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# Cascade sliding mode maximum power point tracking controller for photovoltaic systems

***Introduction.*** *Constant increases in power consumption by both industrial and individual users may cause depletion of fossil fuels and environmental pollution, and hence there is a growing interest in clean and renewable energy resources. Photovoltaic power generation systems are playing an important role as a clean power electricity source in meeting future electricity demands.* ***Problem****. All photovoltaic systems have two problems; the first one being the very low electric-power generation efficiency, especially under low-irradiation states; the second resides in the interdependence of the amount of the electric power generated by solar arrays and the ever changing weather conditions. Load mismatch can occur under these weather varying conditions such that maximum power is not extracted and delivered to the load. This issue constitutes the so-called maximum power point tracking problem.* ***Aim.*** *Many methods have been developed to determine the maximum power point under all conditions. There are various methods, in most of them based on the well-known principle of perturb and observe. In this method, the operating point oscillates at a certain amplitude, no matter whether the maximum power point is reached or not. That is, this oscillation remains even in the steady state after reaching the maximum power point, which leads to power loss. This is an essential drawback of the previous method. In this paper, a cascade sliding mode maximum power point tracking control for a photovoltaic system is proposed to overcome above mentioned problems.* ***Methodology.*** *The photovoltaic system is mainly composed of a solar array, DC/DC boost converter, cascade sliding mode controller, and an output load. Two sliding mode control design strategies are joined to construct the proposed controller. The primary sliding mode algorithm is designed for maximum power point searching, i.e., to track the output reference voltage of the solar array. This voltage is used to manipulate the setpoint of the secondary sliding mode controller, which is used via the DC-DC boost converter to achieve maximum power output.* ***Results.*** *This novel approach provides a good transient response, a low tracking error and a very fast reaction against the solar radiation and photovoltaic cell temperature variations. The simulation results demonstrate the effectiveness of the proposed approach in the presence of environmental disturbances.* References 23, table 1, figures 11.

*Key words:* **renewable energy, photovoltaic system, maximum power point tracking, DC-DC boost converter, sliding mode control.**

***Вступ****. Постійне збільшення енергоспоживання як промисловими, так і індивідуальними користувачами може призвести до виснаження запасів викопного палива та забруднення навколишнього середовища, тому зростає інтерес до чистих та відновлюваних джерел енергії. Фотоелектричні системи виробництва електроенергії відіграють важливу роль як екологічно чисте джерело електроенергії для задоволення майбутніх потреб в електроенергії.* ***Проблема****. Усі фотоелектричні системи мають дві проблеми; по-перше, дуже низька ефективність вироблення електроенергії, особливо в умовах низького опромінення; друга полягає у взаємозалежності кількості електроенергії, що виробляється сонячними батареями, та постійно мінливих погодних умов. У цих погодних умовах, що змінюються, може відбутися невідповідність навантаження, так що максимальна потужність не буде витягнута і передана в навантаження. Ця проблема є так званою проблемою відстеження точки максимальної потужності.* ***Мета****. Було розроблено безліч методів визначення точки максимальної потужності за будь-яких умов. Існують різні методи, здебільшого засновані на відомому принципі збурення та спостережень. У цьому методі робоча точка коливається з певною амплітудою, незалежно від того, досягнуто точку максимальної потужності чи ні. Тобто це коливання залишається навіть у стійкому стані після досягнення точки максимальної потужності, що призводить до втрати потужності. Це значний недолік попереднього способу. У цій статті для подолання вищезазначених проблем пропонується каскадне керування відстеженням точки максимальної потужності в режимі ковзання для фотоелектричної системи.* ***Методологія****. Фотоелектрична система в основному складається з сонячної батареї, перетворювача постійного струму, що підвищує, каскадного контролера ковзного режиму та вихідного навантаження. Дві стратегії проєктування керування ковзним режимом об'єднані для побудови пропонованого контролера. Алгоритм первинного ковзного режиму призначений для пошуку точки максимальної потужності, тобто для відстеження вихідної опорної напруги сонячної батареї. Ця напруга використовується для управління уставкою вторинного контролера ковзного режиму, який використовується через перетворювач постійного струму, що підвищує, для досягнення максимальної вихідної потужності.* ***Результати****. Цей новий підхід забезпечує хорошу перехідну характеристику, низьку помилку відстеження та дуже швидку реакцію на сонячне випромінювання та коливання температури фотогальванічного елемента. Результати моделювання демонструють ефективність пропонованого підходу за наявності збурень довкілля.* Бібл. 23, табл. 1, рис. 11.

*Ключові слова:* **відновлювана енергія, фотогальванічна система, відстеження точки максимальної потужності, DC-DC підвищувальний перетворювач, керування ковзним режимом.**

**Introduction.** Due to the increasing energy demands and environmental protection requirements, renewable and sustainable energy resources are becoming an important part of power generation. Photovoltaic (PV) systems are one of the most promising renewable sources since they exhibit many merits such as availability, cleanness, little maintenance and no noise pollution. Thus, the power generation from PV systems will keep increasing in the future electrical power grid and microgrid systems as well [1-5]. However, PV systems present notable disadvantages, such as a very low electric-power generation efficiency, especially under low-irradiation states; an interdependence of the amount of the electric power generated by solar arrays and changing weather conditions [2-7].

To harvest a maximum amount of energy available under all environmental operating conditions, maximum power point tracker (MPPT) is an important component in a PV system that enables to extract maximum power at maximum power point (MPP). PV systems have nonlinear configurations, which require a robust control scheme for a practical operating environment. Therefore, an efficient MPPT algorithm which considers the nonlinear nature of the plant is necessary and is addressed in this paper.

Many papers have addressed this issue using nonlinear approaches such as backstepping technique [8], perturbation and observation (P&O) method [9], incremental conductance approach (InC) [10, 11] and sliding mode control (SMC) schemes [12, 13]. In most of these approaches, the MPP to track the reference voltage is obtained based on P&O method, InC approach and constant voltage technique (CV) [7, 14, 15]. However, in quickly changing meteorological circumstances, both of these strategies fail [7, 14, 15]. In this paper to improve the operation of the PV system, both power-voltage and characteristic curve of a PV array are analysed and a new MPPT algorithm based on SMC is proposed.

Sliding mode technique provides a robust control law driving system states to a predesigned attractor and on to the operating equilibrium point. The main advantage of this approach is that once system states reach the attractor, the system dynamics remain insensitive to a class of parameter variation and disturbances, which are typical in solar systems. Consequently, some solutions based on this approach have been proposed to provide good performance in attenuating the oscillations of the output voltage and to ensure the tracking of the reference provided by the MPPT algorithm [16, 17]. However, these solutions do not guarantee the existence of the sliding mode throughout the entire operating range.

The **objective** of this work is to develop an improved sliding mode based maximum power point tracking (SMC-MPPT) controller that takes into account all the elements required to ensure the PV system's desired operation, namely, a robust controller that can follow the reference provided by an MPPT algorithm in the presence of environmental disturbances.

The proposed approach ensures a stable sliding regime over the system's desired operating range, while also providing the convergence time and PV voltage overshoot required by an MPPT algorithm. The simulation results demonstrate the efficiency of the improved sliding mode MPPT controller in the presence of environmental disturbances.

**Design of cascade sliding mode controller.** This work presents an improved procedure of designing a sliding mode MPPT controller for PV systems, which forces the PV voltage to follow a reference provided by an external MPPT algorithm and attenuates the disturbances caused by the climatic changes. A DC-DC boost converter constituting the heart of the MPPT is inserted between the PV module and its load to achieve optimum power transfer, such a scheme with a resistive load is illustrated in Fig. 1. The converter is used to regulate the PV output voltage ($v_{pv}$) in order to extract as much power as possible from the PV module.

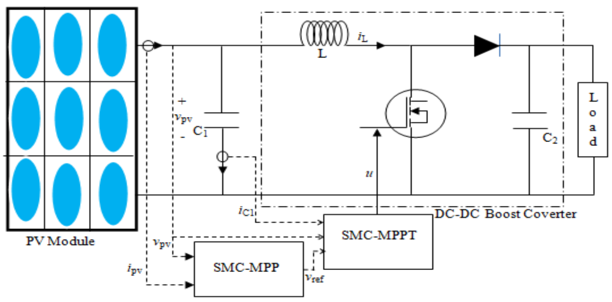

Fig. 1. Block diagram of PV system using cascade SMC-MPPT control

Where the output PV voltage $v_{pv}$ and the output PV current $i_{pv}$ are measured from PV array and sent to the sliding mode maximum power point searching algorithm (SMC-MPP), which generates the reference maximum power voltage $v_{ref}$. Then, the reference voltage is given to the SMC-MPPT controller the maximum power tracking.

**Design of SMC-MPP controller.** The maximum power at any operation point can be performed in an easy way if the SMC is used to generate the reference output voltage by imposing the following sliding equation.

$$\sigma = \frac{dP_{pv}}{dv_{pv}} = i_{pv} + v_{pv}\frac{di_{pv}}{dv_{pv}} = 0 , \qquad (1)$$

where $\sigma$ is the sliding mode surface; $P_{pv}$ is the output PV power.

If (1) is satisfied, the PV array operates at its maximum power point (MPP) and reference voltage $v_{ref}$ is generated.

Now consider the characteristic curve of the PV system as shown in Fig. 2, the SMC-MPP method can be designed according to the following steps.

**Step 1.** As shown in Fig. 2 the sliding mode surface has a positive value in region A, this conduct to a negative value of its derivative, i.e. $\dot{\sigma} \prec 0$ to ensure the local reachability condition $\sigma\dot{\sigma} \prec 0$ of the existence SMC operation [18]. From this analysis, SMC-MPP controller increase $v_{pv}$ from $v_1$ to $v_{ref}$ to track the MPP. Thus $\dot{v}_{pv}$ must be a positive value.

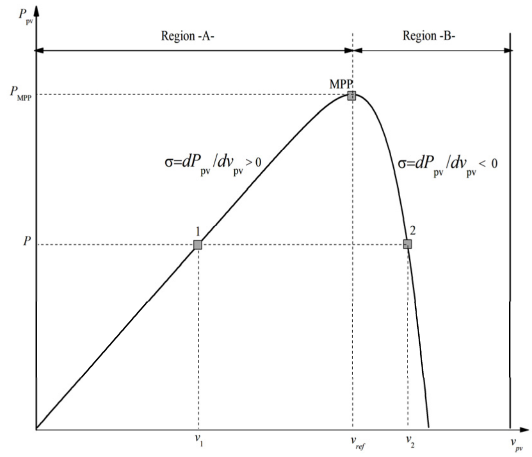

Fig. 2. Power-voltage characteristic curve of a PV system

**Step 2.** In this case, the sliding mode surface has a negative value as shown in Fig. 3 (region B), this conduct to a positive value of its derivative, i.e. $\dot{\sigma} \succ 0$ to ensure the local reachability condition of the existence SMC operation [18]. Due to this analysis, SMC-MPP controller decrease $v_{pv}$ from $v_1$ to $v_{ref}$ to track the MPP. Thus $\dot{v}_{pv}$ must be a negative value.

Now, define the output of the SMC-MPP controller as $v_{ref}$, then combining steps (1) and (2), leads to (2):

$$\dot{v}_{ref} = -\dot{\sigma} . \qquad (2)$$

Thus, the control law of the proposed SMC-MPP controller can be designed as

$$v_{ref} = -\int \dot{\sigma}\, dt . \qquad (3)$$

Based on the exponential reaching law [18], the equation in (3) can also be written as:

$$v_{ref} = \int \left( k\,\sigma + \eta \,\mathrm{sgn}\left(\sigma\right)\right) dt , \qquad (4)$$

where $\eta$ and $k$ are the positive constants.

With sliding mode control law (4), MPP reference voltage can be generated under various weather conditions.

**Design of SMC-MPPT controller.** The proposed controller has advantages over existing solutions which rely on the linearization of the dynamics of the internal current loop, since the chosen sliding surface $S$ is a linear combination of the input capacitor current and the error of PV voltage

$$S = \lambda_1 \left( v_{PV} - v_{ref} \right) + \lambda_2 \, i_{C_1} \, , \tag{5}$$

where $\lambda_1$ and $\lambda_2$ are the constants.

The main advantage of this approach is voltage regulation $v_{pv}$ without additional regulators based on linearized models. A good alternative to define the behavior of PV voltage is to include both the error with respect to the reference voltage given by a SMC-MPP algorithm and the voltage derivative in the expression of the sliding surface. The voltage derivative can be obtained by measuring the current of the input capacitor $i_{C1}$.

This work is based on the choice of a sliding surface $S$ given in (5), which makes it possible to explore the stability of the PV voltage in presence of climatic changes. The dynamic behavior of the DC-DC converter is modeled by (6), (7):

$$i_{C_1} = C_1 . \frac{dv_{PV}}{dt} = i_{PV} - i_L \, ; \tag{6}$$

$$v_L = L \frac{di_L}{dt} = v_{PV} - v_{C2} \left( 1 - u \right) , \tag{7}$$

where $C_1$, $L$ and $v_{C2}$ are respectively the output capacitance, inductance and the output voltage of the boost converter; $i_L$ is the inductor current; $v_L$ is the inductor voltage and $u$ is the control signal.

The PV current $i_{pv}$ can be modeled by the simplified single diode model given by (8) [19]:

$$i_{PV} = i_{SC} - I_R \left( e^{\alpha v_{PV}} - 1 \right) . \tag{8}$$

where $i_{SC}$ is the short-circuit current; $I_R$ is the saturation current of the diode; $\alpha$ is the thermal voltage which depends on the temperature of the panel [20], knowing that the short-circuit current is approximately proportional to the irradiance $E$ [21]:

$$i_{SC} = K_S \, E \, . \tag{9}$$

The design of sliding mode regulators supports the desired performance in a systematic way. It also requires fulfilling three conditions: transversality, equivalent control and reachability [18, 19, 22, 23].

**Transversality condition**. The derivative of the function $S$ with respect to time is given by (10):

$$\frac{dS}{dt} = \frac{d\,v_{PV}}{dt} \left( \lambda_1 + \lambda_2 \frac{d\,i_{PV}}{d\,v_{PV}} \right) - \lambda_1 \frac{d\,v_{ref}}{dt} + + \lambda_2 \frac{d\,i_{SC}}{dt} - \lambda_2 \left( \frac{v_{PV} - v_{C2} \left( 1 - u \right)}{L} \right) . \tag{10}$$

By differentiating (10) versus $u$, we have:

$$\frac{d \frac{dS}{dt}}{du} = - \frac{\lambda_2 \, v_{C2}}{L} \neq 0 \, , \tag{11}$$

since $v_{C2}$ and $L$ are both positive, the transversality condition is then satisfied if the parameter $\lambda_2 \neq 0$.

**Equivalent control condition.** The equivalent control $u_{eq}$ is a continuous function which is used to maintain the variable to be controlled on the sliding surface. It is obtained thanks to the invariance conditions of the sliding surface. For the DC-DC converter, the correct range is given by $0 \prec u_{eq} \prec 1$

$$d \frac{dS}{dt} = 0 \quad \to \; 0 < u_{eq} < 1 \, . \tag{12}$$

By replacing $u$ by $u_{eq}$ in (12), while respecting the inequality given in (11), we obtain:

$$0 < u_{eq} = \frac{L}{v_{C2}} \left[ \left( \frac{\lambda_1}{\lambda_2} + A \right) \frac{d\,v_{PV}}{dt} - \frac{\lambda_1}{\lambda_2} \frac{d\,v_{ref}}{dt} \right] + \frac{L}{v_{C2}} \frac{d\,i_{SC}}{dt} - \frac{v_{PV}}{v_{C2}} + 1 < 1 \tag{13}$$

where:

$$A = -I_R \, \alpha \, e^{\alpha v_{pv}} \, . \tag{14}$$

Considering that the system is maintained on the sliding surface $S = 0$, equation (15) obtained from (5) and (6) describes the dynamics of the sliding mode, which can be analyzed in the Laplace domain as indicated by (14):

$$i_{C_{in}} = C_1 \frac{d\,v_{PV}}{dt} = - \frac{\lambda_1}{\lambda_2} \left( v_{PV} - v_{ref} \right) ; \tag{15}$$

$$\frac{V_{PV}(s)}{V_{ref}(s)} = \frac{1}{\frac{\lambda_2 . C_1}{\lambda_1} s + 1} \, . \tag{16}$$

Equation (16) shows the existence of an equivalent pole $-\lambda_1/\lambda_2 C_1$. Therefore, $\lambda_1$ and $\lambda_2$ must be of the same sign to ensure the stability of the system.

**Reachability conditions.** These conditions allow the sliding surface to have a dynamic of convergence towards zero. As discussed in the previous section, the proposed approach design requires a negative value for the parameter $\lambda_2$; thus, the existence condition in (11) is positive, imposing the reachability conditions (17), (18):

$$\lim_{S \to 0^-} \left. \frac{d\,S}{dt} \right|_{u=1} = \left. \frac{d\,S}{dt} \right|_{u=1,\; S=0} > 0 \, ; \tag{17}$$

$$\lim_{S \to 0^+} \left. \frac{d\,S}{dt} \right|_{u=0} = \left. \frac{d\,S}{dt} \right|_{u=0,\; S=0} < 0 \, . \tag{18}$$

The value of $u$ is imposed for each condition: $u = 1$ for $S \prec 0$ and $u = 0$ for $S \succ 0$ [18, 23]. Substituting (10) in (17) and (18), leads to (19) and (20) which confirm that the condition $S\dot{S} \prec 0$ is satisfied:

$$\lim_{S \to 0^-} \frac{d\,S}{dt} = \frac{d\,v_{PV}}{dt} \left( \lambda_1 + \lambda_2 \, A \right) - \lambda_1 \frac{d\,v_{ref}}{dt} + + \lambda_2 \frac{d\,i_{SC}}{dt} - \lambda_2 \left( \frac{v_{PV}}{L} \right) > 0 \, ; \tag{19}$$

$$\lim_{S \to 0^+} \frac{d\,S}{dt} = \frac{d\,v_{PV}}{dt} \left( \lambda_1 + \lambda_2 \, A \right) - \lambda_1 \frac{d\,v_{ref}}{dt} + + \lambda_2 \frac{d\,i_{SC}}{dt} - \lambda_2 \left( \frac{v_{PV} - v_b}{L} \right) < 0 \, . \tag{20}$$

**Simulation results.** In order to test and compare the performance of the proposed SMC-MPPT algorithm to the conventional P&O algorithm, the PV solar system is modeled and implemented in MATLAB/Simulink software.

The Simulink PV system model shown in Fig. 3 was selected to assess the performance and the effectiveness of the proposed controller SMC-MPPT. Specification parameters PV power generation are given in Table 1.

Table 1

PV system specifications

| Parameter | Value |
|---|---|
| Maximum output power $P_{\max}$, W | 85 |
| Maximum voltage $V_{PMM}$, V | 18 |
| Maximum current $I_{PMM}$, A | 4.72 |
| Open circuit voltage $V_{OC}$, V | 22.1 |
| Short circuit current $I_{SC}$, A | 5 |
| Temperature coefficient of $V_{OC}$, %·°C$^{-1}$ | –0.8 |
| Temperature coefficient of $I_{SC}$, %·°C$^{-1}$ | 0.00065 |

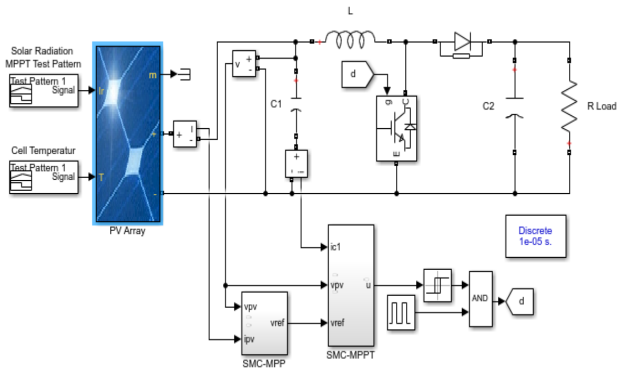

Fig. 3. Simulink PV system model

A comparative study with strictly identical simulation parameters is carried out. The PV system consists of a typical PV generator BP585, a DC-DC boost converter and a load. The input voltage of the DC-DC converter is set to 18 V, the inductance value is equal to 22.5 mH, the input capacitor is set to 132 μF, the output capacitor is equal to 66 μF and the output resistive load is set to 12 Ω. In DC-DC converter applications, hysteresis comparators are commonly used to implement the proposed controller. To limit the switching frequency, a hysteresis band ($h$) must be introduced to the sliding surface [22, 23]. As a result, the sliding surface's limits will be:

$$-\frac{h}{2} \leq S \leq \frac{h}{2}. \qquad (21)$$

Equation (22) which is derived from inequalities (17), (18) shows this constraint:

$$S \leq -\frac{h}{2} \rightarrow u = 1 \wedge S \geq \frac{h}{2} \rightarrow u = 0. \qquad (22)$$

Several simulations were carried out taking into account variations in climatic conditions, namely irradiance and temperature. Obtained results are presented for a period of 1 s. Each figure presents a comparison of the characteristics of the PV system governed by the cascade SMC and P&O approaches. Zooming was carried out at two different locations, the first at the beginning of the profile to illustrate the response time and the second to show the oscillations around the MPP.

**Case 1: variable temperature.** A variable temperature is used with a constant irradiance equal to 1000 W/m$^2$.

It can be noted from Fig. 5–7, that the response times are approximately 2 ms and 17.5 ms. During the transient regime, we notice that the trajectory of the PPM obtained by applying the cascade SMC control is better than that obtained with the P&O. In steady state, the P&O oscillates around the PPM between 81.75 W and 84.45 W as shown in Fig. 4.

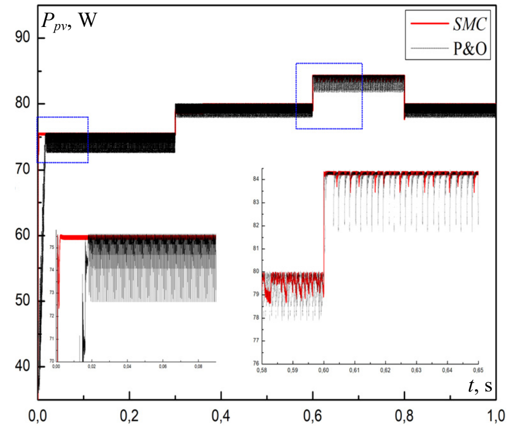

Fig. 4. PV power evolution for case 1

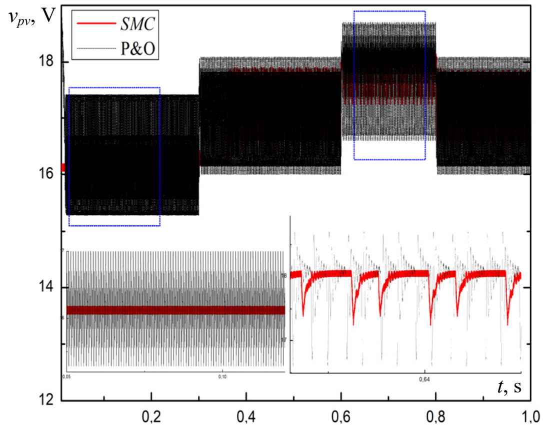

Fig. 5. PV voltage evolution for case 1

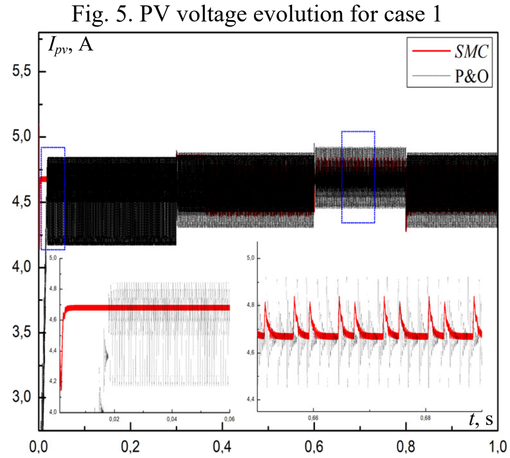

Fig. 6. PV current evolution for case 1

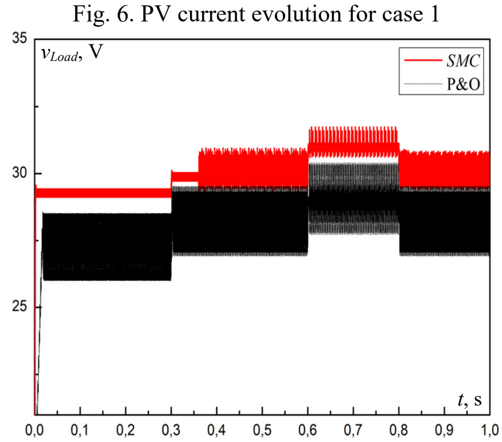

Fig. 7. Load voltage evolution for case 1

**Case 2: variable irradiance.** To validate the effectiveness of the proposed approach, another robustness test was carried out where a trapezoidal irradiance profile was chosen (the temperature is set to 25 °C). The simulation results as given in Fig. 8–11 show that the P&O method exhibits poor performance in its dynamic response. With a constant increase in irradiance in the form of a positive slope, the P&O method fails to follow the true path of the MPP thus causing losses of power and energy. Under decreasing variation in irradiation, the same monitoring problem is observed. In addition, in static mode the power of the PV constantly oscillates around MPP.

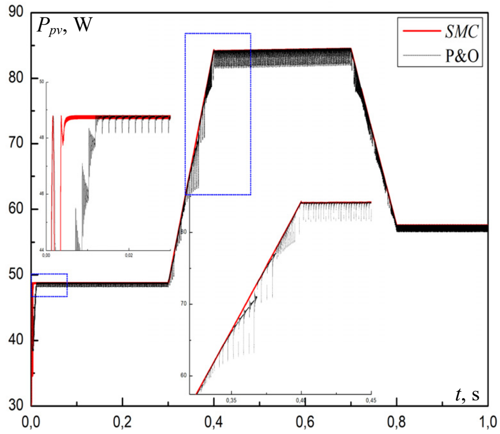

Fig. 8. PV power evolution for case 2

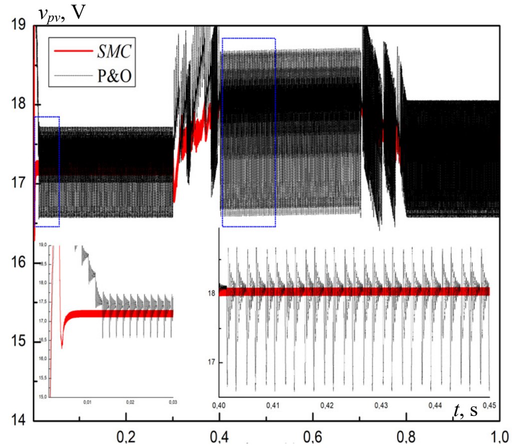

Fig. 9. PV voltage evolution for case 2

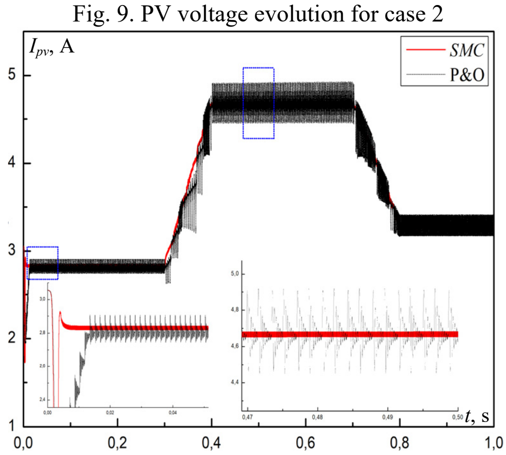

Fig. 10. PV current evolution for case 2

Unlike the P&O algorithm, the proposed approach reveals remarkable performance in all irradiance conditions. The SMC controller perfectly follows the MPP trajectory as shown in the zoomed parts where the tracking of the MPP is perfect and the minimization of power oscillation in static regime is effective.

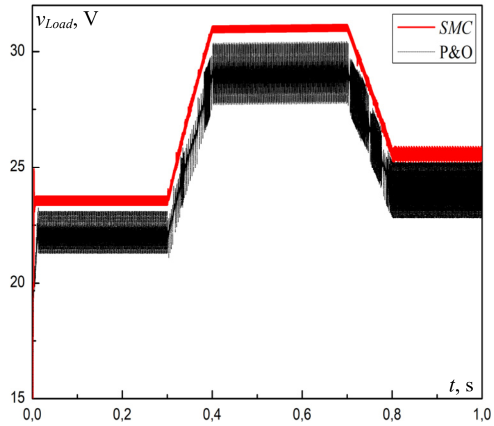

Fig. 11. Load voltage evolution for case 2

**Conclusion.** The study reported in this paper focused on the control of a solar system that uses a DC-DC boost converter to supply electrical clean power. An advanced procedure for the designation of a sliding mode based maximum power point tracking control for photovoltaic systems has been proposed. This control ensures maximum power point operation and robustness to irradiance and temperature fluctuations, as well as reducing oscillations at the converter's output voltage. The simulation results made it possible to demonstrate the performance and robustness of the proposed control law.

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

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