INFLUENCE OF POWER CONVERTERS ON PV MAXIMUM POWER POINT TRACKING EFFICIENCY

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***Abstract* – Maximum power point trackers (MPPT) are employed to maximize the photovoltaic modules output power, since it is strongly affected by changes on the incident solar radiation, surface temperature and load-type. Basically, a MPPT consists on a dc-dc converter (hardware) controlled by a tracking algorithm (software) and the combination of both, hardware and software, defines the tracking efficiency. This paper shows that even when the most accurate algorithm is employed, the maximum power point cannot be tracked, since its imposition as operating point depends on the dc-dc converter static feature and the load-type connected to its output. For validating the concept, the main dc-dc converters, i.e., Buck, Boost, Buck-Boost, Cuk, SEPIC and Zeta are analyzed considering two load-types: resistive and capacitive (regulated dc bus or battery). Simulation and experimental results are compared in order to confirm the theoretical analysis.**

***Keywords* - DC-DC Power Converter, Maximum Power Point Trackers, Photovoltaic, Temperature.**

I. INTRODUCTION

Renewable energy sources are becoming a promissory alternative for clean and sustainable electricity generation, in which photovoltaic (PV) systems are gaining prominence mainly due to the modules efficiency increasing, cost reduction and political incitement.

Unlike voltage or current sources, PV modules cannot naturally impose a specified voltage or current across their terminals, due to their strong dependence on solar radiation and surface temperature, as is exemplified by Figure 1 [1].

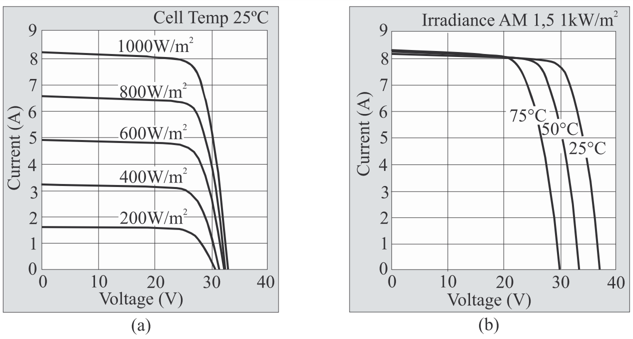

Fig. 1. PV module I-V generation curves: (a) under constant cell temperature and (b) under constant solar radiation.

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In order to avoid hard fluctuations on the PV modules output power and ensure their operation with the highest efficiency, Maximum Power Point Trackers (MPPT) are generally employed.

In most of applications, a MPPT is accomplished thought a dc-dc converter (hardware), a tracking algorithm (software) and external sensors (usually voltage, current or both), as depicts Figure 2.

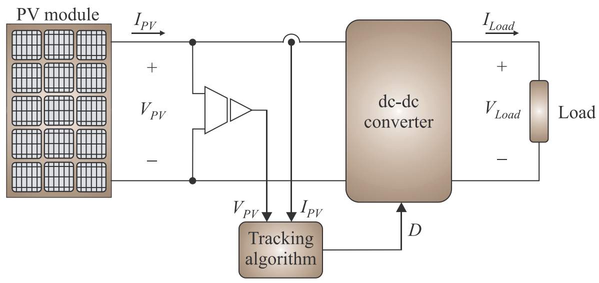

Fig. 2. Traditional MPPT obtained by the arragement of a dc-dc converter (hardware), a tracking algorithm (software) and voltage and current sensors.

From the software point of view, the most commonly applied tracking algorithms are Perturb and Observe (P&O) and Incremental conductance (IncCond). P&O method is simple, however it failure to track the MPP under abrupt changes on solar radiation and present oscillations around the MPP on steady-state [2-5]. IncCond technique is accurate, nevertheless, its implementation is more complex and similarly to the P&O method, it needs a voltage and a current sensor for properly work [6-10].

Several other algorithms, like constant voltage method [5, 11-12], open circuit voltage method [13, 14], short circuit current method [15], Beta method [5] and temperature-based method [16, 17] are also listed on the literature, as alternative.

On the other hand, from the hardware point of view, step up converters, like boost and similar, are frequently applied as tracking converters. This requirement comes from its simplicity, cost, number of components and from the voltage gain needed for this kind of application [18, 19].

Based on the exposed, defining η_S as the tracking algorithm (software) efficiency and η_H as the dc-dc converter (hardware) efficiency, it is possible to found the global tracking efficiency η_G, given by

$$\eta_G = \eta_S \eta_H . \quad (1)$$

For maximizing the algorithm efficiency η_S, the employed tracking method must ensure fast dynamic response and no oscillation in steady-state. Those both features are achieved by the temperature-based method presented in [16], whose tracking factor is established close to 99% [17].

Furthermore, for maximizing the hardware performance η_H, high efficiency dc-dc converters must be used. Commonly, non-insulated dc-dc converters are required in those applications, resulting in conversion efficiencies higher than 95%.

Nevertheless, the employment of high performance dc-dc converters and accurate tracking algorithms are not enough to guarantee the PV array operation on the MPP. This drawback comes from the combination of load and generation curves, whose intersection defines two sectors on the I-V plan: tracking and non tracking regions. Note that PV generation curve depends on both, solar radiation and temperature, while the equivalent load measured from the PV module terminals depends on the dc-dc converter and on its output load.

In [20] is presented a previous analysis describing how the static gain of dc-dc converters may affect the tracking efficiency of MPPT systems, where the Buck, Boost, Buck-Boost, Cuk, SEPIC and Zeta converters were analyzed considering a resistive load-type. As result, the authors concluded that both, Buck and Boost converters were unable to track the MPP for a full range of variation on solar radiation and temperature.

In this paper, the analysis proposed by [20] is reviewed and extended in order to describe the influence of power converters when capacitive loads are considered. Capacitive loads are commonly present in two stage grid connected PV systems, as an intermediary regulated dc-bus, according to Figure. 3. Although this regulated dc-bus behaviors as input source for the second stage (inverter), from the first stage (MPPT) it can be modeled as an equivalent capacitive (constant voltage) load.

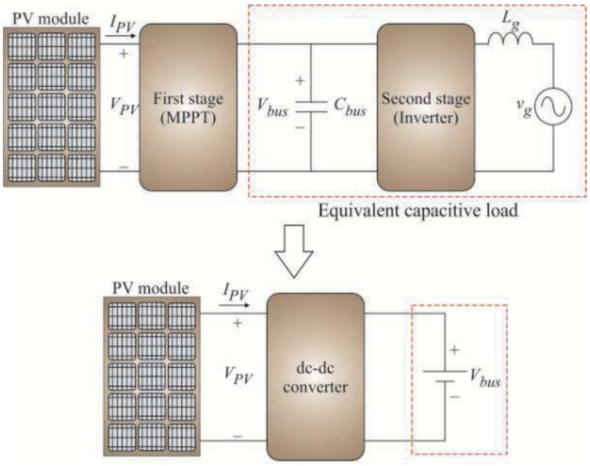

Fig. 3. Typical two stage grid-connected PV system.

II. MPPT FROM THE DC-DC CONVERTER POINT OF VIEW: RESISTIVE LOAD-TYPE

The operating point of a photovoltaic system is defined by the I-V generation and load curves intersection. For understanding how it occurs, firstly considerer a PV module supplying a resistive load, as depicts Figure 4. The load curve is accomplished by the Ohm's Law, in accordance with

$$I_{PV} = \frac{V_{PV}}{R} \tag{2}$$

while the generation curve is related to the PV I-V curve. Both curves are represented at Figure 5.

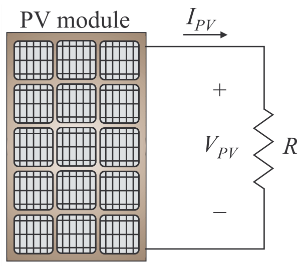

Fig. 4. PV module supplying a resistive load.

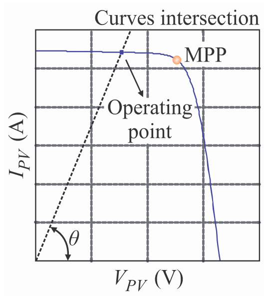

Fig. 5. Definition of the system operating point by the I-V and load curves intersection.

Even when the load resistance is set to intercept the generation curve exactly on the MPP, it is no possible to ensure the maximum power transfer for long time intervals, once when solar radiation or temperature change, the MPP is relocated on the I-V plan.

For solving this problem, in order to maintain the system always operating on the MPP, the load curve should be modified according to solar radiation or temperature changes. For example, in Figure 6, if the PV generation curve is *I-V 1* and the load curve is *Load 1*, the maximum power point is given by *MPP 1*.

Now, considering a solar radiation and temperature change, the generation curve comes from *I-V 1* to *I-V 2*. In this situation, keeping the same load curve (*Load 1*), the system operating point is established at *X2*, i.e., out of the MPP. However, if the load curve is modified from *Load 1* to *Load 2*, the system backs to operate on the MPP, in this case, *MPP 2*.

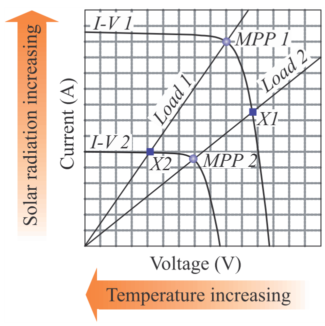

Fig. 6. I-V and load curves intersection for defining the PV system operating point.

Evidently, to modify the load curve in accordance with variations of solar radiation and temperature is not a suitable solution, since the load is defined by the user. Nevertheless, if a dc-dc converter is interposed between the PV module and the load, it is possible to control the converter duty cycle in order to emulate a variable load from the PV module terminals point of view, even when a fixed load is employed. The arrangement presented at Figure 7, composed by a PV module, a dc-dc converter and a load, defines the hardware of a maximum power point tracking system.

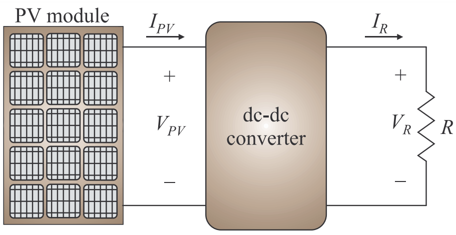

Fig. 7. Maximum point tracker system supllying a resistive load.

It is important to emphasize that the tracking system will present distinct behaviors depending on the employed dc-dc converter. In this section, Buck, Buck-Boost, Boost, Cuk, SEPIC and Zeta converters will be analyzed.

When a resistive load is connected to the dc-dc converter, it is possible to write

$$V_R = RI_R . \tag{3}$$

Taking into account a literal dc-dc converter static gain G, the input system variables (V_{PV} and I_{PV}) can strictly be associated to the output ones (V_R and I_R), through

$$G = \frac{V_R}{V_{PV}} \tag{4}$$

$$G = \frac{I_{PV}}{I_R} . \tag{5}$$

Isolating V_R in (4) and I_R in (5) and substituting the found results into (3), it is possible to obtain

$$\frac{V_{PV}}{I_{PV}} = \frac{R}{G^2} . \tag{6}$$

The term V_{PV}/I_{PV} describes the effective resistance obtained from the PV module terminals. In other words, the dc-dc converter emulates a variable resistance, whose value can be modulated in function of the converter static gain G. This conclusion allows redrawing Figure 7 as Figure 8, mathematically described by

$$V_{PV} = \frac{R}{G^2} I_{PV} . \tag{7}$$

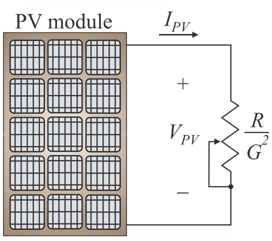

Fig. 8. Effective resistance obtained from the PV module terminals.

When plotted on the I-V plan, (7) results in a straight line whose slope angle θ is modified according to the converter static gain G, as is described by

$$\theta = \text{atan}\left(\frac{G^2}{R}\right). \tag{8}$$

Table I presents static gain G, as a function of the duty cycle D, for the main non-insulated dc-dc converters operating in continuous conduction mode (CCM).

Applying the results from Table I in (8), it is possible to describe the effective slope angle θ as a variable dependent on the duty cycle D. As consequence, Table II is obtained.

TABLE I
Main non-isolated dc-dc converters static gain in CCM.

dc-dc power converter	Static Gain
Buck	$G = D$
Boost	$G = \frac{1}{1-D}$
Buck-Boost, Cuk, SEPIC and Zeta	$G = \frac{D}{1-D}$

TABLE II
Load curve slope angle as a function of the duty cycle *D*.

dc-dc power converter	Effective slope angle θ
Buck	$\theta\text{=atan}\left(\frac{D^2}{R}\right)$
Boost	$\theta\text{=atan}\left[\frac{1}{(1-D)^2 R}\right]$
Buck-Boost, Cuk, SEPIC and Zeta	$\theta\text{=atan}\left[\frac{D^2}{(1-D)^2 R}\right]$

Theoretically, the duty cycle varies from 0 to 1, thus, the effective slope angle becomes restricted to a range whose limits are dependent on the employed dc-dc converter. Considering a Buck converter, for D=0, it is possible to rewrite (8) as

$$\theta\big|_{D=0} = \text{atan}\left(\frac{0^2}{R}\right) = 0 . \tag{9}$$

Otherwise, if the duty cycle is set on its high value, D=1, (8) may be written as

$$\theta\big|_{D=1} = \text{atan}\left(\frac{1}{R}\right). \tag{10}$$

In other to extend the presented analysis for further converters, a similar procedure can be applied, resulting at Table III, from where it is noticed that effective load slope angle defines a sector on the I-V plan where the maximum power can be tracked. For a better understanding, Table III is explained through Figure 9, in which two distinct regions are identified: tracking and non tracking regions.

In order to validate the proposed theory, Buck, Boost and Buck-Boost converters were designed and assembled in laboratory, according to Figure 10. For achieving the experimental tests, the converters duty cycle was linearly varied from 0 to 1, while PV voltage and current were measured. By the use of a scope at XY mode, the I-V curve was acquired, and the found results are shown at Figure 11. Note that the I-V curve is partially plotted on the I-V plan when Buck and Boost converters were tested, and on the whole I-V plan, when buck-boost converter were considered. Additionally, the area in which the I-V curves were plotted is in accordance with the tracking region, previously defined by the theory for each converter.

TABLE II
Minimum and maximum effective slope angle related to the main non-insulated dc-dc converters

dc-dc power converter	Minimum effective slope angle	Maximum effective slope angle
Buck	$\theta\|_{D=0}=0$	$\theta\|_{D=1}=\mathrm{atan}\left(\frac{1}{R}\right)$
Boost	$\theta\|_{D=0}=\mathrm{atan}\left(\frac{1}{R}\right)$	$\theta\|_{D=1}=90°$
Buck-Boost, Cuk, SEPIC and Zeta	$\theta\|_{D=0}=0$	$\theta\|_{D=1}=90°$

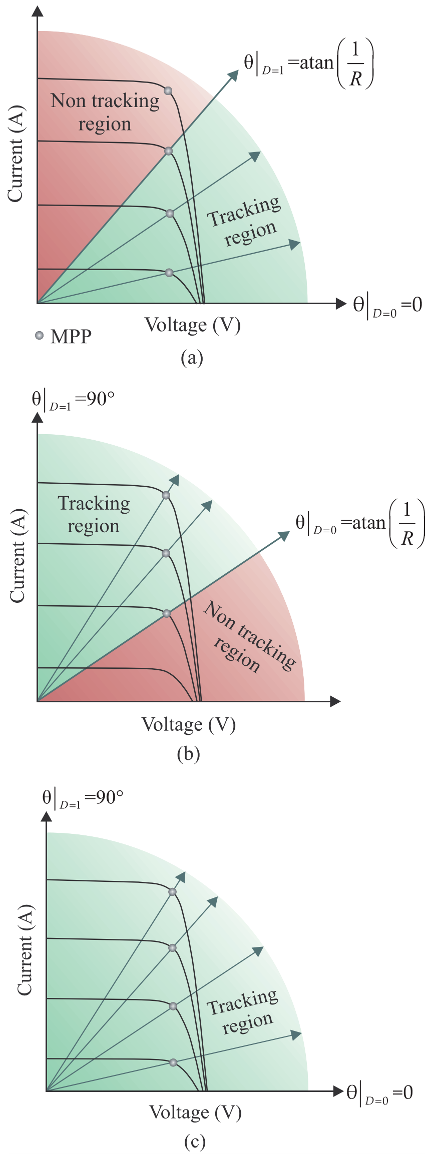

Fig. 9. Tracking and non tracking regions for: (a) Buck converter; (b) Boost converter and (c) Buck-Boost, Cuk, SEPIC and Zeta converters.

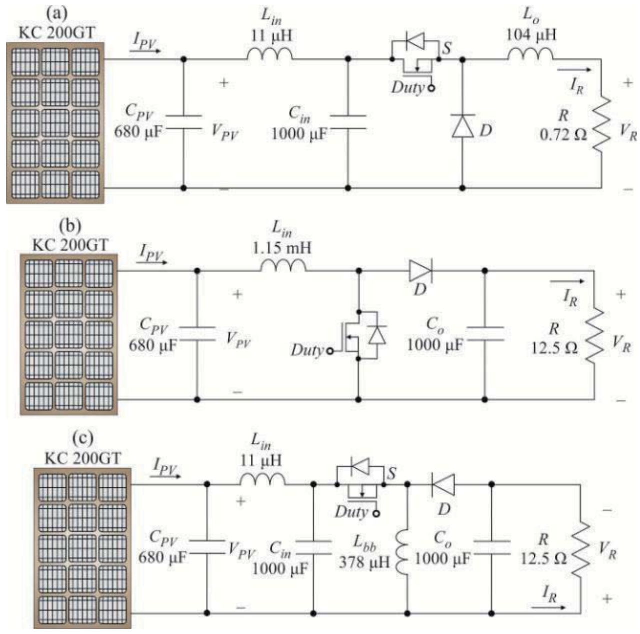

Fig. 10. (a) Buck, (b) Boost and (c) Buck-Boost power converters.

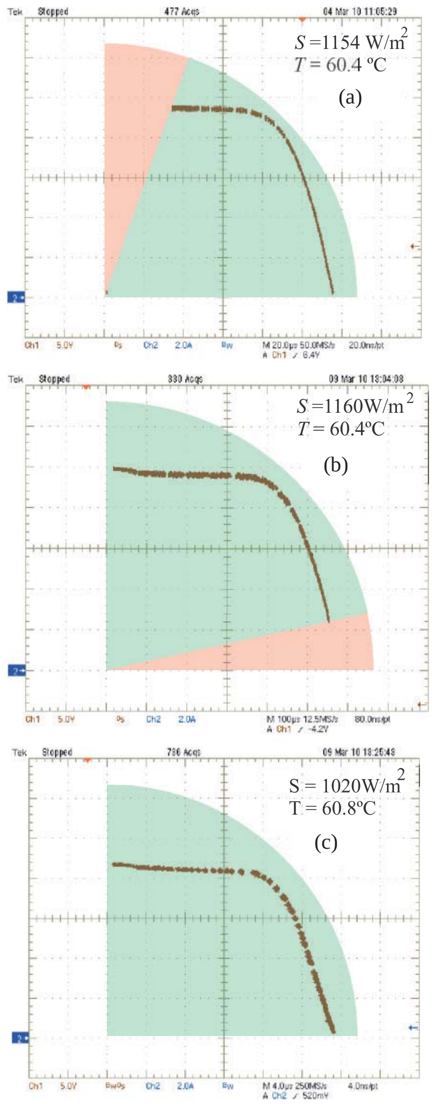

Fig. 11. Experimental results for (a) Buck, (b) Boost and (c) Buck-Boost converters.

III. MPPT FROM THE DC-DC CONVERTER POINT OF VIEW: CAPACITIVE LOAD-TYPE

The analysis concerning to dc-dc converters operating as MPPT when a capacitive load-type (or battery bank) is considered follows the same procedures presented for resistive loads. For beginning, consider the MPPT system shown in Figure 12, in which a dc voltage source is supplied by a PV module through a literal dc-dc converter.

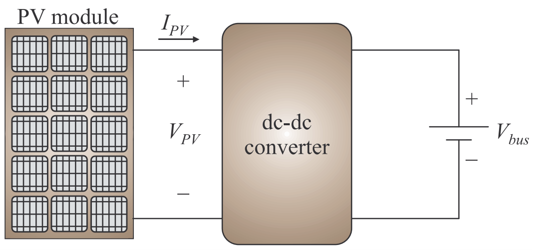

Fig. 12. MPPT supplying a constant voltage load-type.

In this case, the converter output voltage is actively imposed, permitting to model both, dc-dc converter and capacitive load, as a controlled voltage source, in accordance with Figure 13. The controlled voltage source is defined by

$$V_{PV} = \frac{V_{bus}}{G}. \tag{11}$$

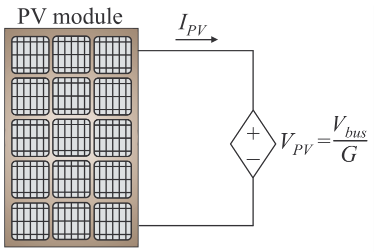

Fig. 13. Equivalent MPPT system obtained from the PV module terminals.

Taking into account the static gain G presented at Table I, it is possible to define the equivalent voltage source related to each dc-dc converter as a function of the duty cycle D, resulting on Table IV.

TABLE IV
Equivalent voltage source value defined in function of the duty cycle *D*

DC-DC power converter	Equivalent voltage source value
Buck	$V_{PV} = \frac{V_{bus}}{D}$
Boost	$V_{PV} = (1-D)V_{bus}$
Buck-Boost, Cuk, SEPIC and Zeta	$V_{PV} = \frac{(1-D)}{D}V_{bus}$

Due to the duty cycle range restriction, $0 < D < 1$, the voltage imposed by the equivalent controlled voltage source across the PV module terminals is also limited. If Buck converter is considered, it is possible to derive

$$V_{PV}\big|_{D=0} = \frac{V_{bus}}{0} \to \infty \tag{12}$$

$$V_{PV}\big|_{D=1} = V_{bus}. \tag{13}$$

Still, it is important to emphasize that the maximum voltage across the PV module terminals is defined by its open circuit voltage V_{oc}, thus (12) is in practice described by

$$V_{PV}\big|_{D=D_{\min}} = \frac{V_{bus}}{D_{\min}} = V_{oc}. \tag{14}$$

Extending the above analysis for further dc-dc converters, Table V is obtained.

TABLE V
Minimum and maximum voltage values across the PV module terminals.

dc-dc power converter	Minimum voltage across the PV module terminals	Maximum voltage across the PV module terminals
Buck	$V_{PV}\big\|_{D=1} = V_{bus}$	$V_{PV}\big\|_{D=D_{\min}} = V_{oc}$
Boost	$V_{PV}\big\|_{D=1} = 0\ \text{V}$	$V_{PV}\big\|_{D=0} = V_{bus}$
Buck-Boost, Cuk, SEPIC and Zeta	$V_{PV}\big\|_{D=1} = 0\ \text{V}$	$V_{PV}\big\|_{D=D_{\min}} = V_{oc}$

Graphical representation allows understanding how the dc-dc converter static gain impacts on the tracking efficiency when constant voltage loads are employed, as Figure 14.

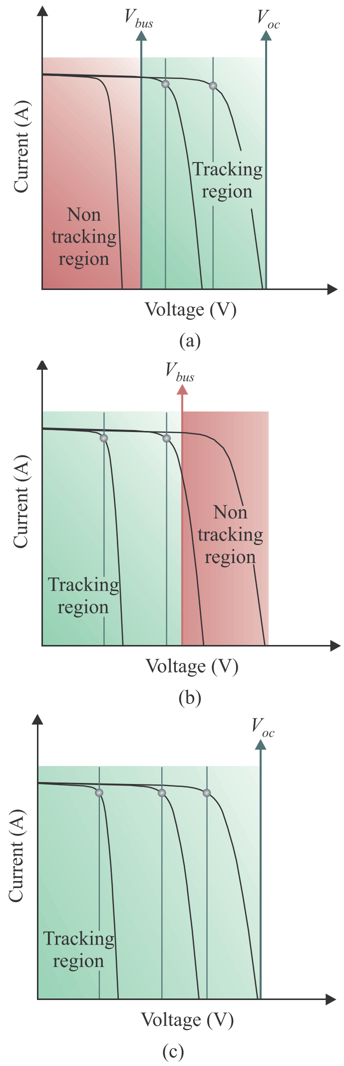

Fig. 14. Tracking and non tracking regions for: (a) Buck; (b) Boost and (c) Buck-Boost, Cuk, SEPIC and Zeta converters.

If the maximum power point is located inside the tracking region, the dc-dc converter is able to adapt the voltage across the PV module terminals until establishes its operation on the MPP, ensuring the maximum power transfer from PV module to the output load. However, if the MPP is located out of the tracking region, even when the duty cycle is varied from zero to the unit, the MPP cannot be imposed as operating point.

According to [21], the maximum power point voltage (V_{mp}) is mathematically given by

$$V_{mp} = V_{mp}^{STC} + (T - T^{STC})\mu_{Vmp} \tag{15}$$

where V_{mp} is the PV module output voltage at MPP for any PV module surface temperature (T), V_{mp}^{STC} is PV module output voltage at MPP obtained from datasheet (specified at STC - Standard Test Condition - T^{STC}=25 °C) and μ_{Vmp} is the temperature voltage coefficient (V/°C), also obtained at PV module datasheet.

From (15) it is note that when the temperature increases the MPP is moved to the left and when the temperature decreases, to the right. Therefore, it is possible to define a range of temperature variation in which the dc-dc converter can tracks the maximum power point. For instance, consider the Buck converter, whose input voltage V_{mp} is necessary higher than the output one V_{bus}, implying on

$$V_{mp} > V_{bus}\,. \tag{16}$$

Therefore, substituting (16) into (15) and isolating T in the found result, it is possible to write

$$T \le T^{STC} - \frac{V_{bus} - V_{mp}^{STC}}{\left|\mu_{Vmp}\right|}\,. \tag{17}$$

Again, extending the above analysis for further converters, Table VI is achieved.

TABLE VI
Temperature range for ensuring the system operation on the tracking region

DC-DC power converter	Temperature range
Buck	$T \le T^{STC} - \frac{V_{bus} - V_{mp}^{STC}}{\left\|\mu_{Vmp}\right\|}$
Boost	$T \ge T^{STC} - \frac{V_{bus} - V_{mp}^{STC}}{\left\|\mu_{Vmp}\right\|}$
Buck-Boost, Cuk, SEPIC and Zeta	$-\infty < T < \infty$

In order to validate the theoretical results, some simulations concerning Buck and Boost converters were achieved. The KC200GT data [1] are presented at Table VII, from where Table VIII can be derived.

Simulations were accomplished considering the same converters presented on Figure 10, however, the load were substituted by a battery bank, in order to ensure constant voltage at the converter output. The PV module mathematical model, employed during simulations, was extracted from [22].

TABLE VII
PV module specification at STC (KC200GT)

PV module parameter	Value
V_{mp}^{STC}	26.3 V
I_{mp}^{STC}	7.61 A
P_{mp}^{STC}	200 W
μ_{Vmp}	-0.14 V/°C
T^{STC}	25 °C

TABLE VIII
Specification of the dc-dc converter output voltage and temperature range for operation in the tracking region.

dc-dc power converter	Output bus voltage	Temperature range for operation at MPP
Buck	20 V	$T \le 70$ °C
Boost	28 V	$T \ge 12.8$ °C
Buck-Boost, Cuk, SEPIC and Zeta	30 V	$-\infty < T < \infty$

Figure 15 shows the PV module surface temperature evaluation during the simulations concerning to the Buck converter.

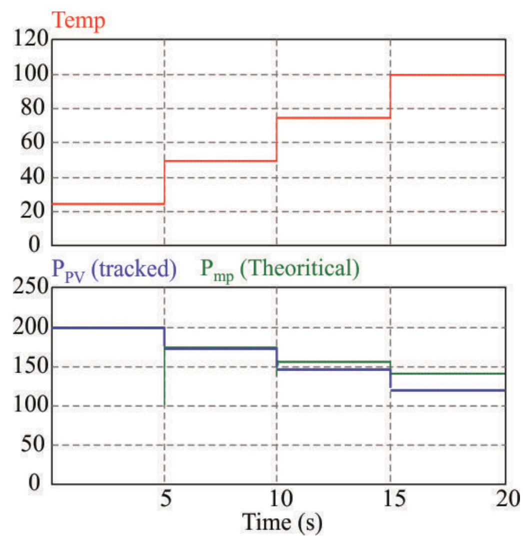

Fig. 15. Simulation results for Buck converter.

From the simulation results it was verified that the MPPT system presents an excellent performance until the PV module surface temperature reaches 70 ºC. After this value, the power delivered by the PV module to the output load is dissimilar to the MPP, since, in this condition, the Buck converter operates at the non tracking region, as shows Table VIII.

Simulation results obtained for Boost converter, Figure 16, show that the tracking only occurs after the PV module surface temperature becomes higher than 12.8 ºC, according to Table VIII.

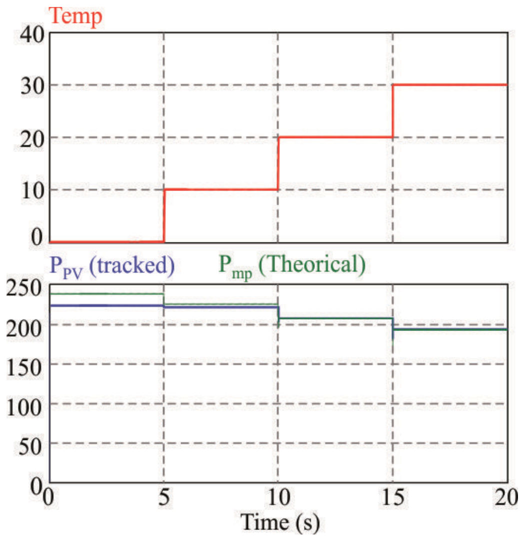

Fig. 16. Simulation results for Boost converter.

IV. CONCLUSION

This paper has presented an analysis concerning the influence of the main dc-dc converters in PV MPPT applications. From the theoretical analysis, it was verified that four parameters directly influence the tracking efficiency:

1) Solar radiation;
2) PV module surface temperature;
3) Load-type;
4) dc-dc converter employed as MPPT.

It was also verified that even when accurate tracking algorithms are employed (like temperature-based method or Incremental Conductance method), the tracking efficiency is not guaranteed, since the dc-dc converter static gain is a key feature on determination of the tracking factor.

From the analysis considering resistive loads, it is concluded that Buck-Boost, Cuk, SEPIC and Zeta are proper converters for tracking applications, while Buck and Boost present some restrictions and its performance as MPPT is ensured only for a limited range of solar radiation and temperature variations.

Furthermore, when capacitive loads are considered, Boost converter may also be a proper choice, once as the temperature increases, the MPP is naturally moved to the left, incoming more and more to the tracking region.

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REFERENCES

[1] KC200GT photovoltaic mdule datasheet.

[2] T. Chee Wei, T. C. Green, and C. A. Hernandez-Aramburo. “Analysis of perturb and observe maximum power point tracking algorithm for photovoltaic applications”, *in 2nd IEEE International Power and Energy Conference*, pp. 237-242, 2008.

[3] N. Fermia, D. Granozio, G. Petrone, and M. Vitelli. "Predictive & Adaptive MPPT Perturb and Observe Method" *in IEEE Transactions on Aerospace and Electronic Systems*, vol. 43, pp. 934-950, 2007.

[4] J. Youngseok, S. Junghun, Y. Gwonjong, and C. Jaeho. "Improved perturbation and observation method (IP&O) of MPPT control for photovoltaic power systems" *in Photovoltaic Specialists Conference*, pp. 1788-1791, 2005.

[5] M. A. G. d. Brito, L. G. Junior, L. P. Sampaio, and C. A. Canesin. "Avaliação das principais técnicas para obtenção de MPPT de painéis fotovoltaicos" *in IEEE/IAS International Conference on Industry Applications*, pp. 1-6, 2010.

[6] L. Bangyin, D. Shanxu, L. Fei, and X. Pengwei. "Analysis and Improvement of Maximum Power Point Tracking Algorithm Based on Incremental Conductance Method for Photovoltaic Array" *in 7th International Conference on Power Electronics and Drive Systems*, pp. 637-641, 2007.

[7] F. Boico and B. Lehman. "Study of Different Implementation Approaches for a Maximum Power Point Tracker" *in IEEE Workshops on Computers in Power Electronics*, pp. 15-21, 2006.

[8] D. Menniti, A. Burgio, N. Sorrentino, A. Pinnarelli, and G. Brusco. "An incremental conductance method with variable step size for MPPT: Design and implementation," *in 10th International Conference on Electrical Power Quality and Utilization*, pp. 1-5, 2009.

[9] Q. Shihong, W. Min, C. Teng, and Y. Xiangling. "Comparative analysis of incremental conductance and perturb-and-observation methods to implement MPPT in photovoltaic system" *in International Conference on Electrical and Control Engineering*, pp. 5792-5795, 2011.

[10] X. Zhou, D. Song, Y. Ma, and D. Cheng. "The simulation and design for MPPT of PV system Based on Incremental Conductance Method" *in International Conference on Information Engineering*, pp. 314-317, 2010.

[11] D. P. Hohm and M. E. Ropp, "Comparative study of maximum power point tracking algorithms using an experimental, programmable, maximum power point tracking test bed" *in Photovoltaic Specialists Conference*, 2000, pp.1699-1702, 2000.

[12] D. Sera, T. Kerekes, R. Teodorescu, and F. Blaabjerg. "Improved MPPT Algorithms for Rapidly Changing Environmental Conditions" *in 12th International Power Electronics and Motion Control Conference*, pp. 1614-1619, 2006.

[13] J. Ghaisari, M. Habibi, and A. Bakhshai. "An MPPT Controller Design for Photovoltaic (PV) Systems Based on the Optimal Voltage Factor Tracking" *in Electrical Power Conference*, pp. 359-362, 2007.

[14] L. C. Wu and T. e. Cheung. "Advanced Algorithm for MPPT Control of Photovoltaic Systems," *in Canadian Solar Buildings Conference Montreal*, pp. 217-233, 2004.

[15] T. Noguchi, S. Togashi, and R. Nakamoto. "Short-current pulse-based maximum-power-point tracking

method for multiple photovoltaic-and-converter module system," *in IEEE Transactions on Industrial Electronics*, vol. 49, pp. 217-223, 2002

[16] R. F. Coelho, F. M. Concer, and D. C. Martins. "A MPPT approach based on temperature measurements applied in PV systems" *in IEEE International Conference on Sustainable Energy Technologies,* pp. 1-6, 2010.

[17] M. A. G. de Brito, L. G. Junior, L. P. Sampaio, G. A. e Melo, and C. A. Canesin. "Main maximum power point tracking strategies intended for photovoltaics," *in Brazilian Power Electronics Conference,* pp. 524-530, 2011.

[18] W. Y. Choi, J. S. Yoo and J.Y. Choi. "High efficiency dc-dc converter with high step-up gain for low PV voltage sources" *in 8th IEEE International Conference on Power Electronics*, pp.1161-1163, 2011.

[19] S.M, Mukhtar. A.R.M, Saad and N.H, Hanafi. "A high efficiency microcontroller-based step-up push-pull DC-DC converter for PV inverter" *in IEEE International Conference on Power and Energy*, pp.141-145, 2010.

[20] Coelho, R.F; Concer, F.M. and Martins, D. “A Study of the Basic DC-DC converters Applied in Maximum Power Point Tracking”. *In 10th Brazilian Power Electronics Conference*, pp. 673-67, 2009.

[21] Coelho, R.F, Concer, F.M and Martins, D.C. "A MPPT approach based on temperature measurements applied in PV systems" *in 9th IEEE/IAS International Conference on Industry Applications*, pp.1-6, 2010.

[22] Coelho, R.F; Concer, F.M. and Martins, D. C. “A Proposed Photovoltaic Module and Array Mathematical Modelling Destined to Simulation” *in IEEE International Symposium on Industrial Electronics*, pp. 1624-1629, 2009.

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