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Application perturb and observe maximum power point tracking with interconnection and damping assignment passive-based control for photovoltaic system using boost converter

Introduction. *Power generation from renewable sources, such as photovoltaic (PV) power, has become increasingly important in replacing fossil fuels. A PV system's maximum power point (MPP) moves along its power-voltage curve in response to environmental changes. Despite the use of maximum power point tracking (MPPT) algorithms, the displacement of the MPP results in a decrease in PV system performance.* ***Problem.*** *Perturb & Observe (P&O) MPPT algorithm is a simple and effective algorithm, it can suffer from some drawbacks, such as oscillations around the MPP, slow tracking of rapid changes in irradiance, and reduced efficiency under temperature variation condition. The new MPPT control strategy for a solar PV system, based on passivity control, is presented. The* ***goal*** *of this study is to enhance the efficiency and stability of MPPT in PV systems by integrating the P&O algorithm with Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC).* ***Methodology****. The new MPPT P&O PBC strategy aims to extract maximum power from the PV system in order to improve its efficiency under some conditions such as the variations of the temperature, the irradiation and the load. IDA-PBC is employed to design a Lyapunov asymptotically stable controller using the Hamiltonian structural properties of the open-loop model of the system. Also, with minimization of the energy dissipation in boost converter of the PV system to illustrate the modification of energy and generate a specify duty cycle applied to the converter. The* ***results*** *with MATLAB clearly demonstrate the advantages of the proposed MPPT P&O PBC, showcasing its high performance in effectively reducing oscillations in various steady states of the PV system, ensuring minimal overshoot and a faster response time.* ***Scientific novelty.*** *Key contributions include methodological improvements such as dynamic adjustment of the cycle for boost converter and a new approach to partner selection, which significantly optimizes the algorithm's performance.* ***Practical value****. A comparative analysis of the proposed MPPT controller against conventional algorithms shows that it offers a fast dynamic response in finding the maximum power with significantly less oscillation around the MPP.* References 46, tables 2, figures 13.

Key words: **photovoltaic generator, boost converter, passivity-based control, port-controlled Hamiltonian, maximum power point tracking.**

Вступ*. Генерація електроенергії з відновлюваних джерел, таких як фотоелектричні (PV) системи, набуває все більшого значення як заміна викопного палива. Точка максимальної потужності (MPP) PV системи зміщується вздовж кривої залежності потужності від напруги в залежності від навколишнього середовища. Незважаючи на використання алгоритмів відстеження точки максимальної потужності (MPPT), зсув MPP призводить до зниження продуктивності PV системи.* ***Проблема****. MPPT алгоритм Perturb & Observe (P&O) є простим і ефективним алгоритм, але він може мати недоліки, такі як коливання біля MPP, повільне відстеження швидких змін освітленості та зниження ефективності в умовах коливань температури. Представлено нову стратегію управління MPPT для сонячної PV системи, засновану на пасивному управлінні.* ***Метою*** *дослідження є підвищення ефективності та стабільності MPPT у PV системах шляхом інтеграції алгоритму P&O з пасивним керуванням на основі міжз'єднання та призначення демпфування (IDA-PBC).* ***Методологія****. Нова стратегія MPPT P&O PBC спрямована на отримання максимальної потужності з PV системи для підвищення її ефективності в певних умовах, таких як коливання температури, випромінювання та навантаження. IDA-PBC використовується для розробки асимптотично стійкого регулятора Ляпунова з використанням гамільтонових структурних властивостей моделі системи з відкритим контуром. Також, з мінімізацією розсіювання енергії у підвищувальному перетворювачі PV системи, щоб проілюструвати зміну енергії та сформувати заданий робочий цикл, що застосовується до перетворювача.* ***Результати****, отримані в MATLAB, показали переваги запропонованої стратегії MPPT P&O PBC, демонструючи її високу ефективність щодо зниження коливань у різних стаціонарних станах PV системи, забезпечуючи мінімальне перерегулювання та швидший час відгуку.* ***Наукова новизна****. Ключові досягнення включають методологічні удосконалення, такі як динамічне налаштування циклу для підвищувального перетворювача, і новий підхід до вибору партнерів, що значно оптимізує продуктивність алгоритму.* ***Практична цінність****. Порівняльний аналіз MPPT-контролера з традиційними алгоритмами показує, що він забезпечує швидкий динамічний відгук при пошуку максимальної потужності зі значно меншими коливаннями біля MPP.* Бібл. 46, табл. 2, рис. 13.

Ключові слова: **фотоелектричний генератор, підвищувальний перетворювач, пасивне керування, гамільтоніан з керуванням портами, відстеження точки максимальної потужності.**

Introduction. The transition away from fossil fuel-based energy sources has been accelerated by concerns about global warming and the depletion of traditional resources. As a result of this shift, governments and industries worldwide are exploring alternative energy solutions to meet growing demands sustainably [1]. The current era is characterized by the fast renewable energy sources (RESs) growth as a key component of addressing the escalating global energy demand. The move toward RESs is driven by a number of reasons, including environmental concerns, modern technologies and economic viability [2]. A growing number of RESs are emerging across the globe, including biogas, wave energy, solar energy, and wind energy. Solar energy in particular is projected to fulfill one-third of the world's electricity demand by 2060. Unlike other RESs, such as wind and hydroelectric energy, solar energy is not limited by geographic availability, making it abundantly accessible worldwide.

Generally, solar energy stands out as the most reliable and effective solution for mitigating the issue of global warming [1, 2]. Its abundant availability, renewable nature, and environmentally friendly attributes make it a key player in efforts to combat climate change. Additionally, solar power systems produce no greenhouse gas emissions during operation, unlike traditional fossil fuel-based energy sources, thereby significantly reducing the carbon footprint associated with energy production. This underscores the importance of harnessing solar energy as a sustainable alternative to conventional power sources in the fight against global warming [3].

Moreover, photovoltaic (PV) panels are distinguished by their ease of use and installation, cost-effectiveness, and minimal maintenance requirements [4]. They find applications in various sectors such as water pumping systems, aeronautical applications, and battery chargers [5]. These features contribute to the widespread adoption of PV technology across different industries and sectors. The PV panel yields energy is subject to the temperature influence and solar irradiation, resulting in the nonlinear behavior of the panel [6]. This nonlinear behavior arises due to the complex interaction between the panel temperature, incident solar radiation, and the material properties of the PV cells [7, 8]. Achieving a PV panel's maximum power point (MPP) under climatic changes, while ensuring reliability and cost-effectiveness, has been a substantial research challenge. Consequently, numerous studies have been conducted to explore potential solutions to this issue [9, 10].

Energy consumption has increased due to the widespread use of electricity. The problem of energy conversion and storage has led to research and development of new supply sources [11, 12]. This interest grew in response to the inevitable exhaustion of fossil fuels, their environmental impact, and the waste they generate. In the era of sustainable development, PV is rapidly progressing due to its significant potential as a RES capable of producing electricity by converting a portion of solar irradiation through a PV cell [13, 14]. PV panels have specific nonlinear electrical characteristics and, therefore, a special operating point called the MPP. Among the most widely employed MPP tracking (MPPT) algorithms in the PV literature is the extreme algorithm known as Perturb & Observe (P&O). This algorithm works by continuously perturbing the PV operating point and monitoring the resulting variation in electrical output or current to determine the direction that leads to the MPP. Despite its simplicity and common usage, P&O may exhibit fluctuations around the MPP under certain conditions, leading to suboptimal performance in dynamic environments.

According to [15], P&O control forces the operating point to oscillate about the MPP at steady state due to the periodic MPP search procedure repetition, causing the system to continuously oscillate to the MPP. This behavior contributes to power transfer losses. In cases of infrequent climate changes, especially abrupt changes in irradiation levels, this algorithm may track in the wrong direction and generate further power loss. Authors [16] proposed modular solutions using a PI controller for PV-DC choppers to monitor the MPPT algorithm. Conventional analysis of the system's stability and dynamic performance is difficult, making it necessary to operate the system at a chosen point and proceed with successive linearization to simplify the nonlinearity issues [17]. The work [17] introduces an MPPT technique based on the Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC). The primary principle of the IDA-PBC controller is to regulate the overall power of the system to maintain stability around an equilibrium point [18]. According to published works, IDA-PBC controllers have shown promising results in various applications because they ensure stability and optimize performance in dynamic systems. Table 1 compares conventional, modern and hybrid categories MPPT control algorithms, highlighting their advantages and disadvantages.

Our contribution is focused on the application of the P&O-MPPT in conjunction with the IDA-PBC, using the boost converters. There are several key objectives served by this combination.

Table 1

Advantages and disadvantages of MPPT control

Type	Algorithm	Advantages	Disadvantages
Conventional algorithms	P&O [19], incremental resistance [20], climbing [21], incremental conductance [22], voltage/short circuit current [23], hill and fractional open circuit [24]	Easy to implement, simple structure, and low-cost	Steady state oscillation, no guarantee for convergence, drift problem, reduced efficiency
Modern algorithms	Particle swarm optimization (PSO) [25], grey wolf optimization [26], cuckoo search [27], fuzzy logic control [28], sliding mode control [29], particle swarm [30]	Robust, no steady-state and transient oscillations, high tracking efficiency, and few parameters require turning	Large search space, high cost
Hybrid algorithms	P&O-humpback whale [31], P&O-ant-colony optimization [32], P&O-PSO [33]	Higher tracking accuracy reduced power oscillation, and tracking efficiency is higher than 98 %	High cost, difficult to control

It facilitates the efficient capture of the MPP of solar panels even under fluctuating climate conditions and varying loads. This capability ensures optimal energy extraction from the solar array.

By reducing undulations around the MPP, the system's stability is significantly enhanced. This stability is crucial for maintaining consistent and reliable power generation from the PV system.

The integration of IDA-PBC with the boost converters leads to a reduction in energy losses. As a result, not only does the system become more efficient, but also costs are reduced, making the system more economically viable.

Additionally, this approach improves the system's response time, allowing it to adapt quickly to changes in environmental conditions or load requirements. This responsiveness ensures that the system operates at peak performance levels, maximizing energy production. Moreover, the boost converter's ability to raise voltage levels further enhances the system's efficiency by minimizing the need for a series connection of solar panels. This feature simplifies system design and installation while also reducing overall system costs.

By integrating the P&O-MPPT with IDA-PBC, this work provides a comprehensive solution to optimize PV system performance. With its ability to address power capture efficiency, stability, energy losses, response time, and system complexity, this approach holds significant promise for advancing solar energy utilization.

The **goal** of this study is to enhance the efficiency and stability of MPPT in PV systems by integrating the P&O algorithm with IDA-PBC. Unlike previous approaches that relied on traditional P&O [19], incremental resistance [20], climbing [21], incremental conductance [22], voltage/short circuit current [23], hill and fractional open circuit [24], this study introduces a novel strategy combining passivity theory and dynamic voltage tracking to improve convergence speed and reduce power oscillations.

PV system modeling. Figure 1 depicts the system under study. It consists of a PV generator (PVG) that supplies power to a load through a boost converter, which acts as an impedance stage. The boost converter and the load together influence the PVG (PVG operating point under changing climatic conditions). IDA-PBC is proposed to address the P&O voltage output behavior issue at steady-state caused by load variations.

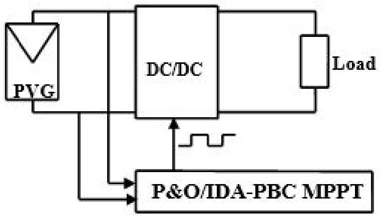

Fig. 1. PV system

Figure 2 shows a PV cell single-diode model, operating within the 1st quadrant of the current-voltage characteristics [34, 35].

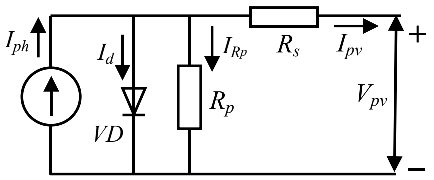

Fig. 2. Electrical equivalent model of PV module

The mathematical model for the same situation is:

$$I = I_{ph} - I_0 \left[\exp\left(\frac{q\left(V + I \cdot R_S\right)}{A \cdot k \cdot T} \right) - 1 \right] - \frac{V + I \cdot R_S}{R_p}, \quad (1)$$

where I_{ph} is the cell photocurrent; I_0 is the diode saturation current; R_s is the series resistance; R_p is the shunt resistance; q is the electron charge; I is the PV cell current; V is the PV cell output voltage; k is the Boltzmann constant; A is the diode ideality factor; T is the temperature.

Figure 3 illustrates the boost converter scheme. Output voltage V_{ch} is linked to its input voltage V [36, 37]:

$$V_{ch} / V = 1/(1 - \mu), \quad (2)$$

where μ is the carrier signal controlling the energy switch duty cycle in the boost converter.

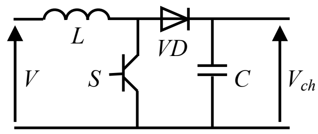

Fig. 3. The boost converter scheme

The boost converter model is:

$$\begin{cases} \dot{x}_1 = -\frac{1}{L} \mu x_2 + \frac{1}{L} V; \\ \dot{x}_2 = -\frac{1}{R_{ch}} x_2 + \frac{1}{C} \mu\, x_1, \end{cases} \quad (3)$$

where $x_1 = I_L$ is the inductor current, which corresponds to the PVG current; $x_2 = V_{ch}$ is the boost converter output voltage, which corresponds to the load voltage.

Traditional P&O MPPT algorithm. Several techniques are commonly utilized for MPPT in PV systems. Among these techniques are:

1) *P&O*. This technique involves perturbing the operating point of the PV and observing the resulting change in energy output. The operating point is then adjusted accordingly to approach the MPP.

2) *Incremental conductance*. This strategy utilizes the incremental conductance of the PV system to determine the direction in which the operating point should be adjusted to approach the MPP. It is particularly effective in tracking the MPP under rapidly changing environmental conditions.

3) *Constant voltage*. In this approach, the voltage across the PV system is maintained at a constant value, and the current is adjusted accordingly to maximize power output. This method is suitable for applications where maintaining a stable voltage is critical.

4) *Constant current*. Similar to the constant voltage technique, the constant current technique maintains a constant current output from the PV system and adjusts the voltage to maximize energy output. It is often used in applications where a stable current supply is required.

These MPPT techniques vary in their complexity, performance under different operating conditions, and hardware requirements. Researchers continue to explore and develop MPPT methods to ameliorate the PV systems efficiency and reliability [38, 39].

The P&O method is widely regarded as the simplest and most useful MPPT technique in the field of PV systems due to its straightforwardness and ease of application. The fundamental principle of P&O involves applying a perturbation to the voltage of the operating point and then observing the resultant impact on power. If the energy increases, the P&O control is moving the search in the correct direction (right) to track the true MPP. It is evident that the disturbance has shifted the operating point toward this MPP. The P&O algorithm will persist in disturbing the voltage in the similar way. Conversely, if the energy decreases, the disturbance has moved the operating point away from the true MPP, necessitating a reversal in direction [40].

Figure 4 shows the P&O control flowchart [41]. The P&O offers the advantage of being straightforward to implement in software or into microcontrollers. However, as drawbacks, it oscillates around the MPP, which introduces power losses and presents slow response times in reaching the MPP. It may even track in the wrong direction under rapid changes in irradiance.

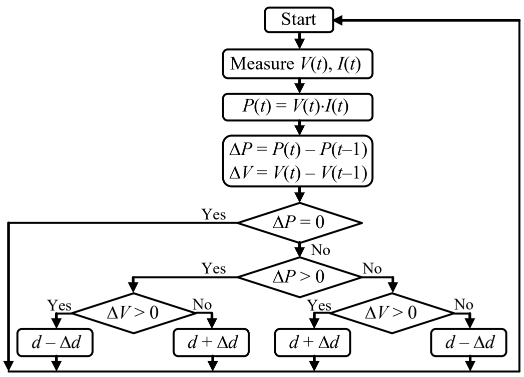

Fig. 4. P&O control flowchart

The enhanced P&O MPPT algorithm, as proposed, builds upon the conventional algorithm by incorporating an IDA-PBC controller. This controller aims to minimize the error between the PV voltage and the voltage produced by the MPPT block. The models are simulated, and the different results are presented next.

Proposed MPPT design strategy. The enhanced IDA-PBC is presented here for a DC-DC boost converter using a P&O algorithm, modeled using a passivity-based control Hamiltonian system framework. The proposed nonlinear regulator guarantees system stability and rapid response even under significant load disturbances and variations in illumination levels. This enhancement builds upon the traditional P&O method, offering improved performance and robustness in PV systems.

Model of DC-DC converter with IDA-PBC control. The PBC establishes a regulator design methodology aimed at stabilizing the system by rendering it passive [42, 43]. This approach ensures a stable and well-behaved system response. The IDA-PBC approach involves identifying the system's natural energy function, referred to as $H(x)$, where the inductor and capacitor total energy are represented by the Hamiltonian function.

The port-controlled Hamiltonian system is derived from the following equation:

$$\begin{cases} \dot{x} = [J(x) - R(x)]\nabla H + g(x)u; \\ y = g^T(x)\nabla H. \end{cases} \quad (4)$$

Stabilization in the IDA-PBC control is attained by targeting the closed-loop dynamics [44]:

$$\begin{cases} \dot{x} = [J_d(x) - R_d(x)]\nabla H_d; \\ y = g^T(x)\nabla H_d, \end{cases} \quad (5)$$

where $H_d(x)$ is the desired total power function that reaches its minimum at x^*, while $J_d = -J_d^T$ and $R_d = R_d^T \geq 0$ are the wanted interconnection and damping matrices respectively.

The boost converter depicted in Fig.3 is represented by its averaged model, which is given by:

$$\begin{pmatrix} L & 0 \\ 0 & C \end{pmatrix}\dot{x} = \left(\begin{pmatrix} 0 & -\mu \\ \mu & 0 \end{pmatrix} - \begin{pmatrix} 0 & 0 \\ 0 & \dfrac{1}{R_{ch}} \end{pmatrix}\right)x + \begin{pmatrix} V \\ 0 \end{pmatrix}, \quad (6)$$

where:

$$x = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} L \cdot i \\ C \cdot V_{ch} \end{pmatrix} = D\begin{pmatrix} i_L \\ V_{ch} \end{pmatrix}. \quad (7)$$

The control objective is to maintain internal stability while regulating the generator voltage to the desired optimal value. This entails stabilizing the desired equilibrium point x^*. So that the wanted equilibrium point is [45]:

$$x^* = \left(x_1^*, x_2^*\right) = \left(\frac{L \cdot V^2}{R \cdot E}, C \cdot V_d\right), \quad (8)$$

where V_d is the output MPPT-P&O voltage delivered to the passivity block command system. The boost converter dynamic can be expressed in the form of port-controlled Hamiltonian (4). To achieve this, the Hamiltonian function of the boost can be described as [46]:

$$H(x) = \frac{1}{2}\frac{x_1^2}{L} + \frac{1}{2}\frac{x_2^2}{C} = \frac{1}{2}x^T D^{-1} x; \quad (9)$$

and

$$J = \begin{pmatrix} 0 & -\mu \\ \mu & 0 \end{pmatrix}, \quad R = \begin{pmatrix} 0 & 0 \\ 0 & 1/R_{ch} \end{pmatrix}, \quad E = \begin{pmatrix} V \\ 0 \end{pmatrix}.$$

Hence, the damping matrix is modified as bellow:

$$R_d = R + R_a, \quad (10)$$

where R_a is the damping matrix added by the controller.

The aim is to represent the boost converter dynamics as the Port-Hamiltonian system:

$$\dot{x} = \left[J_d(\mu) - R_d\right]\frac{\partial H_d}{\partial x}(x). \quad (11)$$

The new $H_d(x)$ exhibits a local minimum at the desired equilibrium point x^*. That:

$$H_d = H + H_a, \quad (12)$$

The primary aim of the IDA-PBC is to determine a command $\mu(x)$, R_a, $J_a(\mu)$ and a vector $K(x)$ satisfying the partial differential equation:

$$[J_d(\mu) - R_d]K(x) = R_a \frac{\partial H}{\partial x}(x) + gE, \quad (13)$$

where:

$$K(x) = \frac{\partial H_a}{\partial x}(x). \quad (14)$$

Verifying:

$$\frac{\partial K}{\partial x}(x) = \left[\frac{\partial K}{\partial x}(x)\right]^T. \quad (15)$$

From (16), result:

$$\dot{H}_d = -\left[\frac{\partial H_d}{\partial x}(x)\right]^T R_d \frac{\partial H_d}{\partial x}(x) \leq 0. \quad (16)$$

It has an asymptotically stable equilibrium at x^* if:

$$\left[\frac{\partial H_d}{\partial x}(x)\right]^T R_d \frac{\partial H_d}{\partial x}(x) = 0 \Rightarrow x = x^*. \quad (17)$$

The desired power function is expressed as:

$$\dot{H}_d = \frac{1}{2}\left(x - x^*\right)^T D^{-1}\left(x - x^*\right). \quad (18)$$

The coefficient matrices and vector are:

$$J_a(x) = 0; \quad (19)$$

$$R_a = \begin{bmatrix} r_1 & 0 \\ 0 & r_2 \end{bmatrix}; \quad (20)$$

$$\dot{H}_d = \frac{1}{2}\left(x - x^*\right)^T D^{-1}\left(x - x^*\right). \quad (21)$$

So:

$$\frac{\partial H}{\partial x}(x) = D^{-1}x \quad \text{and} \quad K(x) = \frac{\partial H_a}{\partial x}(x) = -D^{-1}x^*.$$

Inserting (14) into (11) results to:

$$\left[J_d \quad R_d\right]D^{-1}x^* = -\left[J_a - R_a\right]D^{-1}x + gE. \quad (22)$$

From (22), the dynamic duty ratio is:

$$\mu = \frac{1}{V_d}\left(r_1\left(i - i^*\right) + V_{PV}\right). \quad (23)$$

Using (23) we can compute the converter duty cycle required to maximize the power from the PVG.

Results. To assess the enhanced PV system performance (Fig. 1), MATLAB software was used. The PV system parameters are listed in Table 2. A comparative study was undertaken to evaluate 3 different MPPT techniques: P&O, P&O with PI control, and P&O with an IDA-based PBC algorithm. This comparison focuses on the efficiency and dynamic response characteristics of each technique during a simulation time t = 0.5 s. Notably, all results were obtained under a dynamic load condition of 40 Ω.

Table 2

The PVG module parameters

Parameters	Rated value
Short-circuit current I_{cc}, A	3.24
Maximum energy P_{max}, W	62.2
Open-circuit voltage V_{co}, V	24.93
Current I_{mp} at P_{max}, A	3.04
Voltage V_{mp} at P_{max}, V	20.21

Influence of variation in solar irradiation. The variation in irradiation levels is modeled according to the function shown in Fig. 5, while the temperature remains constant at 25 °C throughout the simulations. The results of the simulations for power, voltage and current are depicted individually for each of the 3 MPPT algorithms in Fig. 6–8, respectively. Additionally, it is worth mentioning that the variation in irradiation levels, as represented by the function in Fig. 5, plays a significant role in determining the PV system performance under different conditions. By keeping the temperature fixed at 25 °C, the focus of the analysis is directed toward the impact of irradiation level changes on the system's power generation capabilities.

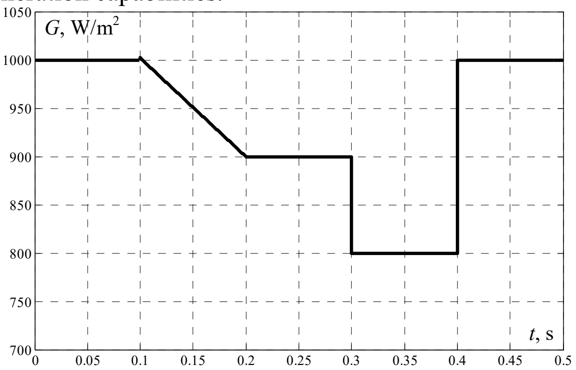

Fig. 5. Changes on irradiation level

Furthermore, the simulation results presented in Fig. 6–8 offer a comprehensive comparison of the effectiveness and efficiency of the MPPT algorithms under consideration. By examining the variations in power, voltage and current across different irradiation levels, insights can be gained into the dynamic response and overall performance characteristics of each MPPT technique.

Overall, these simulation results provide valuable information for optimizing the operation of PV systems under varying environmental conditions, thereby contributing to the advancement of RES technologies.

In Fig. 6 (zoom a), it can be observed that the output energy of the PVG controlled by the P&O/IDA-PBC reaches the MPP at 4.2 ms, compared to the P&O/PI and P&O, which achieve the same MPP at 20 ms and 25 ms, respectively. The P&O/IDA-PBC provides the best tracking of maximum power and voltage compared to the P&O/PI and P&O.

As can be seen in Fig. 6 (zoom b), the P&O/PI and P&O continue to perturb the system in the same direction, resulting in large energy losses during the linear decrease in radiation levels from 1000 W/m^2 to 900 W/m^2. However, the P&O/IDA-PBC overcomes this behavior by significantly reducing undulations around the MPP, thus minimizing energy losses. At the end of the simulation time (0.4–0.5 s) in Fig. 6 (zoom c), as the irradiation level increases to 1000 W/m^2, it can be observed that the P&O/IDA-PBC controls the PVG to maintain more stable power than the P&O/PI and P&O algorithms.

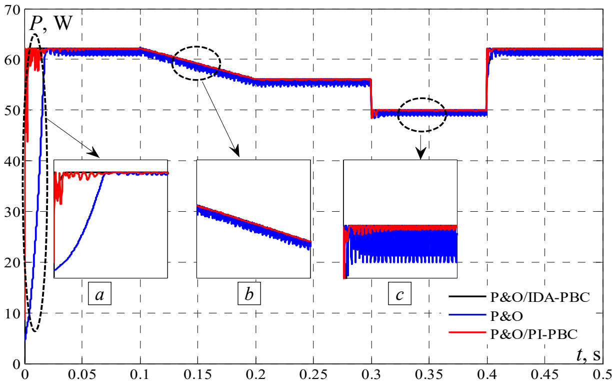

Fig. 6. PVG output power

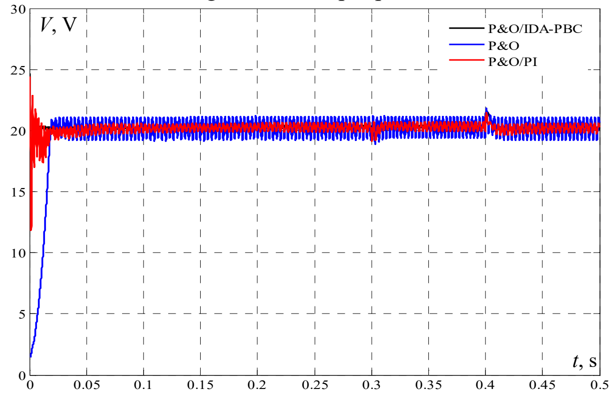

Fig. 7. PVG output voltage

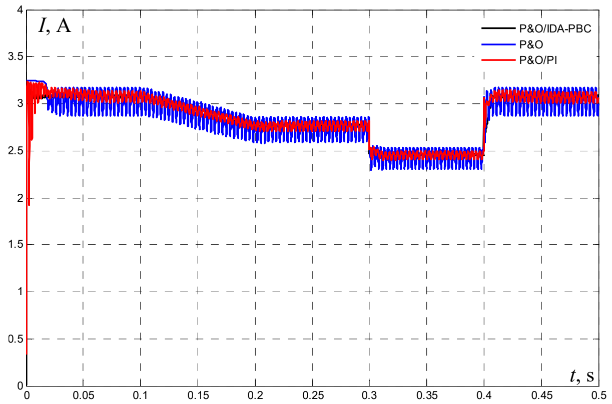

Fig. 8. PVG output current

The percentage reduction in energy of the PVG output power is 2.49 % (P&O), 0.43 % (P&O/PI) and 0.014 % (P&O/IDA-PBC).

As shown in Fig. 7, the ripple rates in PVG voltage are 6.43 % (P&O), 5.19 % (P&O/PI) and 0.44 % (P&O/IDA-PBC). For the PVG current, these rates are 6.18 %, 1.95 % and 0.29 %, respectively. The proposed strategy demonstrates the best control performance of the PV system, as it achieves the fastest MPPT speed with the least fluctuations and energy losses under the influence of variations in solar irradiation.

Influence of temperature variations. The variation in temperature is modeled according to the function illustrated in Fig. 9, while the solar irradiation remains constant at 1000 W/m^2 throughout the simulations.

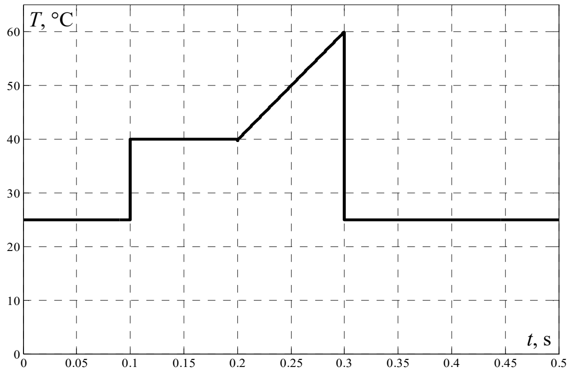

Fig. 9. Temperature variation function

Figures 10–12 show the simulation results for the PV system's output power, voltage and current, controlled by the 3 algorithms under consideration. These results provide insights into how changes in temperature impact the performance of the MPPT and its ability to optimize the energy output of the PV system.

Moreover, the simulation results comparison obtained from the 3 MPPT algorithms allows for a comprehensive evaluation of their efficiency and effectiveness under varying temperature conditions.

In Fig. 10 (zoom *a*), the MPP is reached after 4.2 ms for the P&O/IDA-PBC and after 20 ms and 25 ms for the other MPPTs. These results show that the P&O/IDA-PBC converges very quickly to the MPP compared to the P&O/PI and P&O.

At the time interval 0.2–0.3 s in Fig. 10 (zoom *b*), when the temperature increases linearly from 40 °C to 60 °C, it can be noticed that the P&O/IDA-PBC algorithm tracks the MPP in the correct direction and exhibits fewer oscillations compared to the P&O/PI and P&O.

Figure 10 (zoom *c*) shows that at the simulation interval 0.4–0.5 s, the efficiency of the system controlled by P&O/IDA-PBC is 99.97 %, compared to 99.7 % (P&O/PI) and 97.59 % (P&O). This demonstrates that the PVG output power oscillation in P&O/IDA-PBC is more reduced compared to the P&O algorithm.

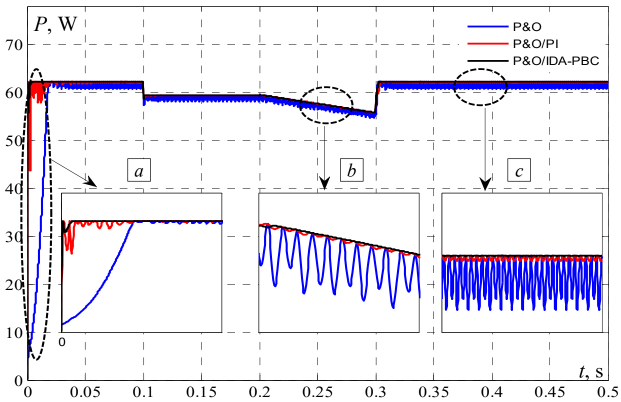

Fig. 10. PVG output power

In Fig. 11 the ripple PVG voltage rate are 5.09 % (P&O), 2.52 % (P&O/PI) and 0.74 % (P&O/IDA-PBC). In Fig. 12, the ripple PVG current rate are 6.51 % (P&O), 1.62 % (P&O/PI) and 0.48 % (P&O/IDA-PBC). These results also prove that enhancing P&O with a PBC strategy significantly reduces oscillations and is more efficient than the P&O.

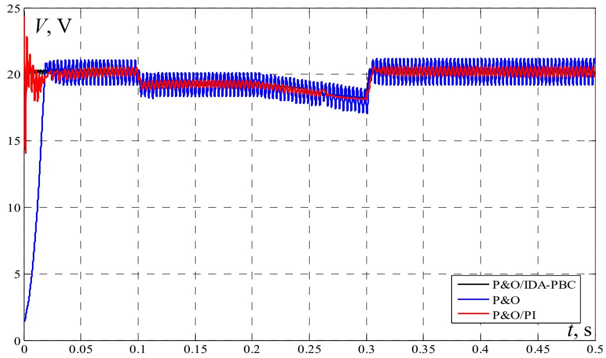

Fig. 11. PVG output voltage

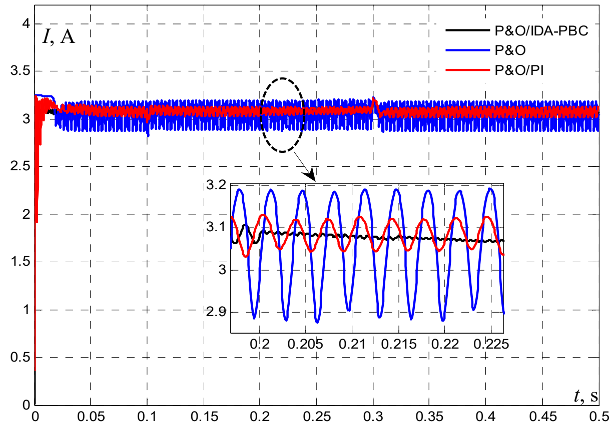

Fig. 12. PVG output current

Abrupt increase in load. The performance evaluation of the system during a load variation at a fixed temperature of 25 °C and irradiation of 1000 W/m^2 is shown in Fig. 13. An abrupt increase in the load was applied by adding a resistor of 5 Ω at t = 0.26 s.

The results show that the use of P&O/IDA-PBC is the most effective compared to P&O and P&O/PI. As shown in Fig. 13 (zoom), the P&O/IDA-PBC ensures a very fast convergence to the MPP, with almost no oscillations around the MPP and, hence, less losses. It is to remark that when the value of the load increases, the decrease in power is important. Furthermore, the system controlled by P&O/IDA-PBC has 99.99 % efficiency compared with the P&O and P&O/PI algorithms are 96.95 % and 99.57 % respectively. It can be concluded that the P&O/IDA-PBC exhibits superior characteristics compared to P&O and P&O/PI.

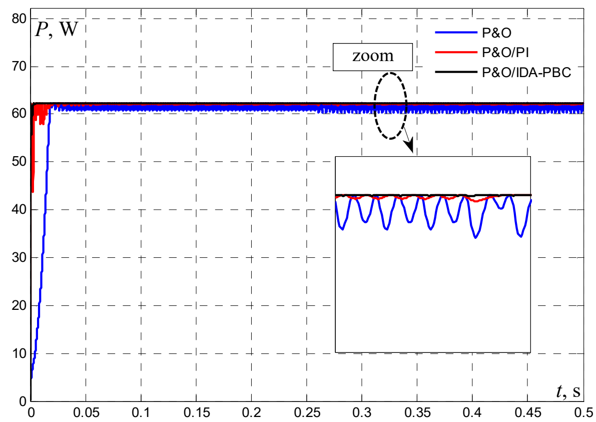

Fig. 13. PVG output power under robustness test for sudden changes of the load

Conclusions. Multiple MPPT algorithms were employed to optimize the PVG energy output. Among these algorithms, the P&O exhibits drawbacks such as inadequate support for sudden variations in irradiation levels and oscillations in power around the actual MPP. The passivity-based control strategy represents a viable approach for enhancing the P&O algorithm.

This work demonstrates the feasibility of leveraging passivity-based control strategies to enhance the characteristics of the P&O technique. Passivity theory has been applied in detail to the boost converter, which serves as an adjustment stage between the load and the PVG. The P&O delivers the measured reference voltage to the designed passivity block in order to significantly improve system efficiency. By applying passivity theory, we developed a P&O variant based on passivity, named the P&O/IDA-PBC technique.

Simulations were performed by comparing the efficiency of the studied system using 3 types of MPPTs: P&O/PI, classical P&O, and the proposed P&O/IDA-PBC. The results support that IDA-PBC greatly improves P&O performance, reduces power losses caused by ripples in the power of the operating MPP, and considerably increases convergence time. It is also worth noting that P&O/IDA-PBC is more robust than P&O/PI and classical P&O, as demonstrated by a set of tests, including temperature dependence on irradiation levels, abrupt variations in irradiation, and changes in load.

According to the simulated results, it can be concluded that the P&O/IDA-PBC method can correctly track the MPP under various operating conditions, providing the best efficiency in tracking the MPP, minimizing power loss, reducing oscillations around the MPP, and ensuring a more stable operating point compared to classical P&O and P&O/PI. Future work involves the practical implementation using the process in the loop technique to test and validate the proposed P&O/IDA-PBC method performance.

Conflict of interest. The authors declare that they have no conflicts of interest.

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