

Adaptive Sliding Mode-Based MPPT and Voltage Regulation for Photovoltaic Systems with Boost/Buck Converter

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Article Info

Article history:

Received , 20/06/2025

Revised , 28/07/2025

Accepted , 10/08/2025

Keywords:

Sliding Mode Control;
Voltage Regulation;
Maximum Power Point
Tracker;
Photovoltaic System;
Boost Converter;
Buck Converter.

ABSTRACT

This paper proposes an Adaptive Sliding Mode Control (ASMC) strategy for a photovoltaic (PV) system equipped with a combined boost/buck converter. The designed controller simultaneously achieves Maximum Power Point Tracking (MPPT) and output voltage regulation despite variations in solar irradiance and load conditions. By dynamically adjusting sliding surface parameters, the ASMC optimizes the converter's duty cycle to enhance power extraction efficiency while ensuring stable DC bus voltage. Numerical simulations validate the approach, demonstrating improved tracking accuracy, increased robustness against disturbances, and reduced chattering phenomenon. The results highlight the effectiveness of the proposed ASMC control in achieving its dual objectives: MPPT and voltage stabilization in PV systems using hybrid DC-DC converters.

I. Introduction

Confronted with climate urgency and the depletion of fossil fuels, renewable energies have emerged as fundamental pillars of the energy transition. Photovoltaic solar energy stands out particularly due to its rapid development and unlimited potential. Photovoltaic (PV) systems directly convert solar radiation into electrical energy, thereby representing an ecological and sustainable solution to meet the world's growing electricity demand.

However, photovoltaic system performance is significantly affected by weather variability and changing environmental conditions (irradiance, temperature), as well as load variations. This sensitivity to external disturbances requires the implementation of sophisticated control strategies capable of continuously optimizing system operation. Furthermore, proper regulation of these systems is essential to maximize power extraction and ensure grid stability while optimizing power quality fed into the network. In this context, Maximum Power Point Tracking (MPPT) constitutes an indispensable feature for any high-performance photovoltaic system [1]-[4]. This technique enables real-time adjustment of solar panels' operating point to extract maximum available power

regardless of sunlight variations. Various MPPT algorithms have been developed, ranging from simple methods (Perturb and Observe [5]-[7], Incremental Conductance [8]-[10]) to more sophisticated approaches based on artificial intelligence [11]-[13]. MPPT efficiency directly impacts the system's overall energy yield, with potential gains reaching up to one third compared to non-optimized systems. For critical applications, the convergence speed and stability of the MPPT algorithm are parameters equally important as tracking accuracy.

In addition to MPPT, voltage regulation in PV systems represents a major technical challenge, particularly for grid-connected installations [14]-[16]. Stable and well-regulated voltage is essential to ensure compliance with interconnection standards and protect downstream equipment. DC-DC converters play a key role here by adjusting voltage to required levels despite photovoltaic output fluctuations [17]-[19]. Poor regulation can lead to malfunctions, reduced power quality, or even unintended grid disconnections. In hybrid or standalone systems, voltage control becomes even more critical to maintain balance between production and consumption, especially during transitions between different operating modes. Among advanced control strategies, Sliding Mode Control (SMC) stands out for its intrinsic robustness against system uncertainties [20]-[24]. Its application to PV systems in adaptive form (ASMC) allows combining two fundamental objectives: efficient MPPT and precise voltage regulation [25]-[28]. The ASMC dynamically adjusts its parameters to adapt to environmental variations, offering faster response times and enhanced stability compared to conventional methods. This dual capability makes it particularly attractive for modern photovoltaic converters.

This work aims to propose an innovative ASMC methodology for PV systems using buck/boost converters, capable of simultaneously optimizing both MPPT and voltage regulation. We will demonstrate how this unified approach improves energy efficiency while ensuring system stability under various operating conditions. The paper is organized as follows: Following this introduction, the paper is organized as follows: Section II presents the photovoltaic system modeling, including the electrical characteristics and mathematical formulation. Section III details the boost converter design and operational principles, while Section IV examines the buck converter topology. The core contribution – an integrated Adaptive Sliding Mode Control (ASMC) for simultaneous MPPT and voltage regulation – is developed in Section V. Section V discusses the simulation methodology and test conditions. Experimental results and comparative analysis are provided in Section VI, followed by concluding remarks and future research directions in Section VII.

II. Modeling of the Photovoltaic System

In this section, we propose the modeling of a cell in a PVS. The electrical diagram of this cell is shown below in Figure 1.

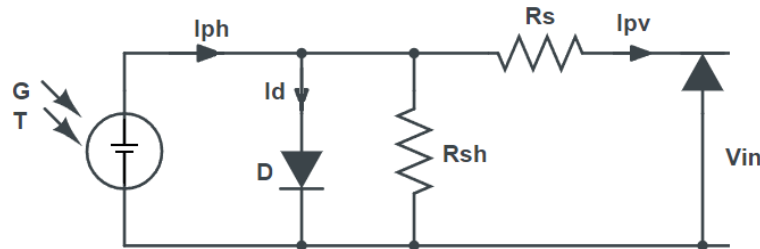


Figure 1. Electrical circuit diagram of a PV cell.

The different variables and parameters of Figure 1 are given as follows:

G : Incident irradiance (W/m^2),

T : Cell temperature ($^{\circ}\text{C}$),

D : Diode D ,

I_{ph} : Photocurrent (A),

I_d : current flowing through the diode D (A),

I_{pv} : current generated by the photovoltaic cell,

R_{sh} : Shunt resistance (leakage resistance due to defects) (Ω),

R_s : Series resistance (from contracts and material) (Ω),

V_{in} Is the total current generated by the photovoltaic panel (V).

The various mathematical equations materializing this electrical diagram of the photovoltaic cell will be given below.

II.1. Equation of the PV module current

The equation for the current of the PV module is given as follows:

$$I_{pv} = I_{ph} - I_0 \left(\exp\left(\frac{V_{pv} + I_{pv} R_s}{a N_s V_{th}}\right) - 1 \right) \quad (1)$$

The different variables and parameters of Eq. 1 are given as follows:

I_0 : Saturation current (A)

V_{pv} : Voltage of the PV module (V)

a : Quality factor of the diode

N_s : Number of PV cells in series

V_{th} : Thermal voltage (V)

II.2. Equation for the total current of the PV system

To obtain this equation, we divide the current of the PV module I_{pv} by the number of PV modules n_p connected in parallel.

$$I_{in} = \frac{I_{pv}}{n_p} \quad (2)$$

I_{in} Is the total current generated by the photovoltaic panel (A).

II.3. Equation of the photo-generated current

The photo-generated current depends on the illumination and the temperature:

$$I_{ph} = (I_{sc,n} + K_i \times (T - T_n)) \times (G/G_n) \quad (3)$$

where the different parameters of Eq. 3 are defined as below:

$I_{sc,n}$: Nominal short-circuit current (A)

K_i : Temperature coefficient of the short-circuit current (%/°C)

T_n : Nominal temperature (°C)

G_n : nominal irradiance (W/m^2)

II.4. Power equation of the PV system

The electrical power generated by the photovoltaic panel is the product of the current given by Eq. 2 and the voltage, and it is expressed as follows:

$$P_{in} = I_{in} \times V_{in} \quad (4)$$

where

P_{in} is the power generated by the photovoltaic panel (W)

V_{in} is the voltage generated by the photovoltaic panel (V)

III. The boost converter

To adapt the output voltage of the photovoltaic system to the load, we plan to choose a boost type voltage converter. The focus will be on the equations relating the input and output voltage of the converter to the current flowing through the inductor circuit. In reality, the inductor current I_L is often confused with the output current of the converter noted I_{out} .

III.1. Presentation of the boost converter

The Boost converter in a photovoltaic system plays a crucial role in optimizing solar power production. Its primary purpose is to increase the variable and often low voltage generated by PV panels to make it compatible with the requirements of the electrical grid, inverters, or batteries (typically 24V, 48V, or higher). Thanks to its MPPT control, it adjusts the operating point of the panels in real-time to extract the maximum available power, even under changing or partially shaded sunlight conditions.

The boost converter is governed by the two known operating modes called 'ON' and 'OFF' and described by the circuit in Figure 2, given below.

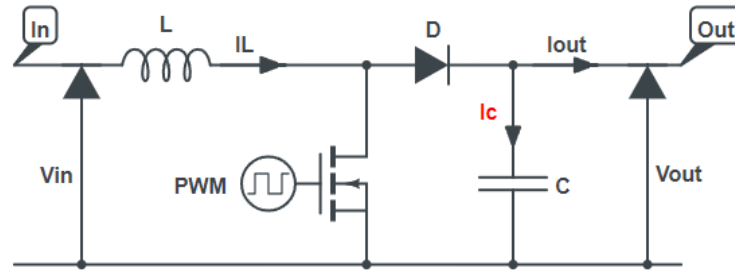


Figure 2. Schematic of the boost converter electrical circuit.

The relationship between the input and output voltage is given by:

$$\begin{cases} L \frac{di_L}{dt} = V_{in} + (\mu - 1)V_{out} \\ C \frac{dv_{out}}{dt} = -i_{out} - (\mu - 1)i_L \end{cases} \quad (5)$$

with

i_L is the instantaneous current of the inductance passing through the coil in (A),

i_{out} is the instantaneous output current in (A),

V_{out} is the output voltage in (V),

C is the capacitance of the boost converter circuit capacitor in (F),

L is the inductance of the coil in (H),

μ is a logical variable that can only take the values 0 or 1 depending on the operating state of the boost converter, such as:

$$\begin{cases} \mu = 0 & \text{switch ON} \\ \mu = 1 & \text{switch OFF} \end{cases}$$

The input voltage V_{in} and output voltage V_{out} can be expressed as:

$$V_{in} = \begin{cases} V_{out} + L \frac{di_L}{dt} & \text{if } \mu = 0 \\ L \frac{di_L}{dt} & \text{if } \mu = 1 \end{cases} \quad (6)$$

and

$$V_{out} = \begin{cases} -\frac{1}{c} \int (i_{out} + i_L) dt & \text{if } \mu = 0 \\ -\frac{1}{c} \int i_{out} dt & \text{if } \mu = 1 \end{cases} \quad (7)$$

In summary, we can reformulate this converter problem based on the dynamics control relying on the voltage V_{in} , voltage V_{out} and current I_L . Afterwards, we will present the sizing of voltages V_{in} and V_{out} as a function of the duty cycle D and then the output power for which we will perform the MPPT.

III.2. Duty cycle of the boost converter

The integration of D_{boost} into the modeling of a photovoltaic system is crucial for optimizing power extraction and ensuring efficient operation of the converter. By adjusting D_{boost} according to sunlight conditions and system characteristics, it is possible to enhance the overall performance of the PVS.

For a boost converter, the duty cycle D_{boost} is defined by:

$$D_{boost} = \frac{V_{out}}{V_{out} + V_{in}} \quad (8)$$

Eq. 8 shows that the duty cycle is proportional to the output voltage relative to the sum of the input and output voltages. A higher duty cycle means that the converter is active for a longer duration, which allows for an increase in the output voltage.

Subsequently, the output voltage of the boost converter is given by:

$$V_{out} = \frac{D_{boost}}{1 - D_{boost}} V_{in} \quad (9)$$

By analogy to Eq. 9, the output current is expressed by the following relationship:

$$I_{out} = \frac{D_{boost}}{1 - D_{boost}} I_L \quad (10)$$

From Eqs 9-10 it is clear that the choice of the duty cycle D_{boost} has a direct impact on the operation of the PVS through power optimization.

Indeed, by adjusting D_{boost} , the system can adapt to variations in sunlight and temperature, thus enabling optimal MPPT.

Moreover, it is important to maintain a certain balance between power and efficiency.

A duty cycle that is too high can lead to overheating losses and a reduction in converter efficiency, while a duty cycle that is too low may not allow reaching the desired output voltage V_{out} .

III.3. Output power of the boost converter

To find an expression for the output power $P_{out,boost}$ in terms of the duty cycle D_{boost} and the input power P_{in} , we can proceed as follows:

$$P_{out,boost} = V_{out} I_{out} \quad (11)$$

with $P_{out,boost}$ is the output power (W). By using Eqs 9-11, we obtain:

$$P_{out,boost} = \frac{D_{boost}^2}{(1 - D_{boost})^2} V_{in} I_L \quad (12)$$

Since $I_{in} = I_L$, we can express the output power of the converter given by Eq. 12 in conventional form in terms of the new duty cycle, described by the expression:

$$P_{out,boost} = D_P P_{in} \quad (13)$$

with D_P is the duty cycle corresponding to the output power of the converter, which can be written in the following form:

$$D_P = \frac{D_{boost}^2}{(1 - D_{boost})^2} \quad (14)$$

Eqs 13-14 highlights the importance of choosing D_p to maximize the output power of a boost converter. Indeed, this relationship indicates that $P_{out,boost}$ is directly proportional to P_{in} .

By maximizing D_{boost} within safe limits, the system can extract the maximum available power from the photovoltaic panel.

IV. The buck converter

IV.1. Presentation of the buck converter

The buck converter (step-down converter) plays a vital role in photovoltaic systems by efficiently reducing higher DC voltages from solar panels to lower, usable levels required by batteries, charge controllers, or DC loads. Its primary function is to maintain optimal voltage compatibility while maximizing energy transfer efficiency (typically 90-95%).

The buck converter is shown in Figure 3 below.

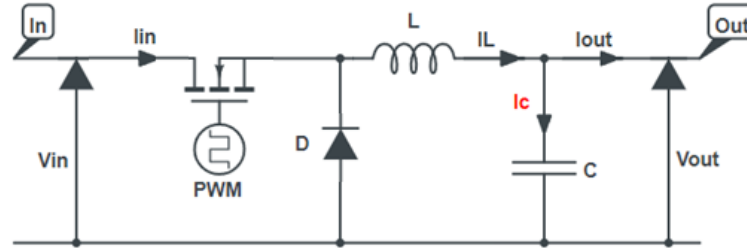


Figure 3. Schematic of the buck converter electrical circuit.

VI.2. Duty cycle of the buck converter

For the buck converter, the relationships are analogous. The output voltage of the boost converter is given by:

$$V_{out} = D_{buck} V_{in} \quad (15)$$

D_{buck} : Duty cycle ratio for the buck converter.

By analogy to Eq. 15, the output current is expressed by the following relationship:

$$I_{out} = \frac{1}{D_{buck}} I_L \quad (16)$$

VI.3. Output power of the buck converter

The output power of the buck converter is given by:

$$P_{out,buck} = V_{out} I_{out} \quad (17)$$

These equations model the behavior of a photovoltaic system with both boost and buck converters, taking into account the duty cycle and the corresponding powers. They allow for the analysis and optimization of the system's operation based on lighting and temperature conditions.

V. Integrated ASMC for MPPT and voltage regulation

The MPPT is an essential system in photovoltaic installations, responsible for optimizing in real time the power extracted from solar panels by adjusting their operating point. Its main role is to track the maximum power point of PV modules, which constantly varies depending on sunlight, temperature, or partial shading. Without MPPT, some of the generated energy would be lost, reducing the overall system efficiency.

The MPPT mainly acts on the DC/DC converter (Boost or Buck): It adjusts the voltage/current ratio at the panel output to maintain the MPP, via PWM modulation (PWM) controlled by an algorithm (Perturb & Observe,

Incremental Conductance). The efficiency gain reaches 30% more than a conventional PWM regulator.

In addition to adaptability to changing weather conditions, the MPPT protects the batteries while preventing their overcharging/deep discharging.

V.1. MPPT synthesis via adaptive sliding mode control

The formulation of the sliding surface S within the framework of the SMC for a PVS using both boost and buck converters must take into account the equations of the PV model and the relationships of the converters. This ensures that the system achieves and maintains optimal performance.

The sliding surface S should incorporate the deviations between the measured values and the reference values.

Initially, we need to determine a surface for each converter. To simplify, we propose to formulate a sliding surface S while incorporating a parameter that allows us to choose the type of converter used. We also integrate the duty cycle ratio for each converter, along with the model equations.

1) MPPT sliding surface

To maximise power extraction, we define a surface based on the derivative of photovoltaic power:

$$S_{MPPT} = \frac{dP_{pv}}{dV_{pv}} = I_{pv} + V_{pv} \frac{dI_{pv}}{dV_{pv}} \quad (18)$$

2) Adaptive law

Surface parameters are dynamically adjusted to compensate for irradiance variations:

$$\alpha(t) = \alpha_0 + k_1 \int |S_{MPPT}| dt \quad (19)$$

3) Duty cycle control

The Mppt duty cycle is computed as:

$$D_{MPPT} = D_{op} + K_p S_{MPPT} \quad (20)$$

where D_{op} is the optimal operating point..

V.2. Robust voltage regulation

1) Voltage regulation surface

To stabilize output voltage V_{out} :

$$S_V = \lambda(V_{ref} - V_{out}) + \frac{d(V_{ref} - V_{out})}{dt} \quad (21)$$

λ is a positive gain determining the rate of convergence.

2) Hybrid control

The finl combies MPPT and voltage regulation via weighting factor $\gamma \in [0,1]$:

$$S_{ASMC} = \gamma S_{MPPT} + (1 - \gamma) S_V \quad (22)$$

γ is the MPPT/voltage weighting (will be adjusted based on irradiance)

3) Unified ASMC synthesis

For the boost converter, the expression of the control law is given as:

$$D_{boost} = \frac{V_{ref}}{V_{in} - V_{ref}} + \eta S_{ASMC} \quad (23)$$

where the first term is provides steady-state and baseline duty cycle for voltage conversion, the second term adds

adaptive correction from the sliding surface and η is a chattering suppression gain (while maintaining 1% voltage ripple).

The buck converter control is given as:

$$D_{buck} = \frac{V_{ref} - V_{out}}{\lambda V_{out}} + \xi S_{ASMC} \quad (24)$$

with ξ is an anti-chattering gain to ensure smoothing transitions (typically ξ is smaller than η) and normalization λV_{out} ensures dimensionless gain and provides inherent overvoltage protection.

Physical limits is defined by :

$$D = \max(0.1, \min(0.9, D)) \quad (25)$$

to prevent duty cycle 100% (switch always on) and 0% duty cycle (switch always off) and to maintain converter stability.

V.3. Lyapunov stability proof

Let's consider a Lyapunov function, described as:

$$V = \frac{1}{2} S_{ASMC}^2 \quad (\text{Positive definite}) \quad (26)$$

The stability condition requires that $\dot{V} < 0$ when $S_{ASMC} \neq 0$. The derivative of the Lyapunov function is given by :

$$\dot{V} = S_{ASMC} \dot{S}_{ASMC} \quad (27)$$

with $\dot{S}_{ASMC} = \gamma \dot{S}_{MPPT} + (1 - \gamma) \dot{S}_V$, we obtain :

$$\dot{V} = S_{ASMC} (\gamma \dot{S}_{MPPT} + (1 - \gamma) \dot{S}_V) \quad (28)$$

La dérivée de la surface MPPT est donnée par :

$$\dot{S}_{MPPT} = \frac{d}{dt} \left(\frac{dP_{pv}}{dV_{pv}} \right) = \frac{dI_{pv}}{dV_{pv}} + V_{pv} \frac{d^2 I_{pv}}{dV_{pv}^2} + \frac{dI_{pv}}{dV_{pv}} \quad (29)$$

The compact form of the MPPT surface derivative:

$$\dot{S}_{MPPT} \approx -\frac{R_s I_0}{aV_{th}} e^{\frac{V_{pv} + I_{pv} R_s}{aV_{th}}} \dot{V}_{pv} \quad (30)$$

Physically interpretation demonstrates that the MPPT surface derivative depends on diode characteristics (I_0, a) and it is sensitive to PV voltage rate of change $\left(\frac{dV_{pv}}{dt} \right)$.

The voltage surface derivative is given as :

$$\dot{S}_V = -\lambda (\dot{V}_{ref} - \dot{V}_{out}) + \ddot{V}_{ref} - \ddot{V}_{out} \quad (31)$$

then we can write the time derivative expansion :

$$\dot{V} = S_{ASMC} \left[\gamma \left(-\frac{R_s I_0}{aV_{th}} e^{\frac{V_{pv} + I_{pv} R_s}{aV_{th}}} \dot{V}_{pv} \right) + (1 - \gamma) (\lambda (\dot{V}_{ref} - \dot{V}_{out}) + \ddot{V}_{ref} - \ddot{V}_{out}) \right] \quad (32)$$

If $\dot{V}(S) < 0$ for $S \neq 0$, this proves that the sliding surface converges to zero.

Consequently, the system is stable and the system's state converges to the desired equilibrium.

To achieve these results, we need to verify the terms of $\dot{V}(S)$. Rewriting this inequality :

The stability conditions are:

Minimal gain requirement:

$$\lambda > \frac{\gamma \frac{R_s I_0}{aV_{th}} e^{\frac{V_{pv} + I_{pv} R_s}{aV_{th}}} \|\dot{V}_{pv}\| + (1 - \gamma) (\|\dot{V}_{ref}\| - \|\dot{V}_{out}\|)}{\|\dot{V}_{ref} - \dot{V}_{out}\|} \quad (33)$$

When considering both converters, we can set ($\gamma \rightarrow 0$) and the stability condition simplifies to :

$$\lambda > \frac{\|\dot{V}_{ref}\| + \|\dot{V}_{out}\|}{\|\dot{V}_{ref} - \dot{V}_{out}\|} \quad (34)$$

Similarly, for the MPPT converter case, we obtain:

$$\frac{R_s I_0}{a V_{th}} e^{\frac{V_{pv} + I_{pv} R_s}{a V_{th}}} < \frac{\lambda \|\dot{V}_{ref} - \dot{V}_{out}\|}{\|\dot{V}_{pv}\|} \quad (35)$$

PV voltage rate limit:

$$|\dot{V}_{pv}| < \frac{a V_{th}}{R_s I_0} e^{\frac{V_{pv} + I_{pv} R_s}{a V_{th}}} \frac{(1 - \gamma) \lambda |\dot{V}_{out}|}{\gamma} \quad (36)$$

VI. Simulation

The simulations conducted in this part of the article are executed in Matlab. We use a photovoltaic module that delivers its power in parallel to the DC/DC boost and buck converter. This module contains 36 cells connected in series. The electrical parameters and characteristics of the photovoltaic system are presented in Table 1 provided below.

Table 1. The values of the photovoltaic system parameters

Designation	value
Nominal short-circuit current ($I_{sc,n}$)	8,21 A
Short-circuit current temperature coefficient ($\mu_{I_{sc}}$)	0,0032 A/°C
Nominal open-circuit voltage ($V_{oc,n}$)	32,9 V
Open-circuit voltage temperature coefficient ($\mu_{V_{oc,n}}$)	-0,1230 V/°C
Nominal current (I_n)	7,61 A
Nominal voltage (V_n)	26,3 V
Number of cells in series (N_s)	54
Diode ideality factor (a)	1,5

The parameters and electrical values of the boost and buck converters are provided in Table 2 below.

Table 2. The values of the boost and buck converters parameters

Designation	Value (boost)	Value (buck)
Inductance of the inductor (L)	2,2 mH	2,2 mH
Capacitance of the capacitor (C)	47 μF	47 μF
Load resistance (R)	100 Ω	100 Ω

Based on these parameters, simulations have been generated illustrating figures that show the ability of the Adaptive Sliding Mode Control (ASMC) to produce better power than the conventional use of converters. Figure 4 presents the solar irradiation profile used as input to the system, reflecting the variations in solar irradiation over time.

The irradiation follows a distribution characterized by successive values of 400 W/m², 1000 W/m², and 700 W/m². This variation in sunlight allows for the simulation of realistic conditions and the evaluation of the

adaptive sliding mode control proposed by ASMC to quickly adapt to changes in irradiation in order to maintain the MPPT of the photovoltaic system.

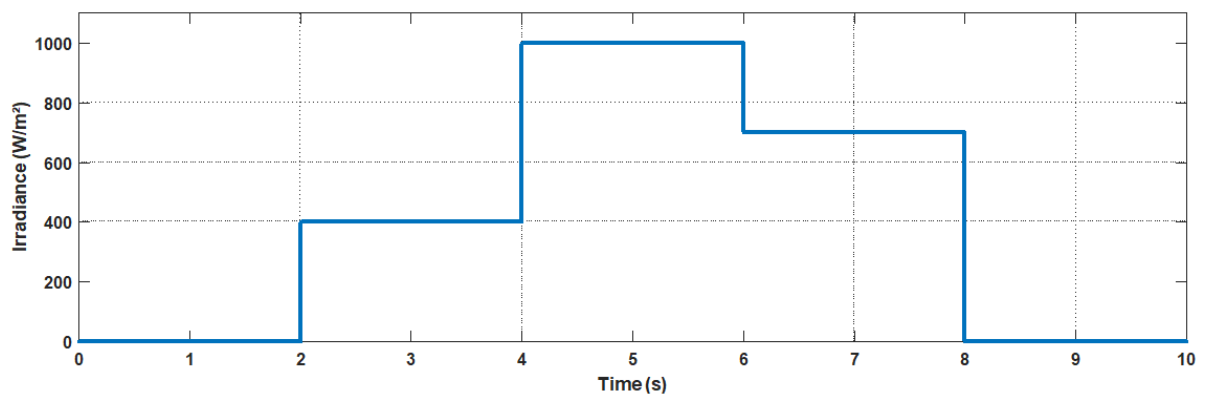


Figure 4. Sunlight profile defined by the received irradiation.

Figures 5, 6, and 7 display the currents, voltages, and powers generated by the photovoltaic system through the various proposed converters, respectively. The results clearly demonstrate that the system is perfectly adapted and accurately follows the solar irradiation profile, as evidenced by the strong correlation between the output characteristics and variations in light intensity.

This optimal matching ensures maximum energy harvesting under variable environmental conditions, thereby validating the robustness and efficiency of the proposed converter topologies in maintaining maximum power point operation.

The consistent performance observed across all measured parameters confirms the system's ability to respond dynamically to irradiance changes while maintaining stable and efficient power conversion.

The current curve closely follows the variations in solar irradiation, exhibiting rapid and stable transitions.

In terms of performance, the absence of raw oscillations indicates excellent regulation by the adaptive ASMC, even during sudden changes in sunlight exposure. The current remains near its optimal value, confirming the system's capability and efficiency in maximizing energy capture.

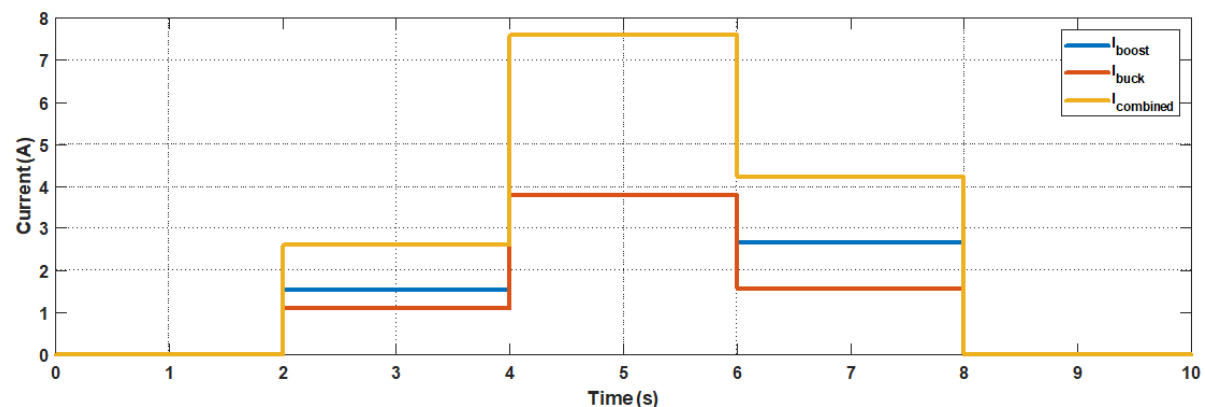


Figure 5. Current response by proposed adaptive ASMC.

The voltage demonstrates remarkable stability despite irradiation fluctuations, with dynamic adjustments. The ASMC method maintains the voltage within a narrow range, preventing overvoltages or sudden drops, thereby demonstrating the robustness of the implemented control.

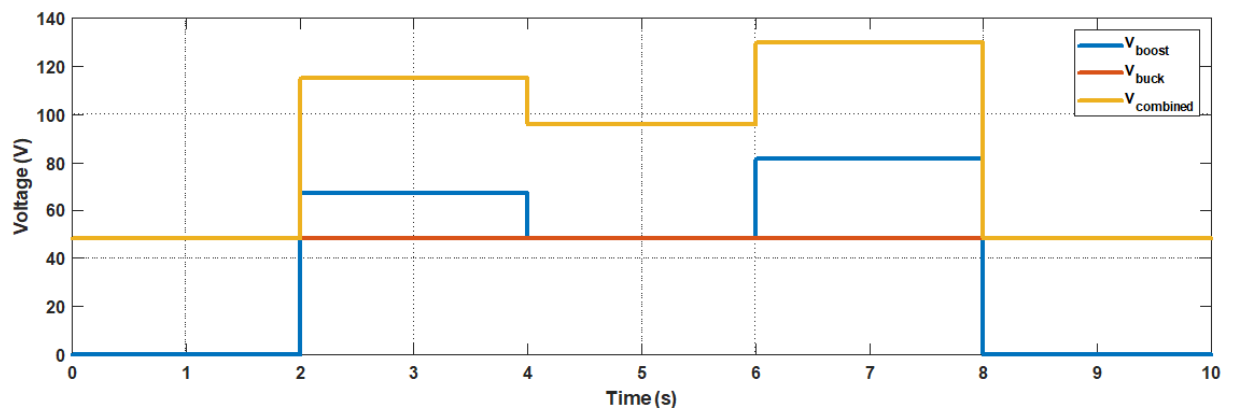


Figure .6 Voltage response by proposed ASMC.

The generated power precisely mirrors the irradiation profile, with minimal stabilization time following each variation. Optimization: The system's ability to maintain operation near the MPP (Maximum Power Point) is clearly demonstrated, even under variable conditions.

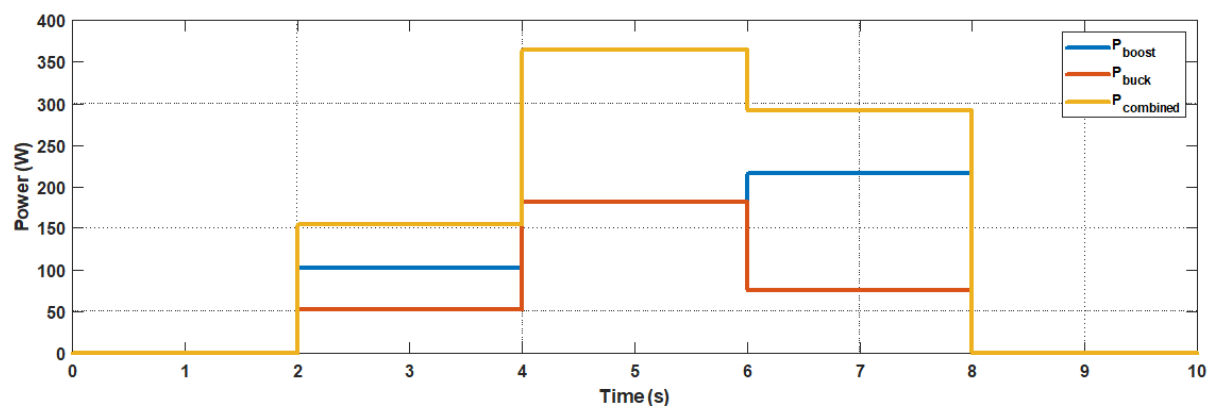


Figure 7. Power response by proposed ASMC.

Figure 8 illustrates the variation of the duty cycle D of the boost, buck, and combined converters under changes in irradiance.

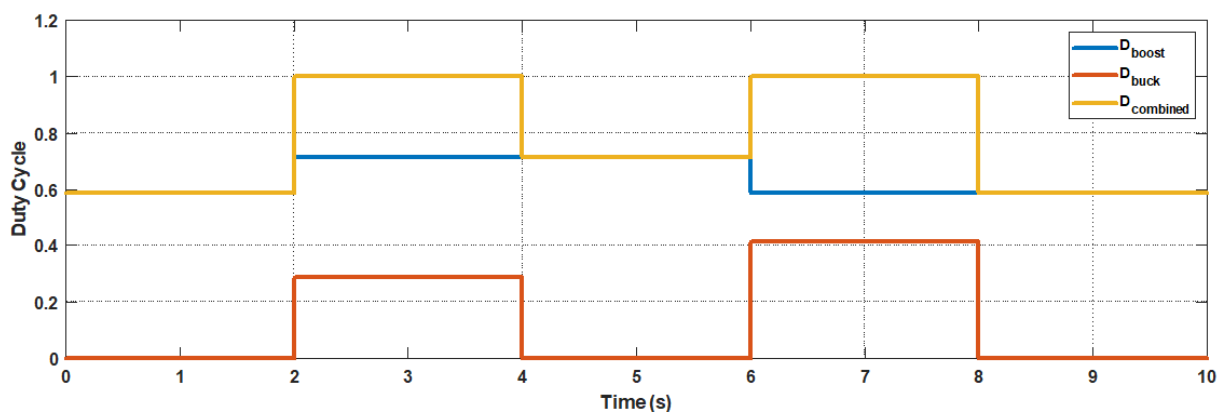


Figure 8. Duty cycle by proposed ASMC.

VII. Results and Discussion

The responses exhibited a typical behavior of sliding mode control that optimizes power while dynamically adjusting the duty cycle of the boost and buck converters. Indeed, the adaptive sliding mode control aims to effectively maximize the output power of the photovoltaic system using a combined duty cycle. This capability is essential for making the most of the available solar energy.

The combination of the two converters allows for better regulation of the output voltage, even with variations in irradiance. This combination enables the provision of different output voltages suited to various loads. The boost converter can increase the voltage when it is too low, while the buck converter can reduce it if necessary.

ASMC offers a major advantage when applied to combined boost and buck converters for MPPT in photovoltaic systems. By integrating these two types of converters, ASMC optimizes power management by dynamically adjusting the duty cycle based on variations in irradiance. The boost converter increases the voltage when it is insufficient, while the buck converter reduces the voltage if necessary, ensuring precise regulation of the energy supplied to the system.

This flexibility and adaptability of ASMC allow for maximizing the extraction of available solar energy while maintaining operational stability and a quick response to changes in environmental conditions. Consequently, the use of ASMC with combined boost and buck converters significantly enhances the overall energy efficiency of the photovoltaic system.

VIII. Conclusion

In this article, we presented a synthesis of adaptive sliding mode control aimed at maximizing the output power of a photovoltaic system through a combined boost-buck converter. The main results of the simulations demonstrate the effectiveness of the proposed control method compared to conventional techniques, particularly under rapidly changing environmental conditions, thereby proving its performance. The simulations confirm that the proposed control method maintains system stability and responds quickly to changes in irradiation, effectively tracking the maximum output power while minimizing oscillations. Overall, the results indicate that the ASMC method not only improves the efficiency of photovoltaic systems but also provides a reliable solution for maximizing energy production in the face of environmental uncertainties. However, it is important to note certain drawbacks associated with the method. Notably, the complexity of implementing APISMC requires intricate modeling. To address this, several perspectives can be considered to improve the reliability and practical application of this control method. In this regard, it would be interesting to integrate the proposed control with artificial intelligence techniques, namely the use of neural networks.

Acknowledgements

The authors acknowledge the support of Prince Sultan University, Riyadh, Saudi Arabia, for this publication. This research is supported by the Automated Systems and Computing Lab (ASCL), Prince Sultan University, Riyadh, Saudi Arabia.

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