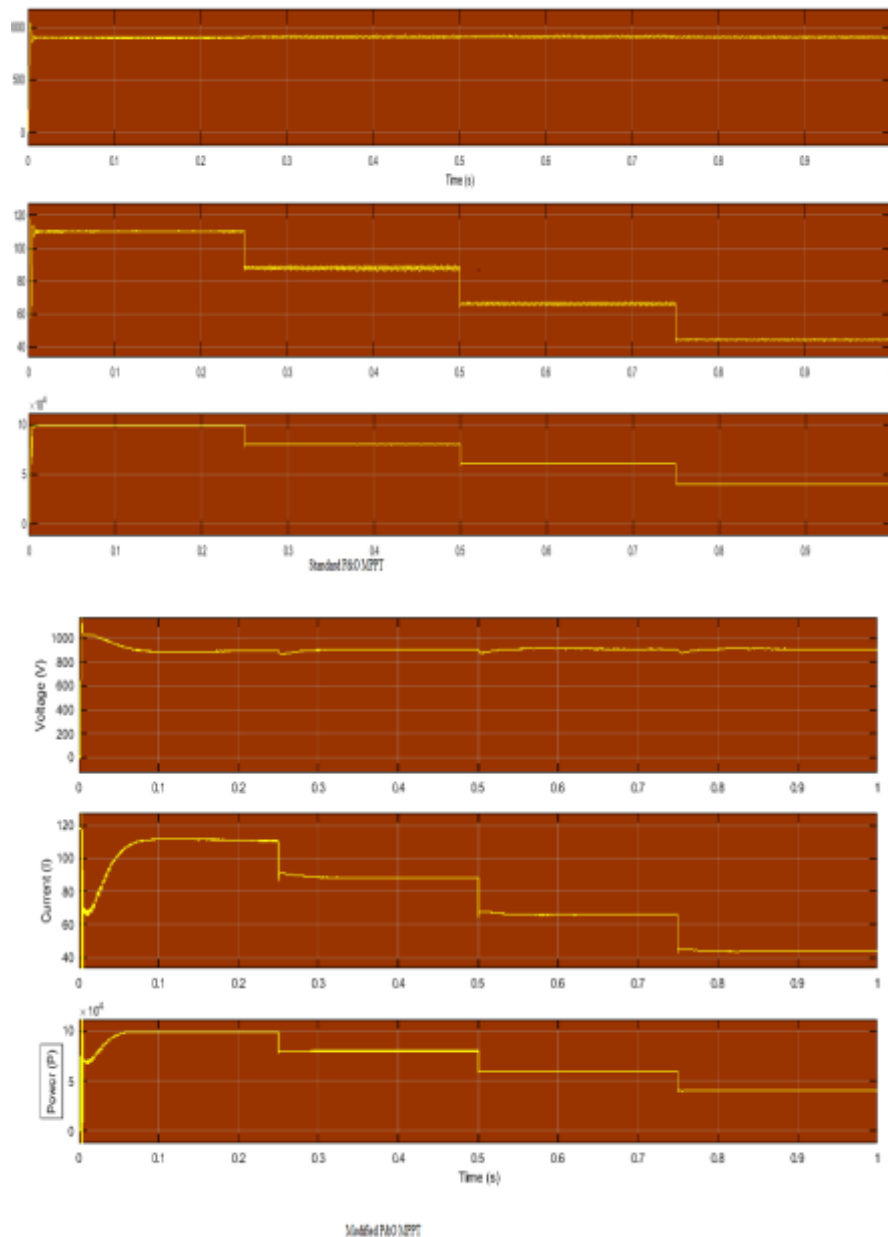


Fig. 3. PV power response under the step irradiance profile for the two P&O step rules.

B. Settling After Irradiance Steps

The time for the array power to remain inside a narrow band around the new maximum was read from the waveforms for each successive step. Under the same plant and control settings, the variable-step rule tends to shorten this interval compared with the fixed-step rule. The reason is that larger updates remain available while the operating point is still far from the peak, whereas a fixed small step must cover the same distance in many more samples. Table IV summarizes the behavior qualitatively for the successive steps; numerical settling times can be read from the waveforms in Fig. 3 and added to the table if a quantitative comparison is required.

TABLE IV. Qualitative Comparison of Transient and Steady Behaviour for Successive Irradiance Steps

Irradiance (W/m ²)	step	Fixed-step P&O	Variable-step P&O	Remark
1000 (start-up)		Orderly approach to the peak; ripple remains after settling.	Large steps early in the transient, then reduced ripple.	Start-up transient from initial conditions.
1000 → 800		Moves to the new peak in uniform increments.	Larger increments during the change, finer near the peak.	Difference in ripple already visible.
800 → 600		Settling governed by the single step size.	Shorter settling; lower steady ripple.	Same trend as previous step.
600 → 400		Ripple persists after settling.	Quicker approach; steady oscillation kept small.	Lowest irradiance in the test.

C. Grid-Current Quality

Once the DC-side quantities have settled, the grid current is close to sinusoidal for both MPPT settings. The measured total harmonic distortion stays within a range that is acceptable for the present simulation study when the current controllers and the LCL filter are left unchanged. Consequently, for the cases examined, the change of MPPT step rule does not by itself push the grid current beyond the distortion levels already achieved by the inner current control and filter design. This is an expected outcome: the MPPT only shapes the reference of the outer loop, whereas the harmonic content is decided mostly by the switching frequency, the filter and the current-loop bandwidth. Fig. 4 shows a representative current waveform together with its harmonic spectrum.

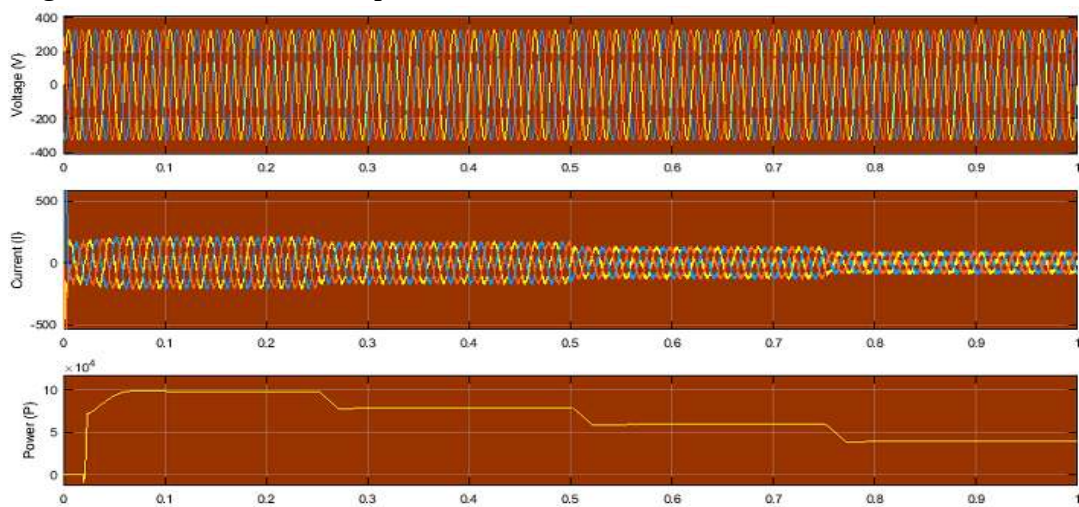


Fig. 4. Representative grid-current waveform and harmonic spectrum in steady state.

D. Discussion

The simulation outcomes support the expected role of a variable perturbation step: faster movement while $|\Delta P|$ is large and quieter behaviour near the maximum power point. Since the inverter control and

the filter were frozen, differences in array-side ripple and settling can be linked mainly to the MPPT update rule. The study does not claim that the chosen step levels are optimal; it only demonstrates their effect on this 100 kW model under a step irradiance.

From the viewpoint of the smart-grid studies reviewed in Section I, the result has a practical meaning. Forecasting, scheduling and reinforcement-learning tools [7]–[11] treat PV output as an input signal, and digital-twin frameworks [12], [13] need component models that reproduce the dynamic behaviour of the plant. A tracker with lower steady ripple and shorter settling produces an output that is smoother and closer to the available maximum, and the energy lost to oscillation around the peak is reduced. In addition, the unchanged current quality means that this improvement does not come at the expense of the power-quality concerns raised in [4].

VI. LIMITATIONS AND FUTURE SCOPE

The work has several limitations. Only uniform irradiance steps at constant temperature are applied, so continuous irradiance ramps, temperature variation and partial shading are not represented, and under partial shading a P&O tracker can settle on a local rather than the global peak. The step levels of the variable-step scheme were chosen by preliminary trials and not by a formal optimisation. The grid is modelled as a stiff source, and weak-grid behaviour, unbalanced faults and grid-code fault ride-through are not examined. Finally, the results come from simulation only, and losses, sensor noise and dead-time effects present in hardware are not included.

Several extensions are natural. The same platform can be tested with realistic irradiance records, with shading patterns that produce multiple peaks, and with a weak-grid impedance. The step levels could be tuned by an optimisation or learning-based procedure of the kind surveyed in [7]–[11], and the model could be embedded in a digital-twin environment [12], [13] or combined with battery storage in a virtual power plant [15].

VII. CONCLUSION

A 100 kW grid-connected PV system with P&O-based MPPT has been assessed in simulation for fixed and variable perturbation steps. Both schemes were run on a common power stage, LCL filter and current-control tuning. Under a descending irradiance staircase, the variable-step rule reduces the steady power ripple and improves settling after irradiance changes in comparison with a constant step, while the grid-current distortion remains in a comparable range for both cases. The work is restricted to uniform step changes in irradiance. Extending it to continuous irradiance profiles and to non-uniform irradiation would need additional tests on the same platform.

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