Backstepping Sliding Mode Controller for MPPT in DC Microgrid Connected Quadratic Boost Converters fed from PV Systems

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***Abstract*— Photovoltaic (PV) systems are crucial for harnessing solar energy; however, environmental factors and the variability of the connected load significantly influence their energy generation capacity. In this context, the effectiveness of the controller used for maximum power point tracking (MPPT) to enhance efficiency relies on a thorough analysis of the nonlinear models of PV systems. Over these last decades, many control techniques have been developed to enhance the energy extraction from PV cells and improve system efficiency. Since real-world systems have real-time variations, it is difficult to continuously update both the system and the controller. The changes can produce steady state errors in the output and reduce the efficiency of the controller. As a solution to this issue, in this work a nonlinear backstepping sliding mode controller (BSMC) is proposed to improve the performance of the MPPT system. The BSMC MPPT, coupled to a DC-DC quadratic boost converter (QBC), is used as the interface between a PV array and a microgrid. Backstepping control ensures global asymptotic stability of the system by achieving the optimal power point, following Lyapunov stability criteria. Simulation and experimental results of the proposed MPPT solution are presented confirming that the system operates as expected.**

Keywords*— *PV systems, MPPT, DC-DC quadratic boost converter, backstepping control.

I. Introduction

The increasing demand for renewable energy resources worldwide has positioned photovoltaic (PV) systems at the forefront as a top technology to sustainably generate energy. PV systems harness sunlight and convert it to electricity cleanly and infinitely compared to conventional fossil fuels. The efficiency of such systems is largely affected by environmental factors, such as solar irradiation, temperature, and load variations [1]. These conditions impose difficulties in achieving maximum energy output and require sophisticated control techniques to maximize power extraction [2,3]. Maximum Power Point Tracking (MPPT) is one of the most efficient techniques used to enhance the efficiency of PV systems by dynamically varying the PV array's operating point to maximize available power extraction [4]. Several MPPT control techniques have been proposed over recent decades based on advances in nonlinear system modeling, power converter topologies, and algorithmic optimizations [5, 6]. Mathematical modeling of PV cells, application of high-efficiency converter topologies, and real-time MPPT algorithms were some of those techniques used. Thus, in literature the MPPT algorithms are distinguished between traditional control methods and intelligent control methods [7]. Traditional MPPT methods are namely Perturb and Observe (P&O) [8], Incremental Conductance (INC) [9] and optimizations like [10], while the intelligent MPPT algorithms encompass fuzzy logic [11, 12], artificial neural networks [13], particle swarm optimization [14], among many others. Based on simulation and experimental results, presented in several research works, intelligent control algorithms have demonstrated greater effectiveness; however, they are often characterized by high complexity and slow convergence speeds, which limits their application in real-world projects.

MPPT control algorithms have also been designed by researchers for grid-tied as well as off-grid PV systems for maximum energy extraction from sunlight [15]. These algorithms are most implemented with DC-DC converters or at times with energy storage facilities such as batteries. The energy from PV arrays can be fed to the grid through a DC-DC converter as an MPPT controller. Although boost converters are the most used, many modified versions have been proposed to increase voltage gain [16, 17]. Some other converter topologies are specifically designed to enhance voltage gain, enabling the system to efficiently reach higher output voltage levels [18, 19].

This paper presents a new MPPT strategy for a PV system connected to a microgrid based on a nonlinear backstepping sliding mode controller (BSMC). Backstepping controllers are useful since they directly address the nonlinear dynamics of converters [20, 21]. Additionally, when combined with Lyapunov stability theory, they enable the design of controllers that are both fast and stable [22]. In this work a non-inverted quadratic boost converter (QBC) is used. This converter is chosen for its high boost factor and efficiency, while the nonlinear controller is selected due to the inherent nonlinear characteristics of the non-inverted boost converter [23, 24]. Asymptotic stability is ensured through Lyapunov stability analysis, and the MPP is successfully achieved under varying temperature and irradiance conditions. Simulation and experimental results, under several perturbations, show the effectiveness of the BSMC in tracking the MPPT,

2025 13th International Conference on Smart Grid (icSmartGrid) | 979-8-3315-2557-6/25/$31.00 ©2025 IEEE | DOI: 10.1109/icSmartGrid66138.2025.11132088

confirming the stability of the system connected to the microgrids.

II. New MPPT Algorithm for PV Systems

The proposed MPPT controller for the PV system, shown in Fig. 1, consists of a solar PV panel, a DC-DC quadratic boost converter with a high voltage step-up/down ratio, and a microgrid supplied by the PV system. The MPPT controller is designed using the backstepping control approach, which is well suited for systems with nonlinear dynamics [21].

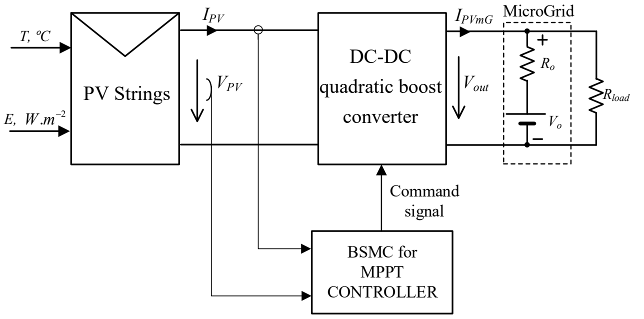


Fig. 1. Bock diagram of the proposed MPPT.

A. PV model System

Solar cells constitute the basic blocks used to build PV arrays employed in photovoltaic systems. When transferring the energy received by incident solar photons to electrical power, a solar cell can be modeled by a two-terminal circuit including diode like characteristics, usually termed the single-diode model. In Fig 2 an equivalent circuit model is presented, where the solar cell appears as a photocurrent source in parallel with a diode and with the shunt resistor to simulate leakage current, with both in series with an internal resistor modeling internal current resistance [24].

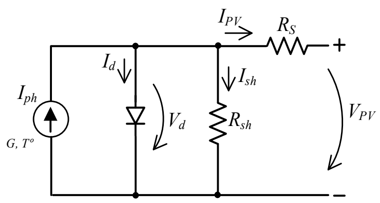


Fig. 2. Equivalent model of a PV Cell.

Based on the Fig. 2 circuit analysis, the I_{PV} current can be derived as follows:

$$I_{PV} = I_{ph} - I_0 \left[exp\left(\frac{q(V_d + R_s I_{PV})}{nKT} \right) - 1 \right] \left[\frac{V_{PV} + I_{PV} R_s}{R_{sh}} \right] \quad (1)$$

where:

I_{ph} current generated by the PV array, A.

I_0 is the reverse saturation current, A.

q is the electron charge = 1.6×10^{-19} C.

R_s is the series resistance of the solar panel, Ω.

R_{sh} is the parallel resistance of the solar panel, Ω.

n is the ideal diode factor

K is Boltzmann's constant $=1.38\times10^{-23}$ J/ºK.

T is the panel temperature, ºK.

V_{PV} is the photovoltaic cell voltage, V

Since a single solar cell generates only a small amount of power (around one watt) multiple cells are connected in series or parallel to produce sufficient electrical power for practical PV panel applications [25]. As shown from Eq. (1), the I-V curve of the PV cell is nonlinear and depends on numerous factors including solar irradiance, temperature in the atmosphere, wind speed, humidity, and pressure in the atmosphere. Normally, only solar irradiance and ambient temperature are considered the main influencing factors.

B. Quadratic Boost Converter Modeling

Most PV panels generate relatively low voltage, which is usually below the voltage levels needed for direct-to-the-load connection or to supply systems that require higher voltages. Boost DC-DC converters are designed to increase voltage levels, and among these, QBC emerges as an efficient option with high-voltage gain and a relatively simple design. This topology is derived from the conventional boost converter and provides both a continuous input current and a quadratic voltage gain, making it well-suited for PV applications. Fig. 3. shows the proposed QBC topology, which is used to validate the effectiveness of the BSMC strategy in section III. In this scheme the QBC is connected to a capacitor C_1 at the output of the PV system to minimize voltage fluctuations around the MPP.

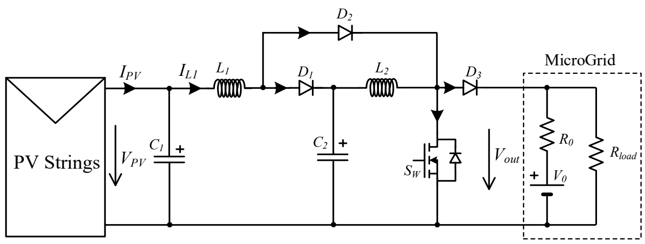


Fig. 3. Scheme of the QBC for PV strings supplying a DC Microgrid.

Assuming ideal semiconductors, resistors, inductors and capacitors, the static voltage gain of the QBC can be expressed as a function of the duty cycle (δ), according to (2) [15].

$$\frac{V_{out}}{V_{PV}} = \frac{1}{(1-\delta)^2} \quad (2)$$

The dynamic equations of the QBC can be expressed by:

$$\begin{aligned} \frac{dV_{C1}}{dt} &= \frac{I_{PV} - I_{L1}}{C_1} \\ \frac{dI_{L1}}{dt} &= \frac{V_{C1} - (1-\lambda)V_{C2}}{L_1} \\ \frac{dV_{C2}}{dt} &= \frac{(1-\lambda)I_{L1} - I_{L2}}{C_2} \\ \frac{dI_{L2}}{dt} &= \frac{V_{C2} - (1-\lambda)(V_o + R_o I_{Vo})}{L_2} \end{aligned} \quad (3)$$

where λ represents the control variable of the power semiconductor, defined as a binary variable, that has a value 1 when S_W is ON and 0 when S_W is OFF.

III. Backstepping Sliding Mode MPPT Controller

A critical factor in the performance of PV systems is the design of the converter control strategy, which is responsible for ensuring efficient energy transfer from the PV panels to the connected loads or microgrids. To ensure fast regulation and stability of the output voltage supplied by a PV system supplying the QBC a backstepping sliding mode control is designed. This control system must be capable of regulating the ON/OFF state of the power switch to maintain the PV array voltage at its MPP. The switching operation directly controls the input inductor current, I_{L1}, and thus allows the system to regulate to a desired reference current. It also affects the capacitor C_1 voltage, thus affecting PV system dynamics. Consequently, there is effective operation of the MPPT algorithm. The controller sets the operating point of the PV system by controlling the power switch S_W state λ to optimize power extraction.

A. Backstepping calculation of the MPP voltage

The controller must maximize the power extraction from the solar panels through MPPT. Thus, the objective is to compute the MPP voltage V_{PVMPP}, which zeros the power derivative regarding V_{PV}:

$$\left.\frac{dP_{PV}}{dV_{PV}}\right|_{V_{PV}=V_{PVMPP}} = 0 \tag{4}$$

Since $P_{PV} = V_{PV} I_{PV}$, for the MPP voltage V_{PVMPP}:

$$\left.\frac{dP_{PV}}{dV_{PV}}\right|_{V_{PV}=V_{PVMPP}} = V_{PVMPP}\frac{dI_{PV}}{dV_{PV}} + I_{PV} = 0 \tag{5}$$

Therefore:

$$V_{PVMPP} = -I_{PV}\frac{dV_{PV}}{dI_{PV}} \tag{6}$$

To compute V_{PVMPP} a virtual control action is defined as V_{PVref}. The MPPT controller will make $V_{PVref} = V_{PVMPP}$ using the power P_{PV} derivative. Therefore, define the virtual control action error as:

$$e_{V_{PV}} = V_{PVMPP} - V_{PVref} \tag{7}$$

Then, apply the second method of Lyapunov to ensure system stability using the positive definite candidate Lyapunov function L_{L1} to ensure stability:

$$L_{L1} = \frac{e_{V_{PV}}^2}{2} \Rightarrow \frac{dL_{L1}}{dt} < 0 \Rightarrow \frac{de_{V_{PV}}}{dt} = -K_V e_{V_{PV}} \tag{8}$$

where $K_V > 0$ is the inverse of the desired time constant of the first order dynamics (8).

By substituting (6) and (7) into the dynamics in (8) and assuming $dV_{PVMPP}/dt = 0$ (under constant environmental conditions, V_{PVMPP} remains constant), expression (9) is obtained.

$$-\frac{dV_{PVref}}{dt} = -K_V\left(V_{PVMPP} - V_{PVref}\right) \tag{9}$$

Solving (9) yields (10):

$$\frac{dV_{PVref}}{dt} = -K_V\left(I_{PV}\frac{dV_{PV}}{dI_{PV}} + V_{PVref}\right) \tag{10}$$

As $I_{PV}\frac{dV_{PV}}{dI_{PV}} + V_{PVref} = \left.\frac{dP_{PV}}{dI_{PV}}\right|_{V_{PV}=V_{PVref}}$, expression (10) is written as:

$$\frac{dV_{PVref}}{dt} = -K_V\frac{dP_{PV}}{dI_{PV}} \tag{11}$$

The V_{PVref} voltage can be obtained by the time integration of (11):

$$V_{PVref} = -k_V\int_o^t \frac{dP_{PV}}{dI_{PV}}\,dt + V_{PVref}(0) \tag{12}$$

This equation shows that if $dP_{PV}/dI_{PV} > 0$, the reference voltage value V_{PVref} should be decreased. Conversely, if $dP_{PV}/dI_{PV} < 0$, then the V_{PVref} value should be increased. This behavior confirms the graphical representation in Fig. 4, which shows that the panel voltage should decrease from point V_1 to point V_2, when $dP_{PV}/dI_{PV} > 0$. The V_{PVref} convergence rate to the MPP voltage V_{PVMPP} depends on k_V and $\frac{dP_{PV}}{dI_{PV}}$ while core P&O and INC methods usually try to converge at constant rates, often exhibiting chattering around the V_{PVMPP} value.

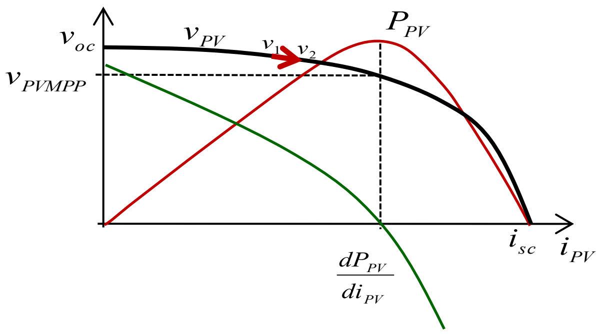


Fig. 4. PV panel voltage and output power.

B. Backstepping tracking of the photovoltaic voltage V_{PV}

Once the MPP V_{PVref} voltage reference has been defined, it becomes essential to design an additional control loop to ensure that the photovoltaic voltage V_{PV} accurately tracks its reference value V_{PVref}. Thus, based on the analysis of the circuit shown in Fig. 3, and considering that $V_{PV} = V_{C1}$, the following equations are obtained.

$$\frac{dV_{C1}}{dt} = \frac{I_{PV} - I_{L1}}{C_1} \tag{13}$$

this implies that V_{PV} can be controlled by controlling the inductor current I_{L1}. Define the tracking error:

$$e_{V_{C1}} = V_{PVref} - V_{C1} = 0 \quad (14)$$

To guarantee the stability of this tracking controller, the second method of Lyapunov is employed using the positive definite Lyapunov function L_{L2}, and the stability condition.

$$L_{L2} = \frac{e_{V_{C1}}^2}{2} \Rightarrow \frac{dL_{L2}}{dt} < 0 \Rightarrow \frac{de_{V_{C1}}}{dt} = -K_{VC1}e_{V_{C1}} \quad (15)$$

where $K_{VC1} > 0$, is the inverse of the time constant.

Equation (15) can be rewritten by substituting equations (14) and subsequently (13), resulting in:

$$\frac{dV_{PVref}}{dt} - \frac{I_{PV} - I_{L1}}{C_1} = -K_{VC1}e_{V_{C1}} \quad (16)$$

Solving Eq. (16) for the I_{L1} inductor current, its virtual reference value I_{L1v}, $I_{L1v} = I_{L1ref}$, is obtained as:

$$I_{L1v} = I_{L1ref} = I_{PV} - C_1\left(K_{VC1}e_{V_{C1}} + \frac{dV_{PVref}}{dt}\right) \quad (17)$$

This implies that the actual inductor current must closely track the reference value I_{L1ref}.

C. Sliding mode tracking of the inductor current

To control the inductor current, I_{L1}, a nonlinear current control strategy for the QBC, is proposed to avoid using a further backstep. As the control action is discrete (switch with two modes, ON λ=1, OFF λ=0), sliding mode is used. Based on the state-space model of the DC-DC converter presented in Eq. (3), it can be verified that the inductor current has a strong relative degree of one [26], since its first derivative explicitly includes the control variable λ. Defining the feedback error as $e_{IL_1} = I_{L1ref} - I_{L1}$, for a strong relative degree of one, the sliding mode surface $S(e_{IL_1}, t)$, designed to ensure robustness of the closed-loop system, is:

$$S(e_{IL_1}, t) = K_{IL1}(I_{L1ref} - I_{L1}) \quad (18)$$

Where $K_{IL1} > 0$, is selected to ensure a given switching frequency, given the switching current tracking error within a certain range $\Delta I_{L1}/2$, as shown in Eq. (19):

$$-\Delta I_{L1}/2 < e_{IL_1} < \Delta I_{L1}/2 \quad (19)$$

where ΔI_{L1} represents the maximum allowable error variation required to ensure that inductor current tracks the reference value in (17) needed to track the photovoltaic voltage V_{PVref}.

The following stability condition, in Eq. (20), ensures the system's convergence to the reference value:

$$e_{IL_1}\frac{d}{dt}(e_{IL_1}) < 0 \quad (20)$$

To satisfy the condition indicated in Eq. (4), a hysteresis comparator can be employed to control the variable λ. Based on Eq. (3) and (17), (18) the switch state is to be driven as:

$$\begin{aligned}&\text{if } e_{IL_1} > \Delta I_{L1}/2\\ &\Rightarrow \dot{S}(e_{IL_1}, t) < 0 \Rightarrow I_{L1} \text{ needs to increase}\\ &\qquad \Rightarrow dI_{L1}/dt > 0 \Rightarrow \lambda = 0\\ &\text{if } e_{IL_1} < -\Delta I_{L1}/2\\ &\Rightarrow \dot{S}(e_{IL_1}, t) > 0 \Rightarrow I_{L1} \text{ needs to decrease}\\ &\qquad \Rightarrow dI_{L1}/dt < 0 \Rightarrow \lambda = 1\end{aligned} \quad (21)$$

The convergence of the system toward the reference value is ensured by the used stability condition, ensuring $S(e_{IL_1}, t)\dot{S}(e_{IL_1}, t) < 0$.

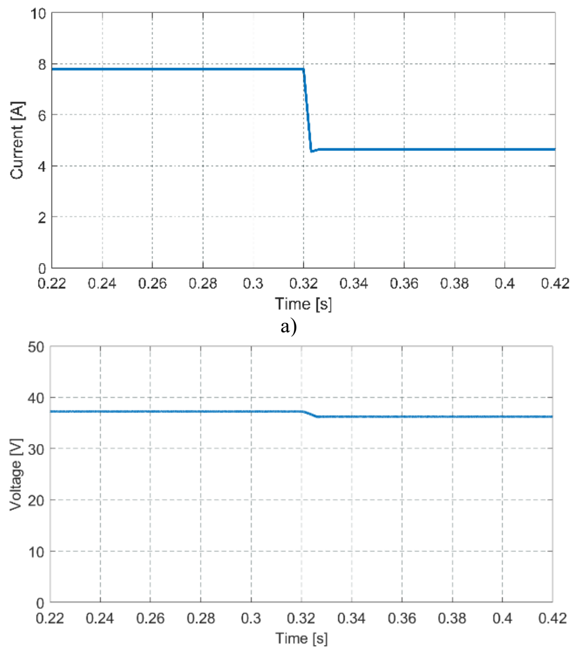
IV. SIMULATION RESULTS

To evaluate the performance of the proposed BSMC for MPPT, a solar PV panel integrated with a QBC and a microgrid powered by the PV system was implemented. The system, shown in Fig. 1, was developed using the MATLAB/Simulink program. The MPPT algorithm was tested through several simulation experiments to evaluate its performance using the following parameters: $L_1 = L_2 = 5$ mH, $C_1 = C_2 = 150$ μF and two resistors with a value of 12 Ω and 100 Ω was also considered, respectively, for DC source and DC line impedance (Ro) and for the load (R_{load}). In table I, the characteristics of PV panels are presented.

TABLE I. CHARACTERISTICS OF PV PANEL.

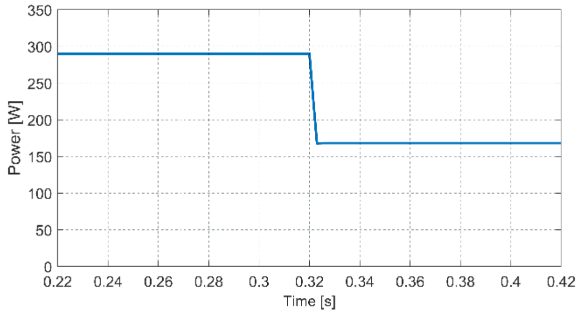
Voc (PV open circuit voltage)	44.50 V
Isc (PV short circuit current)	8.38 A
VMPP (PV MPP voltage)	34.60 V
IMPP (PV MPP current)	6.50 A
PMPP (PV MPP power)	290.0 W

The simulation tests were initially conducted under steady-state conditions, with solar irradiance fixed at its maximum value of 1000 W/m² and a constant temperature of 25 °C. In the first simulation test, the temperature remained constant while the irradiance suddenly decreases from 1000 to 600 W/m², at t= 0.32 s. Fig. 5 presents the transient response of the PV system in terms of the current, voltage, and power of the PV panel, for the proposed MPPT controller.



a)

b)

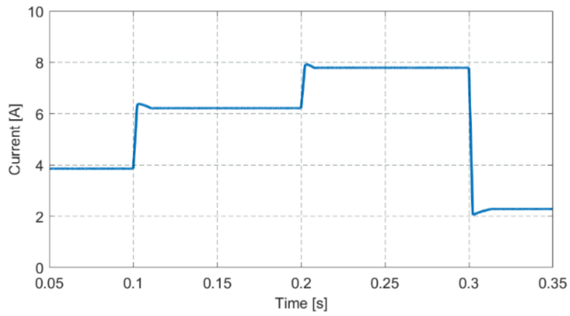


c)

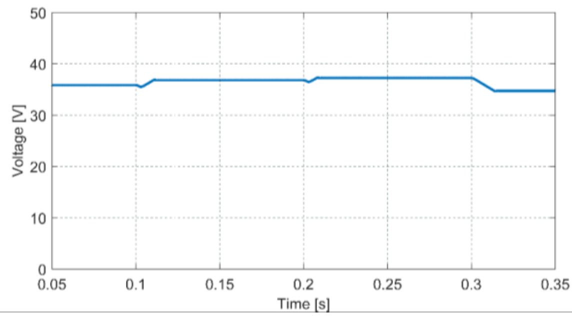
Fig. 5. Simulation results of the PV Panel a) Current b) Voltage; c) Power.

Fig. 5a and Fig. 5b show the voltage and current of the PV panels, respectively. As expected, when a decrease irradiance occurs, a corresponding decrease in the current is observed, while only a slight decrease in voltage is noticeable. Fig.5c) shows the results of power generated by the PV panels, demonstrating capacity of the MPPT controlling to track the specified load power requirement.

A further simulation test was performed to evaluate the proposed MPPT controller, under sequential irradiance variations. The irradiance was initially set to 500 W/m², at 0.1s, it was increased to 800 W/m², at 0.2 s, it was raised to its maximum of 1000 W/m² and at 0.3 s, it abruptly decreased to a final value of 300 W/m². Fig. 6 shows the simulation results for irradiance step changes, indicating that the MPPT controller responds in the same way to each irradiance stimulus. The simulation results for irradiance step changes, presented in Fig.6, demonstrate that the MPPT controller responds the same way to each irradiance stimulus. Figs 6a and 6b present the PV panel voltage and current, respectively, for several step increases in irradiance. As the irradiance increases, the current rises significantly, while the voltage increases only slightly. Figure 6c shows the PV power output, demonstrating the MPPT controller's ability to track the required load power.



a)



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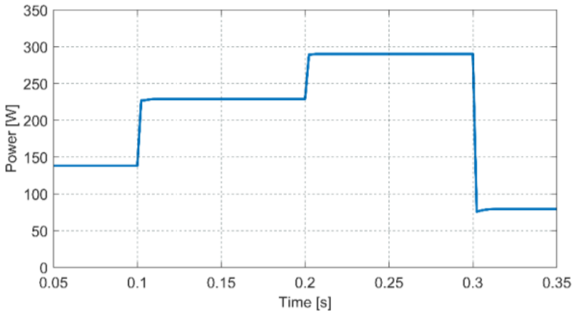

c)

Fig. 6. Simulation results of the proposed MPPT controller, under several irradiance step changes. a) PV current b) PV voltage; c) PV power.

V. Experimental Results

To validate the theoretical analysis and the performance observed in the simulation results of the proposed MPPT method, a laboratory prototype was constructed using the same specifications as those employed in the simulations. A PV simulator was employed to emulate the PV panels, consisting of a remotely controllable EA Elektro-Automatik EA-PS 8160-60 DC power supply. This supply was operated by DSP, DS1104 R&D controller board, operating with a sampling time of 1 µs, where the PV panel characteristics were programmed using values shown in Table 1. Experimental tests were conducted under transient operating conditions for different irradiance levels.

Initially, the irradiance is in a steady state at 1000 W/m². Suddenly, at t=0.3 s, the irradiance decreases to 600 W/m². Fig. 7 it is possible observe the experimental results for the current, the voltage and power of PV panels during the irradiance transient. As observed in the simulation results, a decrease in irradiance is reflected in the current, the voltage, and power of the PV panel, with the decrease in voltage being less significant.

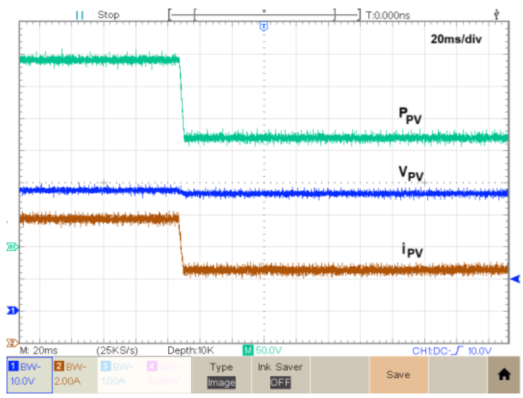

Fig. 7. Experimental results of the proposed MPPT controller during a decrease in irradiance: PV power, PV voltage, and PV current.

In the following experiment, the irradiance was initially set to 500 W/m². At 0.1s, it was increased to 800 W/m², at 0.2s, it was further raised to 1000 W/m² and at 0.3s, it abruptly dropped to a final value of 300 W/m². The correspondent experimental results, presented in Fig 8, show that the several transients in irradiance observed on the PV panel are reflected in corresponding changes in the panel's current, voltage, and power. These results show that the proposed MPPT controller performs well, responding quickly to changes in irradiance.

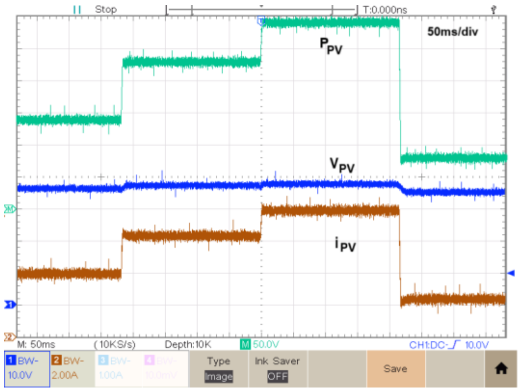

Fig. 8. Experimental results of the proposed MPPT controller, under several irradiance step changes: PV power, PV voltage and PV current.

VI. Conclusions

This paper proposes a nonlinear backstepping sliding mode controller (BSMC) to enhance the performance of the MPPT algorithm in tracking the maximum power point of a grid-connected PV array module, under fast variations in solar irradiation. The proposed MPPT method is designed to ensure fast and efficient performance in PV systems operating under quickly changing environmental conditions. The proposed MPPT solution was tested in simulation software to analyze its performance at multiple operating situations. In addition, to confirm the theoretical work and support in verifying the results from simulation, an experimental setup was built. The comparison between simulation and experimental results proves the success of the BSMC algorithm in maximum power point tracking. The results confirm that the microgrid-connected PV system remains stable and accurate even in rapidly varying and adverse irradiance situations.

Acknowledgment

This work was supported by national funds through FCT, Fundação para a Ciência e a Tecnologia, under project UIDB/50021/2020 (DOI:10.54499/UIDB/50021/2020).

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