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

Julio López Seguel1* S.I. Seleme Jr.2 Lenin M.F. Morais2

Recibido 25 de marzo de 2019, aceptado 09 de junio de 2020
Received: March 25, 2019 Accepted: June 09, 2020

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

1 Universidad Arturo Prat. Facultad de Ingeniería y Arquitectura. Iquique, Chile. E-mail: julioilo@unap.cl
2 Universidade Federal de Minas Gerais. Departamento de Engenharia Eletrônica. Belo Horizonte, Brasil.
E-mail: seleme@cpdee.ufmg.br; lenin@cpdee.ufmg.br
* Autor de correspondencia: julioilo@unap.cl
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, MPP 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 MPP 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. 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 MPP requires a DC-DC power converter acting as an interface between the PV array and the battery bank. The role of the MPP 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 MPP 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 techniques (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.](image-url)
In Ingeniare. Revista chilena de ingeniería, vol. 29 N° 2, 2021

converters studied, and Figure 2 shows the flowcharts of the MPPPT 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.

Table 1. DC-DC converters [23].

| $V_{BAT}/V_{PV}$ | Converter Topology | Circuit |
|------------------|-------------------|---------|
| $\frac{D}{1-D}$  | Buck - Boost      | ![Diagram](image) |
| $D$              | Buck              | ![Diagram](image) |

| $V_{BAT}/V_{PV}$ | Converter Topology | Circuit |
|------------------|-------------------|---------|
| $\frac{D}{1-D}$  | Buck - Boost      | ![Diagram](image) |
| $D$              | Buck              | ![Diagram](image) |

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

232
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 \( (1.602176 \times 10^{-21} \text{C}) \), \( I_{SC} \) the short-circuit current of the cell, \( k_b \) the Boltzmann constant \( (1.38065 \times 10^{-23} \text{J/K}) \), \( \alpha \) is the temperature coefficient of the short-circuit current of the cell, \( T_r \) 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 \( (1.1 \text{ eV}) \), and \( P_{sun} \) the radiance. The manufacturer of the cell generally gives parameters \( \alpha \) 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

| 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 (\( \alpha \)) | \( 2.12 \times 10^{-3} \text{A/ºC} \) |
| Diode ideality factor (\( n \))              | 1.2                 |
| Series resistance (\( R_S \))                | 6.25 mΩ             |
| Parallel resistance (\( R_P \))              | 30 Ω                |
| Reverse saturation current (\( I_{rr} \))    | \( 1.7310 \times 10^{-8} \text{A} \) |

\[ I_{PV} = I_{ph} - \left[ \frac{q (V + I_{PV} \cdot R_s)}{n \cdot k_b \cdot T} - 1 \right] \frac{V_{PV} + I_{PV} \cdot R_s}{R_P} \]  
\[ I_r = I_{rr} \cdot \left( \frac{T}{T_r} \right)^{3/2} \cdot e^{\left[ \frac{q \cdot E_G}{n \cdot k_b \cdot \left( \frac{1}{T_r} - \frac{1}{T} \right)} \right]} \]  
\[ I_{ph} = \left[ I_{SC} + \alpha (T - T_r) \right] \cdot \frac{P_{sun}}{1000} \]
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 MPP 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 $V_{ref} = kV_{oc} \approx V_{MPK}$, dependent on the so-called voltage factor ($k$), and on open-circuit voltage of the PV panel ($V_{oc}$). 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 ($\Delta d$) 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 ($\Delta I/\Delta V$) 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 °C, respectively.

Figure 5. Simulation scheme of the PV system operating with a Buck converter and MPPT algorithms.
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 Tₜ values were previously adjusted to obtain an optimal relation speed of convergence and size of steady-state oscillations of the M PPT techniques to be compared in this work.
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 °C. 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. According to the expression, each MPPT/Converter combination is compared in terms of efficiency in power extracted from the PV panel (4).

\[
\eta(\%) = \frac{\int_0^T P_{PV} \, dt}{\int_0^T P_{MPP} \, dt} \times 100 = \frac{\sum_{i=1}^{n} P_{PV}^i \times 100}{\sum_{i=1}^{n} P_{MPP}^i} \quad (4)
\]

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

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 °C and 45 °C, increasing and then decreasing in steps of 10 °C every 0.1 s. Figure 9 shows the behavior of the PV system operating with the Buck converter and the three MPPT methods.
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 $S = 1000 \text{ W/m}^2$ and $T = 25 ^\circ \text{C}$, 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 97.098% value when $S = 250 \text{ W/m}^2$ and $T = 25 ^\circ \text{C}$, 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 performance in all the analyzed temperatures. 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 $S = 1000 \text{ W/m}^2$ and $T = 45 ^\circ \text{C}$, 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 $P_{MPP}$.

**Table 4. MPPT methods efficiency with Buck converter for variations of radiation with $T = 25 ^\circ \text{C}$.**

| $S$ (W/m²)   | P&O  | CV  | IncCond  |
|--------------|------|-----|----------|
| $S = 250$ W/m² | 99.975 | 99.971 | 97.098 |
| $S = 500$ W/m² | 99.986 | 99.965 | 99.946 |
| $S = 750$ W/m² | 99.979 | 99.967 | 99.970 |
| $S = 1000$ W/m² | 99.983 | 99.975 | 99.929 |

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

| $T$ (°C)  | P&O  | CV  | IncCond  |
|----------|------|-----|----------|
| $T = 15 ^\circ \text{C}$ | 99.970 | 99.967 | 98.461 |
| $T = 25 ^\circ \text{C}$ | 99.983 | 99.975 | 99.929 |
| $T = 35 ^\circ \text{C}$ | 99.987 | 99.979 | 99.809 |
| $T = 45 ^\circ \text{C}$ | 99.987 | 99.986 | 94.206 |
Figure 10. PV system operating with Buck converter and M PPT algorithms for variations in temperature with $S = 1000 \text{ W/m}^2$. (a) PV panel power. (b) PV panel voltage. (c) Duty cycle.

Figure 11. PV system operating with Buck-Boost and M PPT algorithms for radiation variations with $T = 25 \degree \text{C}$. (a) PV panel power. (b) PV panel voltage. (c) Duty cycle.
Table 6. MPPT methods efficiency with Buck-Boost converter for radiation variation with $T = 25$ °C.

| S = 250 W/m² | S = 500 W/m² | S = 750 W/m² | S = 1000 W/m² |
|-------------|-------------|-------------|-------------|
| PMPP = 20.77 W | PMPP = 43.00 W | PMPP = 65.28 W | PMPP = 87.31 W |
| VMPP = 16.79 V | VMPP = 17.23 V | VMPP = 17.41 V | 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 | 99.713 | 99.803 | 99.770 | 99.770 |
| Oscillation of power (W) around MPP | 20.77-20.37 $\Delta = 0.40$ | 43.00-42.82 $\Delta = 0.18$ | 65.27-64.86 $\Delta = 0.41$ | 87.31-86.76 $\Delta = 0.55$ |
| Oscillation of voltage (V) around MPP | 17.51-16.06 $\Delta = 1.45$ | 17.97-16.51 $\Delta = 1.34$ | 18.15-17.22 $\Delta = 0.93$ | 17.75-16.88 $\Delta = 0.85$ |

obtained with the CV method reaching 98.58% when $S = 250$ W/m² and $T = 25$ °C; 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 $T = 45$ °C; 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...
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.

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

| Temperature (°C) | PMPP (W) | VMPP (V) | Efficiency (%) | Oscillation of power (W) around MPP | Oscillation of voltage (V) around MPP |
|------------------|----------|----------|----------------|-----------------------------------|--------------------------------------|
| 15               | 91.01    | 18.22    | 99.70          | 91.01-90.34, Δ = 0.67            | 18.60-17.17, Δ = 0.93               |
| 25               | 87.31    | 17.51    | 99.70          | 87.31-86.76, Δ = 0.55            | 17.75-16.98, Δ = 0.77               |
| 35               | 83.60    | 16.78    | 99.80          | 83.60-83.19, Δ = 0.41            | 17.13-16.33, Δ = 0.80               |
| 45               | 79.87    | 16.04    | 99.70          | 79.87-79.51, Δ = 0.36            | 16.45-15.72, Δ = 0.73               |

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.
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 these oscillations occur around a level that, depending on the climatic condition, can present considerable deviations of the $V_{\text{MPP}}$, 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 $V_{\text{ref}} = kV_{\text{oc}} = 0.8 \times 21.7 \, \text{V} = 17.36 \, \text{V}$, used by the control is only an approximation of the $V_{\text{MPP}}$ 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 $V_{\text{ref}}$, to avoid losses of power due to the necessary disconnection of the PV module at the moment of measuring $V_{\text{oc}}$.

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 $V_{\text{MPP}}$ e $V_{\text{ref}}$ ($\Delta V_{\text{MPP-ref}} = V_{\text{MPP}} - V_{\text{ref}}$). As expected, the worst yields coincide with the highest obtained value of $\Delta V_{\text{MPP-ref}} = 1.32 \, \text{V}$, which happens when $T = 45 \, ^\circ \text{C}$ e $S = 1000 \, \text{W/m}^2$; 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 $\Delta V_{\text{MPP-ref}} = 0.05 \, \text{V}$ when $T = 25 \, ^\circ \text{C}$ e $S = 750 \, \text{W/m}^2$ reaching an efficiency of 99.97%, and in the case of the Buck-Boost for $\Delta V_{\text{MPP-ref}} = 0.13 \, \text{V}$ when $T = 25 \, ^\circ \text{C}$ e $S = 500 \, \text{W/m}^2$ achieving an efficiency of 99.77%.

**CONCLUSIONS**

This work has presented a comparative study of the performance of three classical MPP 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.

REFERENCES

[1] M. Eltawil, Z. Zhao. “MPPT techniques for photovoltaic applications”. Renewable and Sustainable Energy Reviews. Vol. 25, pp. 793-813. 2013. ISSN: 1364-0321.

[2] A. Gupta, Y. Chauhan, R. Kumar. “A comparative investigation of maximum power point tracking methods for solar PV system”. Solar Energy. Vol. 136, pp. 236-253. 2016. ISSN: 0038-092X.

[3] REN21. “Renewables 2018 Global Status Report”. Available: http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web-1.pdf. [accessed 26/07/2018].

[4] F. Zaions, J. Balbino, C. Baratieri, A. Stankiewicz. “Comparative analysis of buck and boost converters applied to different maximum power point tracking techniques for photovoltaic systems”. Brazilian Power Electronics Conference (CObEP). Juiz de Fora, Brazil. 19-22 November 2017.

[5] B. Jyoti, M. Manas, S. Sen. “Comparative study on Buck and Buck-Boost DC-DC converters for MPPT tracking for photovoltaic power systems”. Second International Conference on Computational Intelligence & Communication Technology (CICT). Ghaziabad, India. 12-13 February 2016.

[6] M. Taghvaea, M. Radzi, S. M osavain, H. Hashim, M. Hamiruce. “A current and future study on non-isolated dc-dc converters for photovoltaic applications”. Renewable and Sustainable Energy Reviews. Vol 17, pp. 216-227. 2013. ISSN: 1364-0321.

[7] N. Karamia, N. Moubayedb, R. Outbibc. “General review and classification of different MPPT techniques. Renewable and Sustainable Energy Reviews”. Vol 68, pp. 1-18. 2017. ISSN: 1364-0321.

[8] D. Verma, S. Nema, A. Shandilya, S. Dash. “Maximum power point tracking (MPPT) techniques: Recapitulation in solar photovoltaic systems”. Renewable and Sustainable Energy Reviews. Vol. 54, pp. 1018-1034. 2016. ISSN: 1364-0321.

[9] A. Reisi, M. Moradi, S. Jamasb. “Classification and comparison of maximum power point tracking techniques for photovoltaic system: A review”. Renewable and Sustainable Energy Reviews. Vol 19, pp. 433-443. 2013. ISSN: 1364-0321.

[10] P. Mohanty, G. Bhuvaneswari, R. Balasubramanian, N. Dhaliwal. “MATLAB based modeling to study the performance of different MPPT techniques used for solar PV system under various operating conditions”. Renewable and Sustainable Energy Reviews. Vol. 38, pp. 581-593. 2014. ISSN: 1364-0321.

[11] R. Faranda, S. Leva. “Energy comparison of MPPT techniques for PV systems”. WSEAS Transactions on Power Systems. Vol. 3, pp. 446-455. 2008. ISSN: 1790-5060.

[12] O. Ezinwanna, F. Zhongwena, L. Zhijun. “Energy performance and cost comparison of MPPT techniques for photovoltaics and other applications”. Energy Procedia. Vol. 107, pp. 297-303. 2017. ISSN: 1876-6102.
López, Seleme Jr. and M.F. Morais: Comparison of the performance of MPPT methods applied in converters Buck...

[13] G. Dileep, S. Singh. “Selection of non-isolated DC-DC converters for solar photovoltaic system”. Renewable and Sustainable Energy Reviews. Vol. 76, pp. 1230-1247. 2017.

[14] M. Bella, S. Perez, E. Duran, J. Enríquez. “New Single-Input, Multiple-Output Converter Topologies: Combining Single-Switch Nonisolated dc-dc Converters for Single-Input, Multiple-Output Applications”. IEEE Industrial Electronics Magazine. Vol. 10, pp. 6-20. 2016. ISSN: 1932-4529.

[15] R. Reshma, S. Sreejith. “Converter topologies in photovoltaic applications - A review”. Renewable and Sustainable Energy Reviews. Vol. 94, pp. 1-14. 2018. ISSN: 1364-0321.

[16] R. Coelho, F. Concer, D. Martins. “A Study of the basic DC-DC converters applied in maximum power point tracking”. Brazilian Power Electronics Conference (COBEP). Mato Grosso do Sul, Brazil. 27 September -1 October. 2009.

[17] C. Hua, C. Shen. “Study of maximum power tracking techniques and control of DC/DC converters for photovoltaic power system”. 29th Annual IEEE Power Electronics Specialists Conference. Fukuoka, Japan. 22-22 May 1998.

[18] J. Figueiredo, F. Tofoli, R. Alves. “Comparison of nonisolated DC-DC converters from the efficiency point of view”. Brazilian Power Electronics Conference (COBEP). Praia de Búzios, Brazil. 11-15 September. 2011.

[19] J. Enríquez, E. Durán, M. Sidrach de Cardona. J. Andújar. “Theoretical assessment of the maximum power point tracking efficiency of photovoltaic facilities with different converter topologies”. Solar Energy. Vol. 81, pp. 31-38. 2007. ISSN: 0038-092X.

[20] D. Kumar, M. K. Khaliuuzaman. “Comparing efficiency of PV array connected to DC-DC converters applying modified P&O algorithm in real time hardware”. 5th International Conference on Informatics, Electronics and Vision (ICIEV). Dhaka, Bangladesh. 13-14 May. 2016.

[21] A. Kchaou, A. Naamane, Y. Koubaa, N. Sirdi. “Comparative study of different M PPT techniques for a stand-alone PV system”. 17th International Conference on Sciences and Techniques of Automatic control & computer engineering (STA). Sousse, Tunisia. 19-21 December 2016.

[22] N. El Hichami, A. Abbou, S. M arhraoui, S. Rhali. “Comparison between both commands photovoltaic M PPT of the system: algorithm P&O and IncCond, using converter Boost”. International Conference on Engineering and Technology (ICET). Antalya, Turkey. 21-24 August 2017.

[23] L. El mentaly, A. Amghar, H. Sahsah. “Comparison between HC, FOCV and TG M PPT algorithms for PV solar systems using buck converter”. International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS). Fez, Morocco. 19-20 April 2017.

[24] H. Rezk, A. Eltamaly. “A comprehensive comparison of different M PPT techniques for photovoltaic systems”. Solar Energy. Vol. 112, pp. 1-11. 2015. ISSN: 0038-092X.

[25] M. Basoglu, B. Cakir. “Hardware based comparison of buck-boost converter topologies in M PPT systems”. 9th International Conference on Electrical and Electronics Engineering (ELECO). Bursa, Turkey. 26-28 November 2015.

[26] M. Dursun, A. Gorgun. “Analysis and Performance Comparison of DC-DC power converters used in photovoltaic systems”. 4th International conference on electrical and electronic engineering (ICEEE). Ankara, Turkey. 8-10 April 2017.

[27] B. Sah, G. Venkata. “A Comparative study of different M PPT techniques using different dc-dc converters in a standalone PV system”. IEEE Region 10 Conference (TENCON). Singapore, Singapore. 22-25 November. 2016.

[28] D. Hart. “Power Electronics”. McGraw Hill. First edition. Chapter 6, pp. 202-222. Indiana, USA. ISBN: 978-0-07-338067-4. 2011.

[29] H. Siddique, P. Xu, R. De Doncker. “Parameter extraction algorithm for one-diode model of PV panels based on datasheet values”. International Conference on Clean Electrical Power (ICCEP). Aigles, Italy. 11-13 June 2013.

[30] M. Mendes, D. Cruz. “Photovoltaic array model aimed to analyses in power electronics through simulation”. Brazilian journal of...
[31] Kyocera Corporation. “Data sheet of PV module Kyocera K C85TS”. Available: https://www.kyocerasolar.com/dealers/product-center/archives/spec-sheets/KC85TS.pdf. [accessed 27/08/2018]

[32] T. Esram, P. Chapman. “Comparison of photovoltaic array maximum power point tracking techniques”. IEEE Transactions on Energy Conversion. Vol. 22, pp. 439-449. 2007. ISSN: 0885-8969.

[33] D. Takeshi, W. Komatsu. “A MPPT algorithm implementation using FPGA for an experimental PV system”. 9th Brazilian Power Electronics Conference (COBEP). Santa Catarina, Brazil. 30 September - 4 October 2007.

[34] S. Jain, V. Agarwal. “Comparison of the performance of maximum power point tracking schemes applied to single-stage grid-connected photovoltaic systems”. IET Electric Power Applications. Vol. 1, pp. 753-762. 2007. ISSN: 1751-8660.

[35] M. Masoum, H. Dehbonei, E. Fuchs. “Theoretical and experimental analyses of photovoltaic systems with voltage and current based maximum power point tracking”. IEEE Transactions on Energy Conversion. Vol. 17, pp. 514-522. 2002. ISSN: 0885-8969.

[36] B. Bendib, H. Belmili, F. Krim. “A survey of the most used MPPT methods: Conventional and advanced algorithms applied for photovoltaic systems”. Renewable and Sustainable Energy Reviews. Vol. 45, pp. 637-648. 2015. ISSN: 1364-0321.

[37] N. Femia, G. Petrone, G. Spagnuolo, M. Vitelli. “Optimization of perturb and observe maximum power point tracking method”. IEEE Transactions on power electronics. Vol. 20, pp. 963-973. 2005. ISSN: 0885-8993.

[38] B. Subudhi, R. Pradhan. “A comparative study on maximum power point tracking techniques for photovoltaic power systems”. IEEE Transactions Sustainable Energy. Vol. 4, pp. 89-98. 2013. ISSN: 1949-3029.

[39] M. Osakada, K. Hussein, I. Muta, T. Hoshino. “Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions”. IEEE Proceedings - Generation, Transmission and Distribution. Vol. 142, pp. 59-64. 1995. ISSN: 1350-2360.

[40] Y. Cheddadi, F. Errahimi, E. Najia. “Design and verification of photovoltaic MPPT algorithm as an automotive based embedded software”. Solar Energy. Vol. 171, pp. 414-425. 2018. ISSN: 0038-092X.

[41] F. Liu, S. Duan, B. Liu, Y. Kang. “A variable step size INC MPPT method for pv systems”. IEEE Transactions on Industrial Electronics. Vol. 55, pp. 2622-2628. 2008. ISSN: 0278-0046.