Comparison of the performance of MPPT methods applied in converters Buck and Buck-Boost for autonomous photovoltaic systems

Comparación del desempeño de métodos MPPT aplicados en conversores Buck y Buck-Boost para sistemas fotovoltaicos autónomos

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ABSTRACT

In photovoltaic (PV) generation systems, the energy produced is limited by the low efficiency of the solar panels, the variability of weather conditions, and the characteristics of the load connected, so the use of maximum power point tracking (MPPT) methods is essential to maximize the power supplied. Implementing an MPPT requires a power converter as the interface between the PV array and the load, so the converter's behavior is also an important factor to be considered in the overall performance of a PV system. Several MPPT techniques have been proposed over the years, but little literature is still available when required to be compared to the combined performance of different MPPT/converter sets. In this context, the present work presents a comparative study of the performance of three MPPT techniques: constant voltage (CV), perturb and observe (P&O), and incremental conductance (IncCond), acting on two different topologies of DC-DC power converters: Buck and Buck-Boost. Each combination is analyzed considering its transient response and steady-state average efficiency. The study was carried out based on simulations in Matlab/Simulink environment. To obtain more realistic conditions, a model for the commercial PV module Kyocera KC85TS was developed. Results obtained from the PV system operating under various radiation and temperature conditions are compared and discussed, which show that the CV/Buck-Boost combination showed the best transient behavior and that the IncCond/Buck combination had the highest steady-state efficiency.

Keywords: Buck, Buck-Boost, constant voltage, perturb and observe, incremental conductance, PV stand-alone system.

RESUMEN

En sistemas de generación fotovoltaica (PV), la energía producida es limitada por la baja eficiencia de los paneles solares, la variabilidad de las condiciones climáticas y las características de la carga conectada, así el uso de métodos de ajuste del punto de máxima potencia (MPPT) es esencial para maximizar la potencia suministrada. La implementación de un MPPT requiere de un conversor de potencia como interface entre el arreglo PV y la carga, así el comportamiento del conversor también es un factor importante a ser considerado en el rendimiento global de un sistema PV. A lo largo de los años diversas técnicas MPPT han sido propuestas, pero poca literatura hay todavía disponible cuando se

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requiere comparar el desempeño combinado de diferentes conjuntos MPPT/conversor. En este contexto el presente trabajo presenta un estudio comparativo del desempeño de tres técnicas MPPT: voltaje constante (CV), perturba y observa (P&O), y conductancia incremental (IncCond), actuando en dos diferentes topologías de conversores de potencia CD-CD: Buck y Buck-Boost. Cada combinación es analizada considerando su respuesta transiente y eficiencia media en estado estable. El estudio fue desarrollado en base a simulaciones en ambiente Matlab/Simulink. En orden a obtener condiciones más realistas, un modelo para el módulo PV comercial Kyocera KC85TS fue desarrollado. Resultados obtenidos del sistema PV operando bajo diversas condiciones de radiación y temperatura, son comparados y discutidos, los cuales muestran que la combinación CV/Buck-Boost presentó el mejor comportamiento transiente, y que la combinación IncCond/Buck, la mayor eficiencia en estado estacionario.

Palabras clave: Buck, Buck-Boost, voltaje constante, perturba y observa, conductancia incremental, Sistema Fotovoltaico Aislado.

INTRODUCTION

The continuing increase in energy demand in the world has lead society to seek alternative energies to fossil fuels due to the depletion of those conventional energy resources and their undesirable impacts on the environment [1]. Among the available renewable energies, PV solar energy is considered one of the most promising, reliable, and favorable with several advantages such as contamination-free, long life, and low maintenance [2]. Currently, PV solar energy has become one of the most important renewable sources for the generation of electric power. By the end of the year 2017, it is estimated that the capacity of PV solar power installed in the world has reached approximately 402 GW [3]. Nevertheless, PV solar energy has the problem of low efficiency, which is generally lower than 18% for commercial modules [4, 5]. Additionally, the generated power depends on the conditions of irradiation and temperature to which the modules are exposed, along with the characteristics of the load.

The power versus voltage curve (P-I) of a PV module presents nonlinear characteristics. The maximum power of a PV panel is attained at the point of inflection of the P-I curve, known as the maximum power point (MPP). When the load is connected directly to the panel, it is forced to operate at the current level which matches the load's impedance value, which does not correspond necessarily to the MPP. To guarantee the MPP operation despite the environmental and load variations, MPPT techniques associated eventually with energy storage devices are generally used, which improve generation efficiency between 30 and 40% [6].

Over the years, a wide variety of MPPT techniques have been developed [1, 7-9]; all of these methods vary in many respects, such as implementation complexity, convergence speed, effectiveness, hardware and sensor requirements, costs. [10]. However, many techniques are not used due to their high complexity and cost because simpler and less costly techniques may lead to similar results. Thus, in practice, only a small number of techniques is commonly implemented; among them are: constant voltage (CV), perturb and observe (P&O), and incremental conductance (IncCond) [11, 12].

In an isolated photovoltaic system, the implementation of an MPPT requires a DC-DC power converter acting as an interface between the PV array and the battery bank. The role of the MPPT is to regulate the converter's duty cycle to control its voltage or current and make it converge to the MPP, thus extracting the maximum possible power from the PV modules and transferring it to the batteries. Buck, Boost, Buck-Boost, Cuk, Sepic, and Zeta are the most commonly used converters for MPPT implementation, each with their operating characteristics when applied to PV systems [13]. Within this group of nonisolated DC-DC converters, the topologies Buck, Boost and Buck-Boost present a better compromise of the simplicity of implementation, low cost, and power conversion efficiency, and therefore, they are usually preferred by designers [35-37]. In PV applications, it is not trivial to choose among these three converters concerning efficiency, given that their performance varies with their operation condition (duty cycle, load impedance, current and voltage levels, switching frequency). The right choice will depend on the application and its operation condition. In literature, works comparing the efficiency of these three topologies among, which some show that the Buck converter presents higher efficiency [6, 34, 40], and others point the Buck-Boost with higher efficiency [39, 41]. A judicious converter selection is also an important factor in the overall performance of a given photovoltaic system and its reliability.

There are several studies of MPPT algorithms applied in DC-DC converters in the literature, which generally focuses on electing a particular converter to test the performance of a particular MPPT technique or a group of them [10, 14-17]. Also, although less commonly, an MPPT technique is chosen to predict the performance of a group of converters [18, 19], a comparative analysis that makes it possible to discern which particular MPPT/converter combination performs better for a given climatic condition, has not yet been much explored in the literature. There are only two works in literature, To the authors' knowledge, presenting a similar approach. In [4], the authors compare the Buck and the Boost converters operating with three different MPPT (Temp, P&O, and IncCond); in [38], the Buck-Boost and the Sepic are compared operating with two different MPPT (P&O and IncCond). In this context, the present work presents as its main contribution a new comparative study of three MPPT technics (CV, P&O, and IncCond), applied in two different DC-DC converters (Buck and Buck-Boost) that act as interfaces to maximize the solar energy conversion in an autonomous system of low power, composed of PV panel and a battery, which is typically used in isolated regions with the need for a continuous supply of energy.

The study was carried out based on simulations performed with Matlab/Simulink. A model for the PV panel was developed and validated following the Kyocera KC85TS commercial module's electrical characteristics to obtain more realistic conditions. Results regarding the dynamic response and steady-state mean efficiency of each MPPT/converter combination, operating under various weather conditions are analyzed and discussed.

SYSTEM DESCRIPTION

In an autonomous photovoltaic system, when a PV module is connected directly to a battery, the operating point of the system is given by the intersection of the current-voltage (I-V) curve of the PV module and the battery voltage, which generally does not correspond to the MPP of the PV panel, with the consequent loss of available solar energy. To overcome this problem, a DC-DC power converter is inserted as the interface between the PV panel and the battery. The DC-DC converter used in this case works as an impedance adaptor by controlling the duty cycle and adjusting its input impedance to that of the PV panel aiming to achieve the MPP. This is usually accomplished by measuring the electrical parameters of the PV panel and using an MPPT algorithm to drive the duty cycle. Figure 1 shows the proposed general scheme for the accomplishment of this work. Table 1 presents the topologies of the

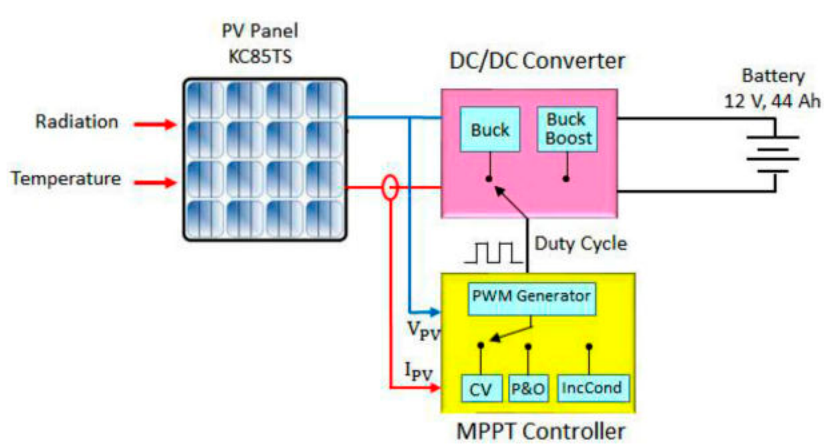
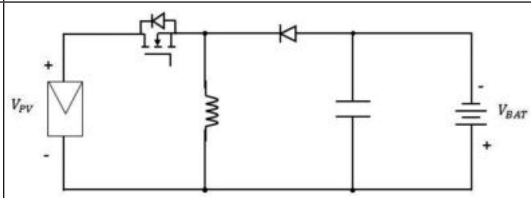
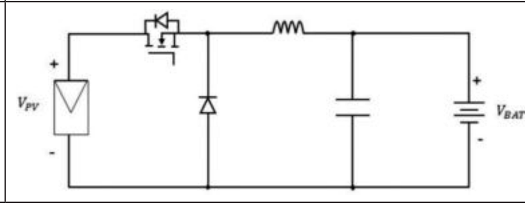


Figure 1. Proposed scheme to evaluate the PV system.

Table 1. DC-DC converters [23].

V_{BAT}/V_{PV}	Converter Topology	Circuit
$-\frac{D}{1-D}$	**Buck - Boost**	
D	**Buck**	

converters studied, and Figure 2 shows the flowcharts of the MPPT approaches tested.

MODELING OF A PV MODULE

An actual PV cell can be modeled by an equivalent electric circuit composed of a current source in parallel to a diode and a resistor network, as shown in Figure 3 [20], where I_{PH} represents the current generated by the incident radiation, I_d the current at the PN junction according to the Schockley equation, R_S describes the voltage drop through the ohmic losses of the semiconductor material. In the metal contacts and the metal contact with the semiconductor, R_P describes the losses that arise mainly through electrical disturbances between the front and back of the cell, as well as point perturbations in the transition zone PN, I_{PV} the current generated by the cell to the external circuit and V_{PV} is the voltage at the output terminals.

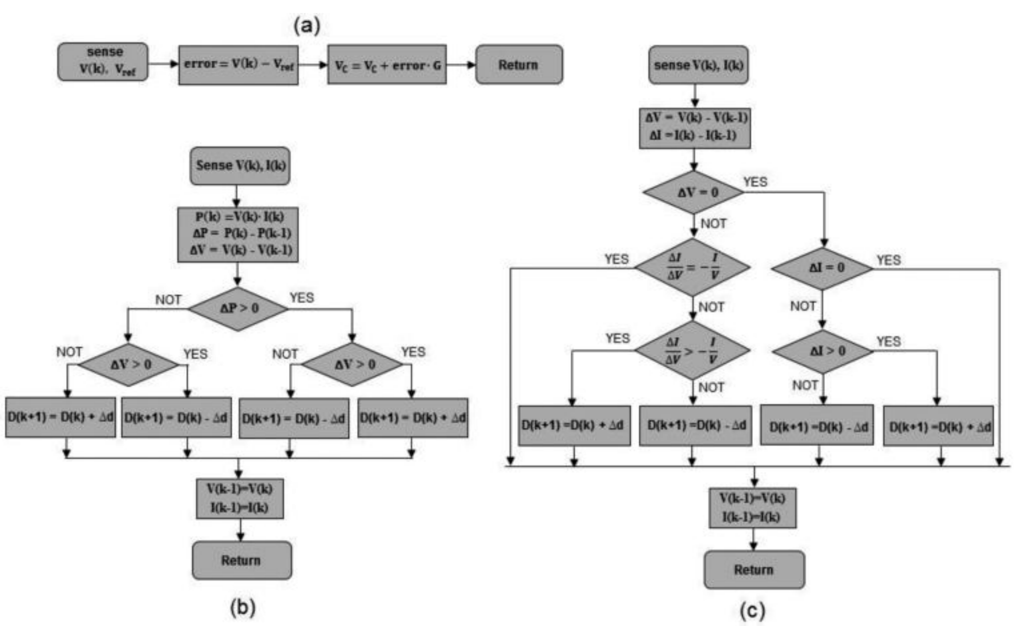


Figure 2. Flowcharts of the MPPT algorithms. (a) CV method [26]. (b) P&O method [19]. (c) IncCond method [15].

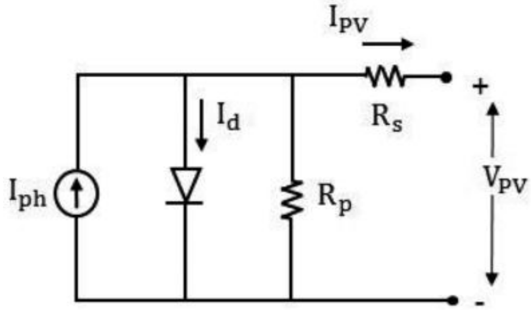


Figure 3. PV cell model.

$$I_{PV} = I_{ph} - \left[e\frac{q\left(V + I_{PV} \cdot R_s\right)}{n \cdot k_b \cdot T} - 1 \right] - \frac{V_{PV} + I_{PV} \cdot R_s}{R_P} \quad (1)$$

$$I_r = I_{rr} \cdot \left(\frac{T}{T_r}\right)^3 \cdot e\left[\frac{q \cdot E_G}{n \cdot k_b} \cdot \left(\frac{1}{T_r} + \frac{-1}{T}\right)\right] \quad (2)$$

$$I_{ph} = \left[I_{SC} + \alpha\left(T - T_r\right)\right] \cdot \frac{P_{sum}}{1000} \quad (3)$$

Equations (1)-(3) describe the model of a solar cell: where I_r corresponds to the reverse saturation current, T is the cell temperature, n the junction ideality factor, q the electron charge (1.602176 x 10^{-21} C), I_{SC} the short-circuit current of the cell, k_b the Boltzmann constant (1.38065 x 10^{-3} J/K), α is the temperature coefficient of the short-circuit current of the cell,

Table 2. Electrical characteristics for the KC85TS photovoltaic panel [22].

Parameters	Values
Maximum power current (I_{MPP})	5.02 A
Maximum power voltage (V_{MPP})	17.4 V
Maximum power (P_{MPP})	87 W ± 10%
Short circuit current (I_{SC})	5.34 A
Open circuit voltage (V_{oc})	21.7 V
Short circuit temperature coefficient (α)	2.12 x 10^{-3} A/ºC
Diode ideality factor (n)	1.2
Series resistance (R_S)	6.25 mΩ
Parallel resistance (R_P)	30 Ω
Reverse saturation current (I_{rr})	1.7310 x 10^{-8} A

T_r is the temperature in standard test conditions, I_{rr} the reverse saturation current at temperature T_r, E_G the band-gap energy of silicon (1.1 eV), and P_{sun} the radiance. The manufacturer of the cell generally gives parameters α and I_{SC}. The parameters n, $I_{rr,}$ $R_{S,}$ and R_P have to be estimated through some mathematical algorithm.

In this work, a routine in Matlab was developed for the PV panel simulation; the model was adjusted to the electrical characteristics of the Kyocera KC85TS commercial module, parameters not provided by the manufacturer were estimated using the procedure and recommendations described in [21]. Table 2 presents a summary of the parameters adjusted for the commercial module. Figure 4a presents the P-V characteristic for several temperature levels of the

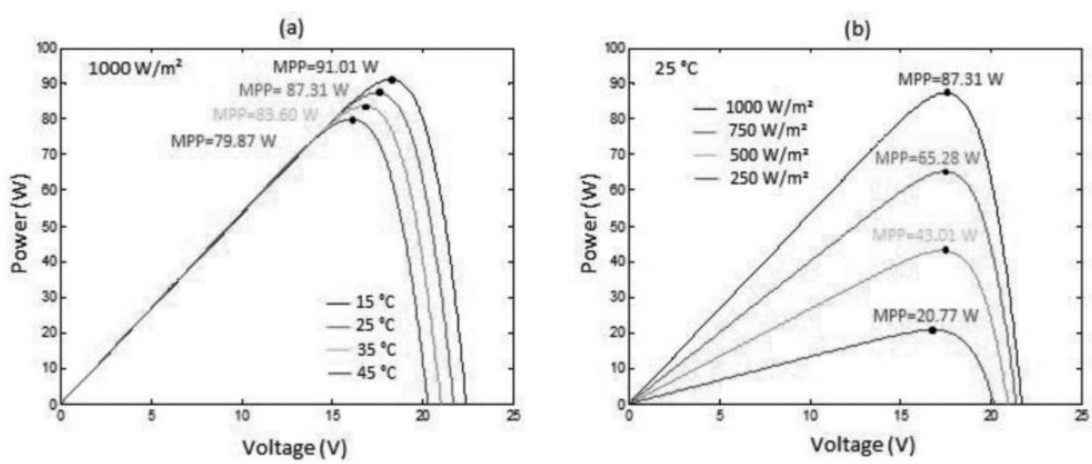


Figure 4. P-V curves from the obtained model of the KC85TS. (a) Various temperature levels and constant radiation of 1000 W/m². (b) Various levels of radiation and a constant temperature of 25 ºC.

obtained model, and Figure 4b presents the P-V characteristic for various radiation levels of the obtained model.

SIMULATIONS

The general scheme of the PV system shown in Figure 1 was simulated. Figure 5 shows the system for testing the Buck converter, and an identical structure was implemented for the Buck-Boost converter case.

The block "Electronic control switch" represents the MPPT methods evaluated in this work. Figure 6 presents the CV algorithm developed according to the flowchart of Figure 2a, in which it can be noticed that the structure of this technique corresponds basically to a proportional control with gain G applied to the voltage error regarding to a reference $Vref = kVoc \approx VMPP$, dependent on the so-called voltage factor (k), and on open-circuit voltage of the PV panel (Voc). It is worth mentioning that k is an internal parameter of the commercial PV panel, which is variable generally in the range of 0.7 to 0.8. More details of these techniques are available in [14, 24-27]. Figure 7 presents the block diagram developed for the P&O algorithm following Figure 2b. As can be observed, there is a periodic perturbation (Δd) in the PV panel voltage, which keeps happening if the panel's power increases, as far as the MPP is reached. If the PV panel power decreases, the perturbation reverses its signal. More details can be found in [5, 15, 19, 28-32]. Figure 8 depicts the logic developed for the algorithm IncCond as shown in the flowchart of Figure 2c. There it can be observed that, from the measured panel current and voltage, the incremental conductance (ΔI/ΔV) is derived and compared with the instantaneous conductance (I/V). If the difference is zero ($\Delta P/\Delta V = I + V \cdot \Delta I/\Delta V = 0$) it means that the panel is at the MPP and the duty cycle is kept constant; if $\Delta I/\Delta V > I/V$ it means that the MPP has changed, and a perturbation in the duty cycle in the sense as to reach the new MPP, whereas if $\Delta I/\Delta V < I/V$, the perturbation goes in the other sense. More details are found in [2, 7, 15, 29, 33].

The "photovoltaic array" block contains the routine created for the numerical solution of the current generated by the PV panel according to expression (1) and particularized for the commercial module KC85TS. The inputs S and T of the panel represent the radiation in W/m² and temperature in ºC, respectively.

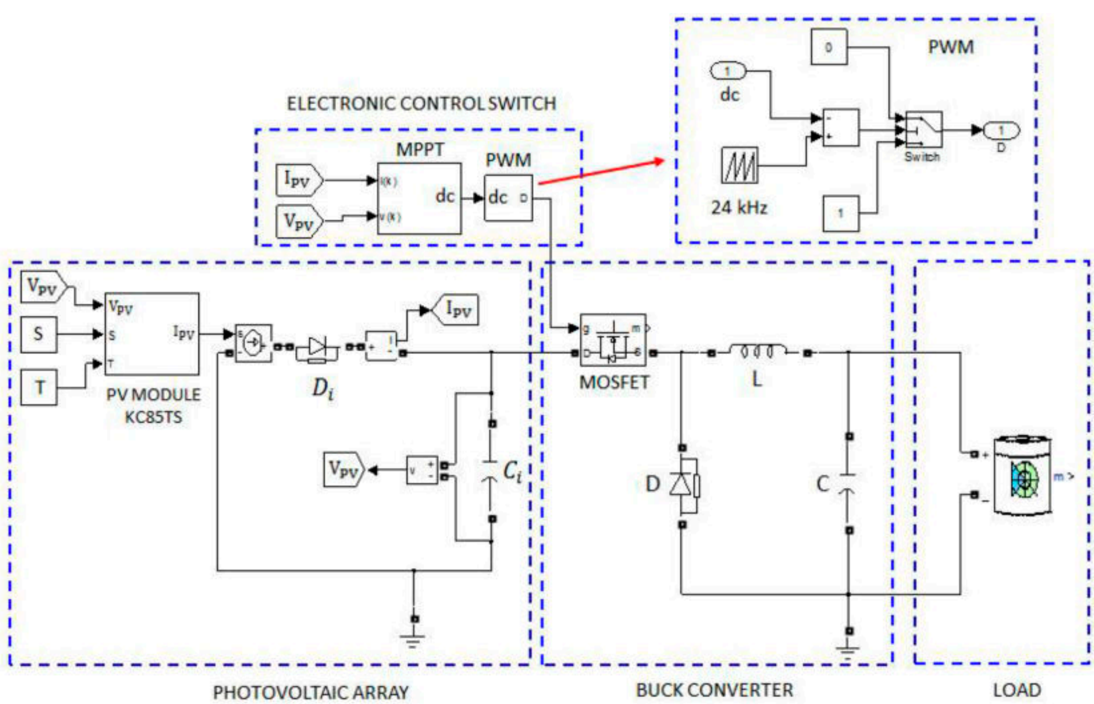


Figure 5. Simulation scheme of the PV system operating with a Buck converter and MPPT algorithms.

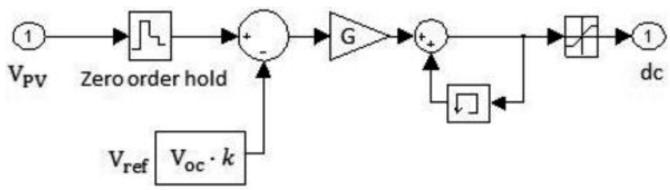


Figure 6. CV MPPT algorithm implemented with Simulink/Matlab.

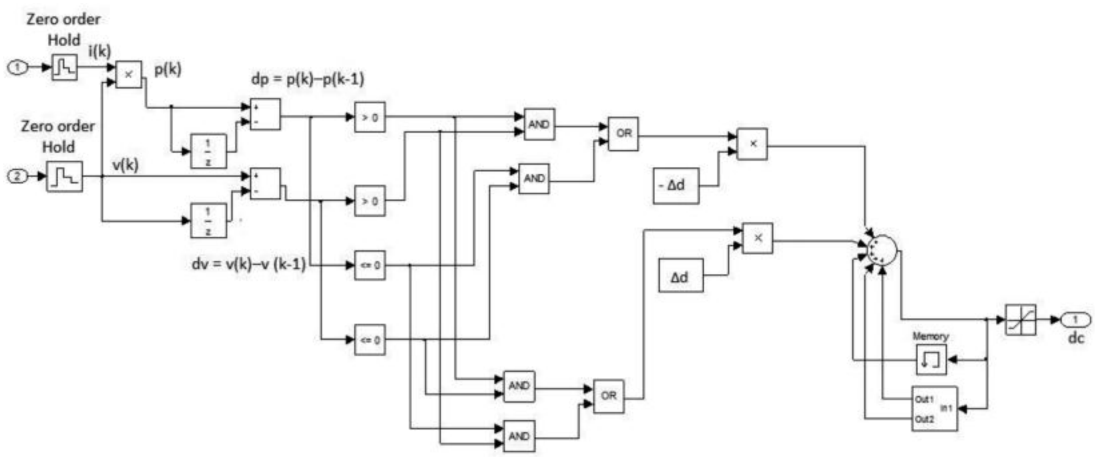


Figure 7. P&O MPPT algorithm implemented in Simulink/Matlab.

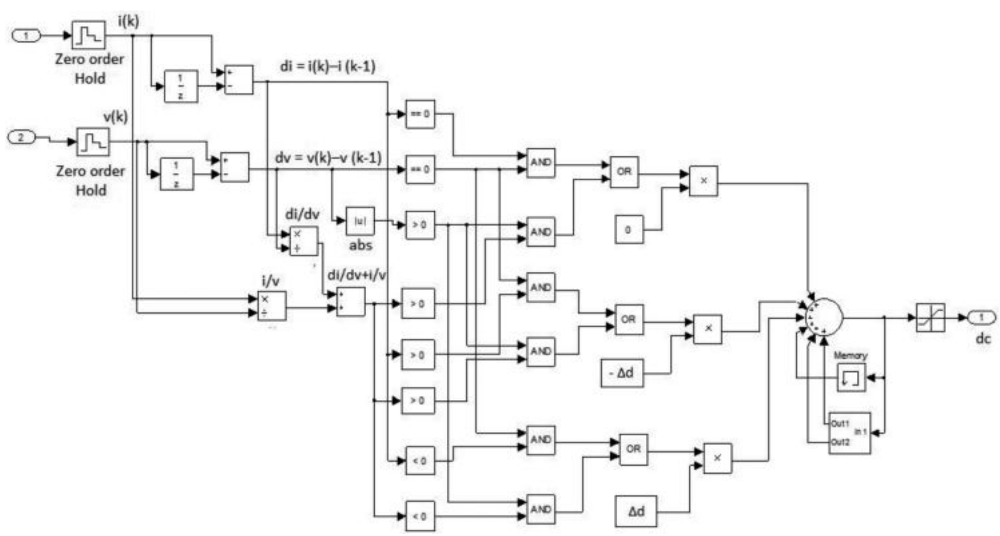


Figure 8. IncCond MPPT algorithm implemented in Simulink/Matlab.

As a load, the generic model for lead-acid batteries available in the Simulink Power Systems package was used, nominally particularized at 12 V and 44 Ah. Table 3 presents a summary of the parameters used in the simulations. G, Δd, and T_a values were previously adjusted to obtain an optimal relation speed of convergence and size of steady-state oscillations of the MPPT techniques to be compared in this work.

Table 3. Simulation parameters.

Component	Values
Converter switching frequency (f_S)	24 kHz
Voltage factor (k)	0.8
Open circuit voltage (V_{OC})	21.7 V
Gain (G)	0.02
MPPT perturbation increment (Δd)	0.0025
MPPT sampling period (T_a)	2 mS
Input capacitor (C_i)	1000 µF
Capacitor (C)	220 µF
Inductor (L)	560 mH

TRACKING EFFICIENCY

Two tests were performed to observe the steady-state follow-up efficiency. First, a profile with abrupt radiation changes was applied as input, with a constant temperature at 25 ºC. The incident radiation was varied between 250 W/m² and 1000 W/m² in an increasing and decreasing manner in steps of 250 W/m² per 0.1 s.

Next, a profile with abrupt changes of temperature was applied as input, where the radiation was maintained constant at 1000 W/m², and the temperature was varied between 15 ºC and 45 ºC, increasing and then decreasing in steps of 10 ºC every 0.1 s. According to the expression, each MPPT/Converter combination is compared in terms of efficiency in power extracted from the PV panel (4).

$$\eta(\%) = \frac{\int_0^t P_{PV}}{\int_0^t P_{MPP}} \times 100 \cong \frac{\sum_{i=1}^{n} P_{PV}}{\sum_{i=1}^{n} P_{MPP}} \times 100 \qquad (4)$$

Where P_{PV} is the power provided by the PV system, and P_{MPP} corresponds to the maximum power generated by the PV module during the simulation.

TRACKING EFFICIENCY BUCK

Figure 9 shows the behavior of the PV system operating with the Buck converter and the three MPPT methods

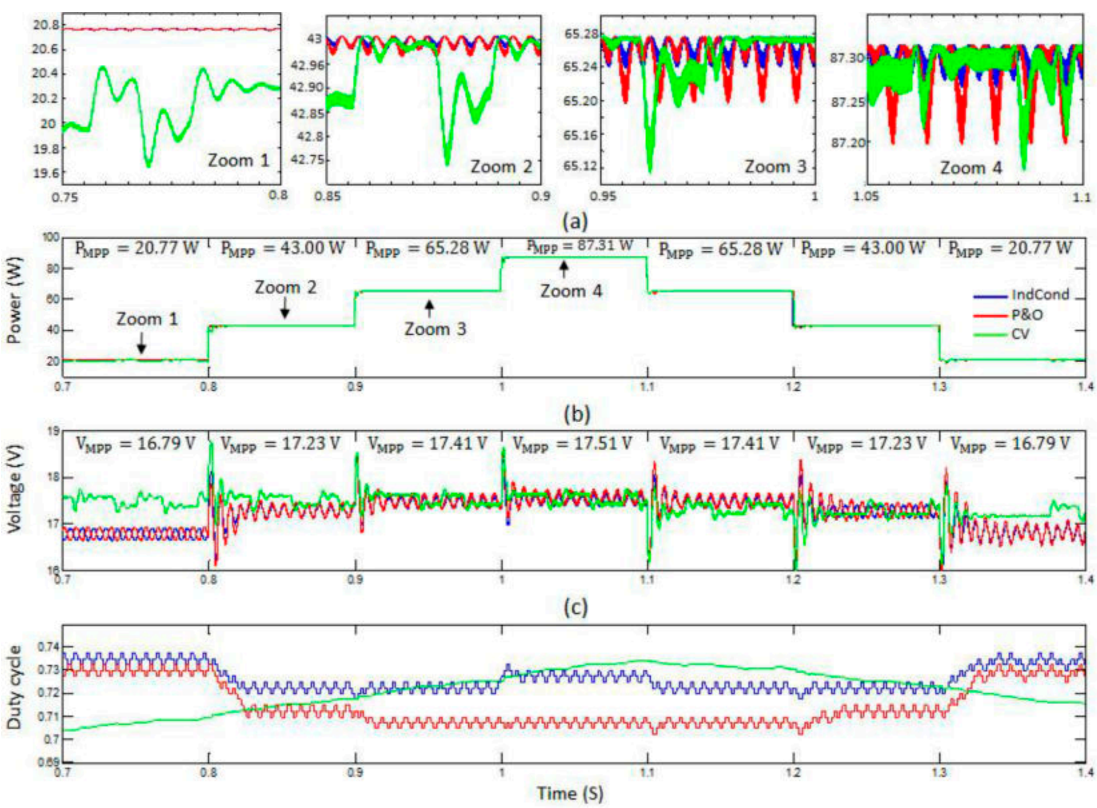


Figure 9. PV system operating with Buck converter and MPPT algorithms for radiation variations with T = 25 ºC. (a) PV panel power. (b) PV panel voltage. (c) Duty cycle.

when variations in incident radiation occur. The efficiency, maximum power ripple, and maximum voltage ripple data produced for each radiation level are summarized and presented in Table 4. It can be observed that, compared to P&O and CV, the IncCond technique showed the highest efficiency for all the radiation levels tested, reaching its maximum value of 99.98% for S = 1000 W/m² and T = 25 ºC, known as Standard Test Conditions (STC). In this condition, IncCond, had a power oscillation around the MPP of 0.05 W, equivalent to 0.057% of the P_{MPP}. On the other hand, the lowest efficiency was obtained with the CV method reaching a 97.09% value when S = 250 W/m² and T = 25 ºC, generating a power swing of 0.54 W, equivalent to 2.6% of the P_{MPP}.

Figure 10 shows the PV system's behavior operating with the Buck converter and the three MPPT methods for temperature variations. Table 5 summarizes efficiency, maximum power ripple, and maximum voltage ripple data produced for each temperature level. It can be observed that IncCond reached the highest efficiency for all the analyzed temperatures. However, this maximum efficiency was shared with P&O when S = 1000 W/m² and T = 45 ºC, where both techniques presented the maximum registered value of 99.98%; in this climatic condition, the power oscillation obtained by both techniques was 0.03 W, equivalent to 0.037% of the P_{MPP}. The three techniques' worst performance was obtained in the same atmospheric condition, where CV reached an average efficiency of 94.20% and an oscillation of 2.53 W, equivalent to 3.16% of P_{MPP}.

TRACKING EFFICIENCY BUCK-BOOST

Figure 11 shows the PV system's behavior operating with the Buck-Boost converter and the three MPPT methods for radiation changes. Table 6 summarizes the average efficiency, maximum power ripple, and maximum voltage ripple data produced for each radiation level. IncCond presented the best performance in all the radiation conditions, reaching its maximum value of 99.80% for the STC and generating a power ripple of 0.55 W, equivalent to 0.62% of the P_{MPP}. The lowest efficiency was

Table 4. MPPT methods efficiency with Buck converter for variations of radiation with T = 25 ºC.

	S = 250 W/m² PMPP = 20.77 *W* VMPP = 16.79 *V*			S = 500 W/m² PMPP = 43.00 *W* VMPP = 17.23 *V*			S = 750 W/m² PMPP = 65.28 *W* VMPP = 17.41 *V*			S = 1000 W/m² PMPP = 87.31 *W* VMPP = 17.51 *V*		
	IncCond	**P&O**	**CV**	**IncCond**	**P&O**	**CV**	**IncCond**	**P&O**	**CV**	**IncCond**	**P&O**	**CV**
Efficiency (%)	99.975	99.971	97.098	99.976	99.965	99.846	99.979	99.967	99.970	99.983	99.975	99.929
Oscillation of power (W) around MPP	20.77-20.76 Δ = 0.01	20.77-20.76 Δ = 0.0	20.63-20.09 Δ = 0.54	43.00-42.98 Δ = 0.02	43.00-42.97 Δ = 0.03	43.00-42.74 Δ = 0.26	65.27-65.24 Δ = 0.03	65.27-65.20 Δ = 0.07	65.27-65.11 Δ = 0.16	87.31-87.26 Δ = 0.05	87.31-87.25 Δ = 0.06	87.31-86.97 Δ = 0.34
Oscillation of voltage (V) around MPP	16.91-16.64 Δ = 0.27	16.93-16.65 Δ = 0.28	17.71-17.36 Δ = 0.35	17.41-17.12 Δ = 0.29	17.46-17.12 Δ = 0.34	17.64-17.27 Δ = 0.37	17.60-17.31 Δ = 0.29	17.66-17.31 Δ = 0.35	17.75-17.39 Δ = 0.36	17.66-17.38 Δ = 0.28	17.73-17.41 Δ = 0.32	17.77-17.37 Δ = 0.40

Table 5. MPPT methods efficiency with Buck converter for temperature variations with S = 1000 W/m².

	T = 15 ºC PMPP = 91.01 W VMPP = 18.22 *V*			T=25 ºC PMPP=87.31 W VMPP=17.51 *V*			T = 35 ºC PMPP = 83.60 W VMPP = 16.78 *V*			T = 45 ºC PMPP = 79.87 W *VMPP* = 16.04 *V*		
	IncCond	**P&O**	**CV**	**IncCond**	**P&O**	**CV**	**IncCond**	**P&O**	**CV**	**IncCond**	**P&O**	**CV**
Efficiency (%)	99.978	99.967	98.461	99.983	99.975	99.929	99.987	99.979	99.089	99.987	99.986	94.206
Oscillation of power (W) around MPP	91.01-90.95 Δ = 0.06	91.01-90.91 Δ = 0.10	90.31-88.73 Δ = 1.58	87.31-87.26 Δ = 0.05	87.31-87.25 Δ = 0.06	87.31-86.97 Δ = 0.34	83.60-83.57 Δ = 0.03	83.60-83.53 Δ = 0.07	83.38-82.28 Δ = 1.10	79.87-79.81 Δ = 0.06	79.87-79.84 Δ = 0.03	75.65-73.12 Δ = 2.53
Oscillation of voltage (V) around MPP	18.40-18.08 Δ = 0.32	18.44-18.05 Δ = 0.39	17.49-17.09 Δ = 0.40	17.66-17.38 Δ = 0.28	17.73-17.41 Δ = 0.32	17.77-17.37 Δ = 0.40	16.91-16.66 Δ = 0.25	16.96-16.67 Δ = 0.29	17.50-17.16 Δ = 0.34	16.22-15.99 Δ = 0.23	16.18-15.94 Δ = 0.24	17.55-17.25 Δ = 0.30

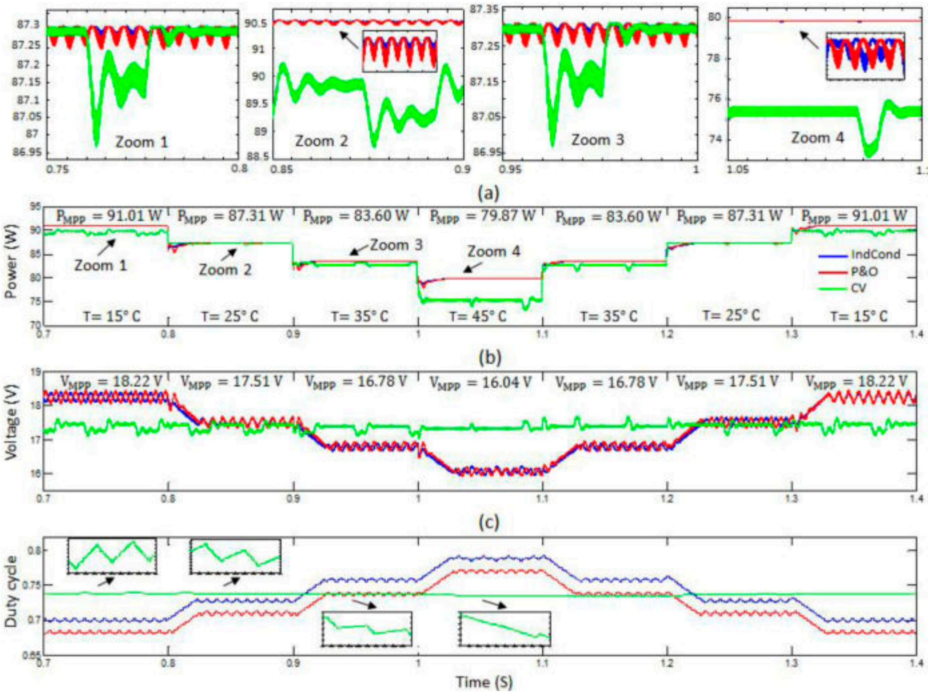


Figure 10. PV system operating with Buck converter and MPPT algorithms for variations in temperature with S = 1000 W/m². (a) PV panel power. (b) PV panel voltage. (c) Duty cycle.

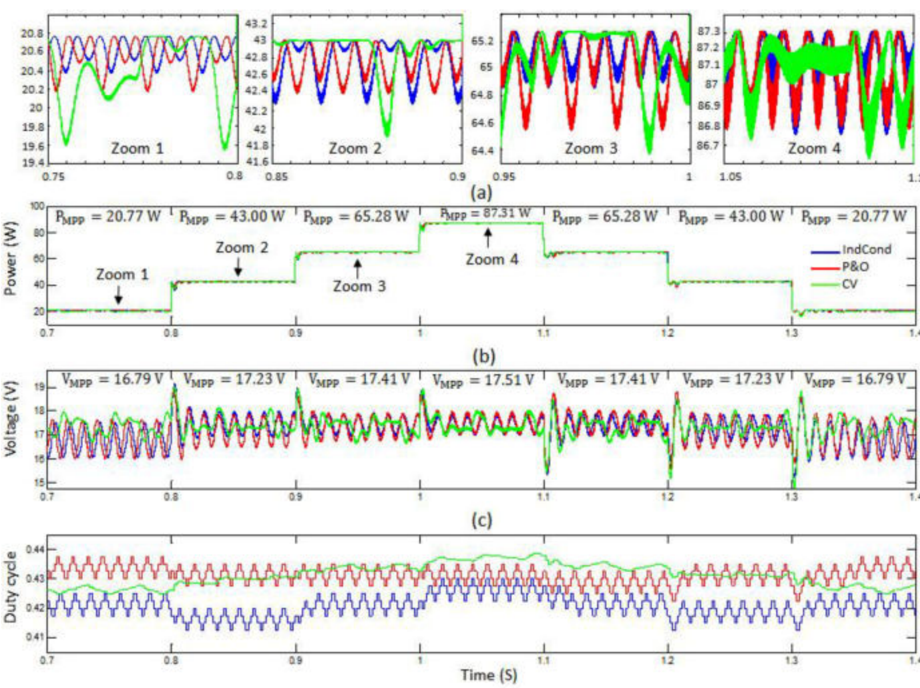


Figure 11. PV system operating with Buck-Boost and MPPT algorithms for radiation variations with T = 25 ºC. (a) PV panel power. (b) PV panel voltage. (c) Duty cycle.

Table 6. MPPT methods efficiency with Buck-Boost converter for radiation variation with T = 25 ºC.

	S = 250 W/m² PMPP = 20.77 *W* VMPP = 16.79 *V*			S = 500 W/m² PMPP = 43.00 *W* VMPP = 17.23 *V*			S = 750 W/m² PMPP = 65.28 *W* VMPP = 17.41 *V*			S = 1000 W/m² PMPP = 87.31 *W* VMPP = 17.51 *V*		
	IncCond	P&O	CV	IncCond	P&O	CV	IncCond	P&O	CV	IncCond	P&O	CV
Efficiency (%)	99.260	99.011	98.585	99.465	99.405	99.771	99.740	99.608	99.713	99.803	99.770	99.770
Oscillation of power (W) around MPP	20.77-20.37 Δ = 0.40	20.77-20,17 Δ = 0.60	20.77-19.55 Δ = 1.22	43.00-42.28 Δ = 0.72	43.00-42.40 Δ = 0.60	43.00-41.83 Δ = 1.17	65.27-64.86 Δ = 0.41	65.27-64.64 Δ = 0.63	65.27-64.36 Δ = 0.91	87,31-86.76 Δ = 0.55	87.31-86.80 Δ = 0.51	87.31-86.62 Δ = 0.69
Oscillation of voltage (V) around MPP	17.51-16.06 Δ = 1.45	17.66-16.04 Δ = 1.62	17.97-16.92 Δ = 1.05	17.99-16.93 Δ = 1.06	17.85-16.51 Δ = 1.34	18.15-17.22 Δ = 0.93	17.92-16.96 Δ = 0.96	17.91-16.74 Δ = 1.17	17.87-16.91- Δ = 0.96	17.75-16.98 Δ = 0.77	17.97-17.01 Δ = 0.96	18.03-17.18 Δ = 0.85

obtained with the CV method reaching 98.58% when S = 250 W/m² and T = 25 ºC; for this atmospheric condition, CV presented a power swing of 1.22 W, corresponding to 5.87% of the P_{MPP}.

Figure 12 shows the PV system's behavior operating with the Buck-Boost converter and the three MPPT methods for temperature variations. Table 7 shows the summary of efficiency, maximum power ripple, and maximum voltage ripple data produced for each temperature level. It can be observed that IncCond presented the best yield for all the analyzed temperatures, reaching a maximum value of 99.86% when S = 1000 W/m² and T = 45 ºC; in this climatic condition, IncCond generated an oscillation of 0.36 W corresponding to 0.45% of P_{MPP}. The minimum efficiency was obtained by CV in this same atmospheric condition, with 93.47% and an oscillation of 5.77 W, equivalent to 7.22% of P_{MPP}.

TRANSIENT TRACKING TIME

To analyze the transient behavior, the following test was performed. The PV system was simulated

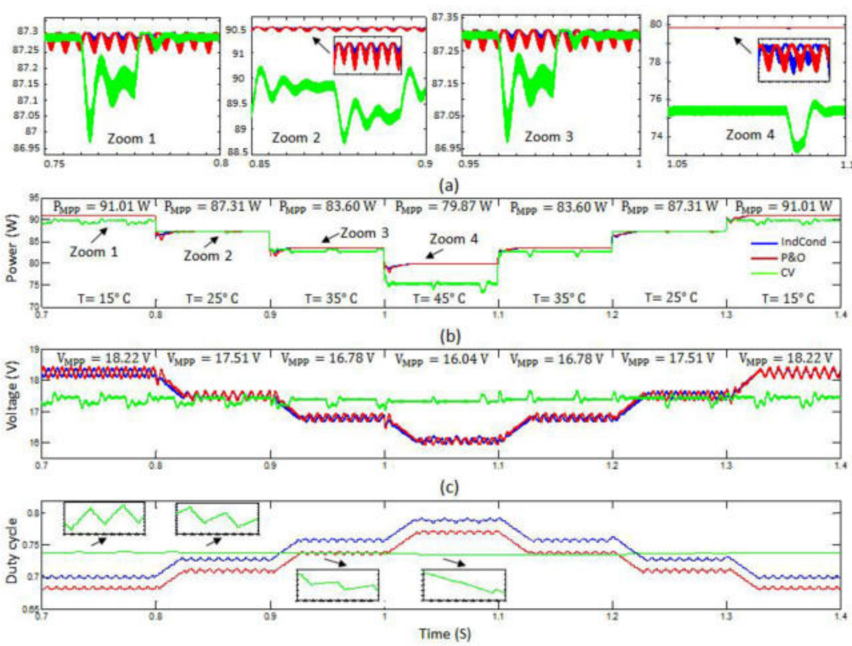


Figure 12. PV system operating with Buck-Boost and MPPT algorithms for temperature variations with S = 1000 W/m². (a) PV panel power. (b) PV panel voltage. (c) Duty cycle.

Table 7. MPPT method efficiency with Buck-Boost converter for temperature variations with S = 1000 W/m².

	T = 15 ºC PMPP = 91.01 W VMPP = 18.22 *V*			T = 25 ºC PMPP = 87.31 W VMPP = 17.51 *V*			T = 35 ºC PMPP = 83.60 W VMPP = 16.78 *V*			T = 45 ºC PMPP = 79.87 W *VMPP* = 16.04 *V*		
	IncCond	**P&O**	**CV**	**IncCond**	**P&O**	**CV**	**IncCond**	**P&O**	**CV**	**IncCond**	**P&O**	**CV**
Efficiency (%)	99.760	99.730	98.202	99.803	99.770	99.770	99.842	99.799	98.963	99.860	99.797	93.471
Oscillation of power (W) around MPP	91.01-90.34 Δ = 0.67	91.01-90.38 Δ = 0.63	91.01-87.37 Δ = 3.64	87,31-86.76 Δ = 0.55	87.31-86.78 Δ = 0.51	87.31-86.62 Δ = 0.69	83.60-83.19 Δ = 0.41	83.60-83.10 Δ = 0.50	83.55-80.27 Δ = 3.28	79.87-79.51 Δ = 0.36	79.87-79.31 Δ = 0.56	77.39-71.62 Δ = 5.77
Oscillation of voltage (V) around MPP	18.60-17.67 Δ = 0.93	18.73-17.71 Δ = 1.02	18.15-17.20 Δ = 0.95	17.75-16.98 Δ = 0.77	17.97-17.01 Δ = 0.96	18.03-17.18 Δ = 0.85	17.13-16.33 Δ = 0.80	17.23-16.33 Δ = 0.90	17.87-17.15 Δ = 0.72	16.45-15.72 Δ = 0.73	16.40-15.52 Δ = 0.88	17.68-17.09 Δ = 0.59

considering the STC input, and for each MPPT/Converter combination, the convergence time (t) at which the system reached 95% of the ideal maximum power available in the PV panel was determined as recommended in [26]. Figure 13 shows the behavior of the MPPT techniques with the Buck converter, in which it is observed that the CV method presented the fastest transient response with t = 391.7 ms and that IncCond with t = 547.8 ms presented the slowest response. Figure 14 shows the MPPT techniques' behavior with the Buck-Boost converter, where it is observed that CV again has the fastest transient response with t = 236.4 ms and that the slower response was achieved in this case by P&O with t = 338.7 ms.

DISCUSSION

The IncCond e P&O techniques working with both the Buck converter and the Buck-Boost converter can adequately regulate the drive duty cycle for all tested climatic conditions; as shown in Figures 9-12, V_{PV} is always oscillating around V_{MPP}. In general, the size of the voltage oscillations generated with IncCond are always slightly smaller compared to P&O, as shown in Tables 4-7, which explains the small difference in average efficiency in favor of IncCond over P&O. As expected, none of the methods can eliminate the oscillations of power. However, those oscillations are small, guaranteeing minimum losses in power provided by the PV panel.

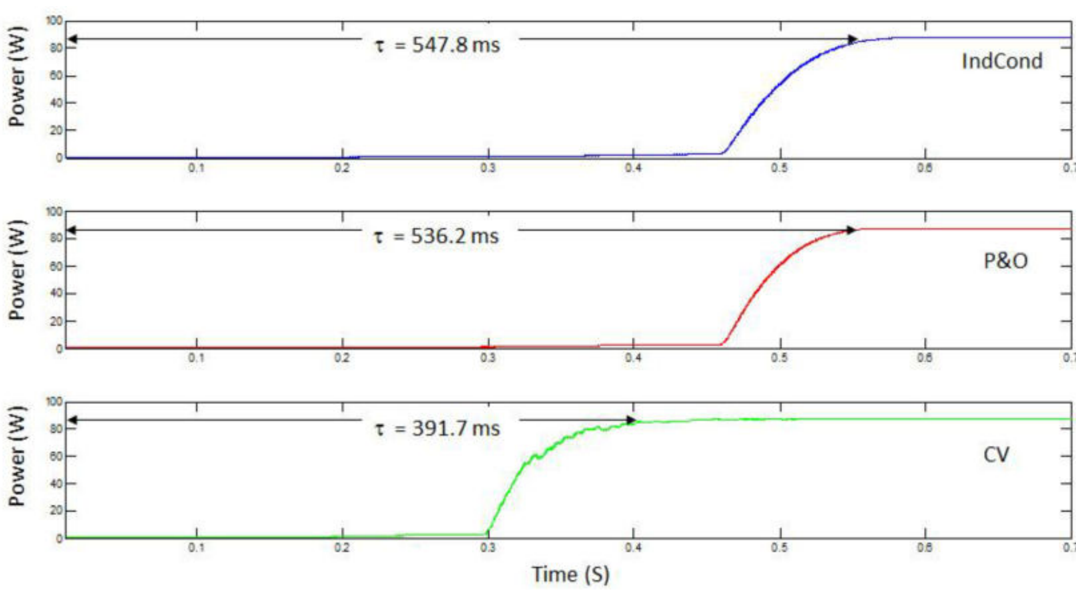


Figure 13. Response time of the MPPT methods operating with the Buck converter.

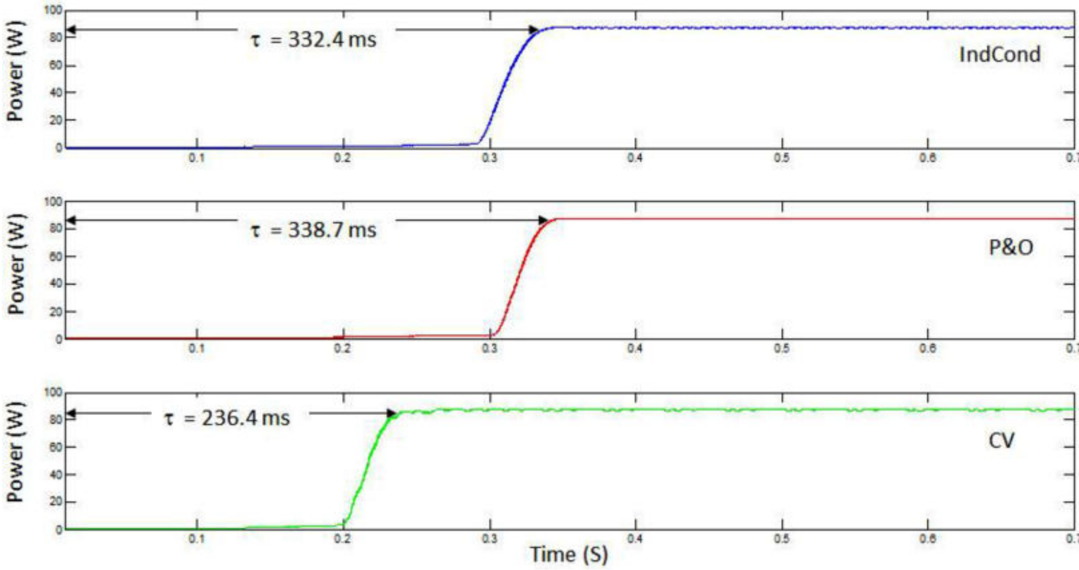


Figure 14. Response time of the MPPT methods operating with the Buck-Boost converter.

In the case of the CV technique, it is observed that climate changes, mainly of temperature, significantly affect its behavior. This method presents voltage oscillations in general of the same order of magnitude as the IncCond and P&O techniques. However, the problem is that those oscillations occur around a level that, depending on the climatic condition, can present considerable deviations of the V_{MPP}, reducing the technique's efficiency. This steady-state error is attributed to the very nature of the proportional control used by the method to regulate the drive duty cycle; additionally, the reference voltage $V_{ref} = kV_{oc} = 0.8{\cdot}21.7$ V = 17.36 V, used by the control is only an approximation of the V_{MPP} because the factor k of the PV panel is not exactly constant as it changes with the variations of radiation and temperature. On the other hand, we opted in this work, to omit the periodic correction of V_{ref}, to avoid losses of power due to the necessary disconnection of the PV module at the moment of measuring V_{oc}.

Nevertheless, this also contributes to adding the error in steady-state under certain conditions of atmospheric conditions. In this way, there is an inverse relationship between the technique's performance and the difference between V_{MPP} e V_{ref} ($\Delta V_{MPP\text{-}ref} = V_{MPP}\text{-}V_{ref}$). As expected, the worst yields coincide with the highest obtained value of $\Delta V_{MPP\text{-}ref} = 1.32$ V, which happens when T = 45 ºC e S = 1000 W/m²; in this climatic condition, the CV technique operating with the Buck converter reached an efficiency of 94.20% and operating with Buck-Boost, of 93.47%. On the other hand, the best result of this technique with the Buck converter was obtained for $\Delta V_{MPP\text{-}ref} = 0.05$ V when T = 25 ºC e S = 750 W/m² reaching an efficiency of 99.97%, and in the case of the Buck-Boost for $\Delta V_{MPP\text{-}ref} = 0.13$ V when T = 25 ºC e S = 500 W/m² achieving an efficiency of 99.77%.

CONCLUSIONS

This work has presented a comparative study of the performance of three classical MPPT methods acting on two different topologies of CD-CD power converters used as interfaces to maximize the solar energy conversion at variable operation conditions in a typical low power configuration isolated from the grid. The study was performed based on the transient response and average steady-state efficiency, considering the analysis of various radiation and temperature conditions.

Simulations developed in Matlab/Simulink show that regardless of the converter used, the IncCond and P&O techniques present an excellent in steady-state performance, reaching both methods efficiencies above 99% in all environmental conditions analyzed. although both techniques produce similar efficiencies, IncCond showed in all cases being slightly higher than P&O. On the other hand, the MPPT methods generally achieve greater efficiency when operating with the Buck converter than with the Buck-Boost converter, so then the IncCond/Buck combination showed the best performance. On the other hand, CV is the technique that presents the worst behavior, so then CV/Buck-Boost is the combination that produces the lowest average efficiencies. The CV algorithm shows to be particularly imprecise for temperature changes, generating in these environmental conditions the greatest MPP deviations. Although CV shows worse performance compared to IncCond and P&O, in absolute terms, it has an acceptable behavior, reaching in all climatic conditions, efficiencies above 93%.

As for the transient performance test, the three MPPT techniques acting in conjunction with the Buck-Boost converter converge around the MPP faster than the same ones operating with the Buck converter, and in particular, the CV/Buck-Boost combination achieved the shortest response time.

Finally, the conclusions and tables presented can be used as a valuable source of information for the decision to implement a particular MPPT/Converter set studied in this work.

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