DC-DC CONVERTERS IN A MULTI-STRING CONFIGURATION APPLIED TO A STAND-ALONE PHOTOVOLTAIC SYSTEM

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***Abstract* –As an alternative to centralized autonomous photovoltaic systems, this paper proposes a modular configuration that utilizes a distributed input energy processing, maximum power point tracking and a bidirectional converter to control the battery bank power flow. Experimental results demonstrate that the proposed system presented an increase of 16% on the generated energy at the DC bus, in situations in which one or more photovoltaic panels are shaded, damaged or aged.**

***Keywords* - MPPT, Multi-String Converters, Photovoltaic Systems.**

I. INTRODUCTION

Demand for electricity in the worldwide has grown dramatically over the last decades. This situation, besides the fact that our society has become heavily technologically dependent, has increased the requirement for additional provision of electrical energy. Unfortunately, the investments on the electrical energy generation sector do not had been compatible with this demand growing, leading some countries to experiment a beginning of a collapse in their energetic system, inducing a global warning about this issue. Furthermore, the energy generation in the world is highly dependent of non-renewable energy sources derived from fossil fuel, which represents an important negative environmental impact.

The concern of the society regarding environmental problems and the shortage of fossil fuels have led to an increased interest in alternative ways for solving the issue of the growing global energy demand, where ecologically correct solutions are highly desired [3].

Among all alternative sources, photovoltaic (PV) energy has the advantage of being one of the primary sources that produces less pollution. Also, it is renewable, silent, modular and has a short period of installation. Another feature which makes PV energy more attractive is linked with the fact that this system can locally generate energy, without the need of long transmission lines, reducing the losses, and generating a low environmental impact [1, 2].

PV systems can be classified as: grid-connected systems and stand-alone systems.

Grid-connected systems are characterized by the absence of an energy storage system. These systems directly deliver the generated/excess energy to the grid, being considered as a complementary power source to the utility.

On the other hand, stand-alone photovoltaic systems make use of energy storage system, usually implemented by a battery bank [1, 3]. In these systems all load is only supplied by the generated energy from the photovoltaic panels. These systems are considered as an alternative ecologically attractive and economically viable of electrical energy generation for remote communities and isolated residences, distant from grid distribution lines [1, 4]. However, in such systems, the battery bank is considered as one of the most expensive components of the whole system [1, 5, 6], representing up to 15% of initial costs for the installation of a photovoltaic system, or even up to 46% when is considered the maintenance costs [7]. This cost increase is mainly due to ineffective charge and discharge management techniques of the battery bank, what can lead to a larger number of replacements of the batteries.

Concerning the possible configurations of PV systems, the centralized topology is, up to now, the most widely used. Owing to the employment of a single converter to perform the maximum power point tracking (MPPT), the generation capability of the PV array is not fully utilized in situations in which the panels are shaded, damaged and/or aged, contributing to decrease the efficiency and increase the costs of the generated energy of such systems.

As an alternative to this configuration, this paper proposes a stand-alone photovoltaic system which uses in the input stage a distributed energy configuration. This configuration provides a better utilization of the energy generated by the panels, through individualized maximum power point tracking, as well as a better management of the stored energy in the battery bank, aiming at an increased life cycle and a reduction in the maintenance costs.

II. CENTRALIZED STAND-ALONE PHOTOVOLTAIC SYSTEM

Figure 1, show an stand-alone photovoltaic centralized system utilized to provide energy for residences sited at remote locations, far from grid distribution lines [4, 5, 8].

These systems are composed by a single array of photovoltaic panels, implemented in series and/or parallel connection, depending on the power level of the system. Moreover, these systems have a charge controller (which protects the battery bank from overcharges and/or overdischarges and realizes the maximum power point tracking) and a DC-AC converter. Generally, the battery bank is connected in series with the energy flow, reducing the life cycle of the batteries, due to the fact that it will be charged/discharged continuously.

The employment of a single DC-DC converter to realize the maximum power point tracking also represents a drawback for this topology, given the low utilization of the generated energy in those situations in which one or more photovoltaic panels are exposed to shading, or in cases of failure and defects [9-16].

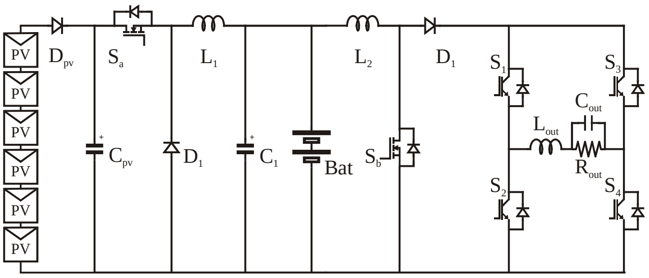


Fig. 1. Centralized Stand-alone Photovoltaic System

This reduction in the efficiency is due to the fact that in a photovoltaic array, where the panels are connected in series, all of them will conduct the current from the shaded panel [14, 17], being forced to work away from their maximum power points.

Owing to the fact that in the centralized systems the energy conversion is made by a single converter, the reliability of such systems is reduced when compared to other systems which utilize a decentralized configuration. This is due to the fact that in case of failure of the power converter, the energy supply to the load is completely shutdown, as well as when the converter is being repaired and also during panel or battery replacements.

III. PROPOSED DECENTRALIZED STAND-ALONE PHOTOVOLTAIC SYSTEM

As mentioned in [11], the decentralized configurations were developed for utilization in the “1000 Roofs Program”, funded by the German Federal Government. Nowadays, they are largely utilized in grid-connected photovoltaic systems as mentioned in [10-12, 18].

This configuration offers some advantages when compared to centralized configurations, mainly in cases of shading/defect of one or more panels, where this configuration provides a better utilization of the generated energy by the photovoltaic panels. However, this configuration has not been explored yet for applications in stand-alone photovoltaic systems, where modularity would provide better employment of the generated energy by the photovoltaic panels, as well as would increase system reliability. This is due to the fact that, notwithstanding the failure of one of the input converters, the system can maintain delivering partially energy to the load. This possibility minimizes an important drawback when treating of energy systems with a single primary source.

The proposed decentralized system, shown in figure 2, is based on the topologies utilized in grid-connected systems, which were presented in [10, 14, 15, 19]. Its main feature is to separate the PV array in strings, where each of them has its own DC-DC boost converter. The DC bus is obtained by series connection of the output capacitors of these converters. A full-bridge inverter fed by the DC bus provides energy to the AC load. It also distinguishes from traditional topologies for stand-alone photovoltaic systems because it features integrated buck and boost converters, with bi-directional power flow control, dedicated to the battery bank. It provides a better control of the charge and discharge processes of the batteries, allowing a longer life cycle and reduced costs regarding the maintenance of the system.

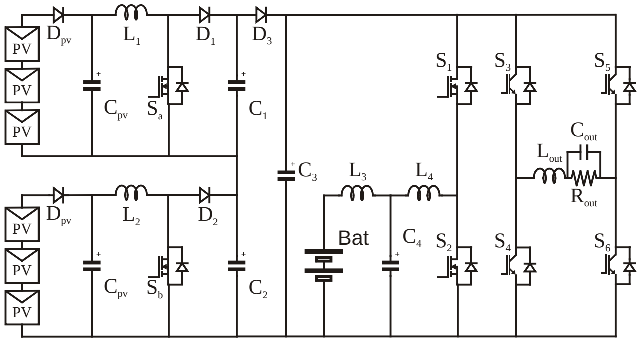


Fig. 2. Decentralized Stand-alone Photovoltaic System

This modular structure, employing a DC-DC converter for a reduced number of photovoltaic panels, provides an individualized maximum power point tracking, reducing the effects of shading/failure of photovoltaic panels and maximizing the energy generated by the system. In addition, the utilization of more than a single DC-DC converter also allows the disconnection of damaged strings, without having to shut down the whole system. The utilization of more than a single DC-DC converter also enables the utilization of power semiconductors with smaller power rating, which are cheaper and are easily found on the market, resulting on not only reduced costs, but also improved ($)/Wh rate.

IV. MAXIMUM POWER POINT TRACKING (MPPT) ALGORITHM

Some important drawbacks concerning energy generation through PV panels are the high installation costs and the low efficiency of the PV panels. Therefore, it is very important to draw the maximum energy available from the PV panels in order to increase the efficiency of the system and reduce the costs of the generated energy. However, due to the unique features of PV panels, the maximum energy point is variable and dependent of the climatic conditions such as, the solar radiation levels and the temperature. So, in order to extract the maximum energy of the PV array, it is utilized the maximum power point tracking technique which enables to generate a higher output power without adding more panels [20]. In the literature is mentioned that this technique can provide an increase between 15 and 30% of generated energy [5, 21, 22].

Concerning several maximum power point tracking techniques presented in the literature, in the proposed system was selected the incremental conductance technique, once it presents a very good compromise between performance and complexity. This technique employ the Power versus Voltage curve of the PV array in order of to track the maximum power point [20].

The allocation of the point where the maximum power can be drawn from the panels is given by (1).

$$\frac{dP}{dV} = 0 \qquad (1)$$

The flowchart of the Incremental Conductance technique is presented by figure 3.

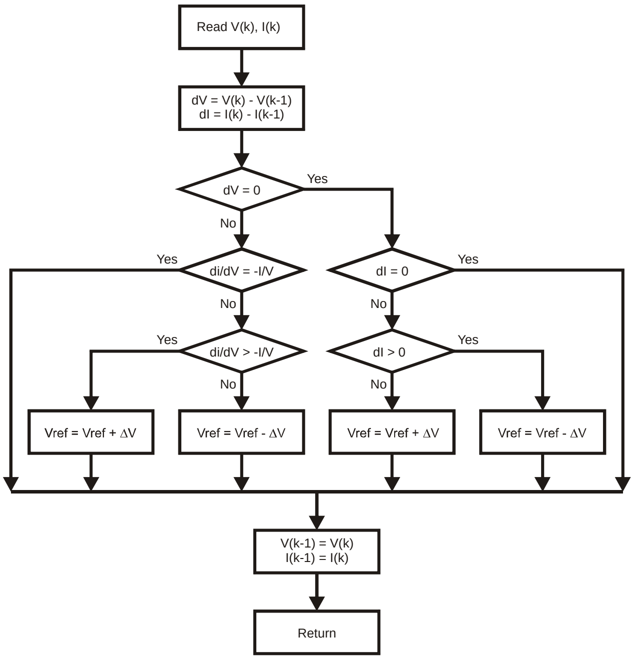


Fig. 3. Flowchart of the Incremental Conductance technique

For simulation and analysis of the behavior of the chosen MPPT technique, the algorithm presented in figure 3 was implemented through Matlab®. Figure 4 shows simulation results for several levels of solar radiation.

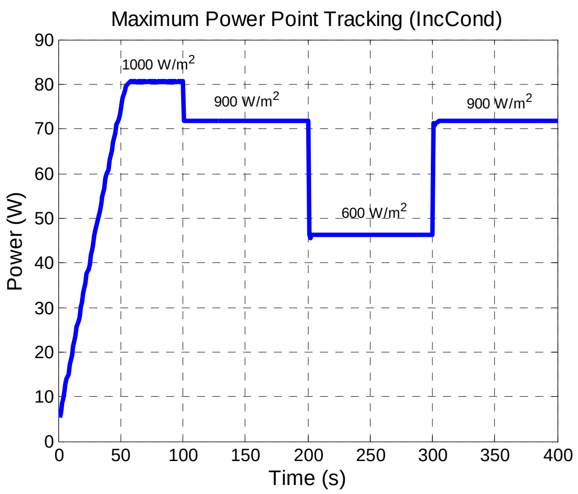


Fig. 4. Simulation results of Incremental Conductance technique for several levels of solar

This technique does not present oscillations surrounding the maximum power point and it has a reduced steady state error, obtaining a high utilization of the energy generated by the PV array.

V. SIMULATION RESULTS

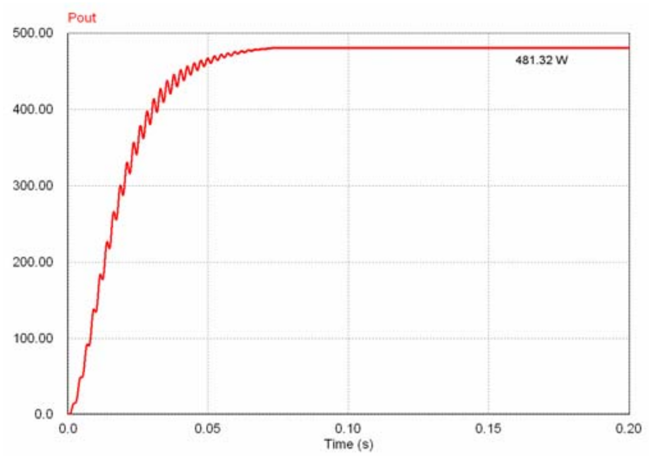
In this section it is presented the simulation results for the input stage of both centralized and decentralized stand-alone photovoltaic systems. The simulations comparisons were obtained for the following conditions: i.) both systems are under uniform radiation over all the PV panels; ii.) half of the PV panels which compose the arrays are submitted to a reduced solar radiation, characterizing shading/failure/aging of such panels. The simulations were made in a software that simulate the electric model of a PV panel, which was presented in [23].

The input stage of the centralized system is composed by 6 panels of 80Wp connected in series, totalizing a generation capacity close to 480Wp under radiation of 1000W/m^2 and 25°C.

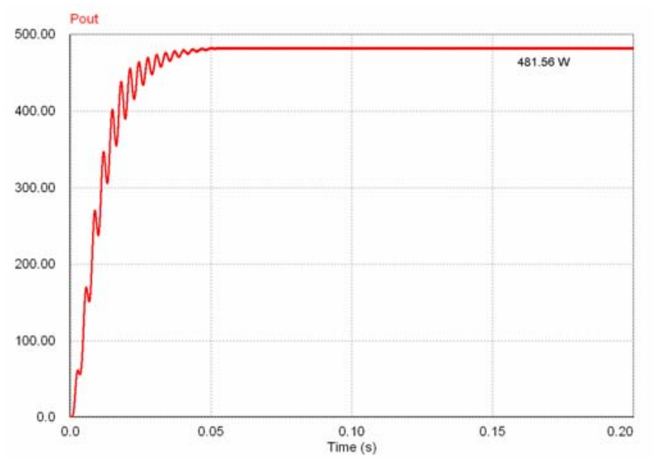
The input stage of the proposed system is composed by two PV strings, each one containing 3 panels of 80Wp connected in series, figure 2, totalizing 240 Wp for each string, constituting a system whose generation capability is near 480Wp under radiation of 1000W/m^2 and 25°C.

In figures 5(a) and 5(b) are shown the power delivered to the DC bus by the input stage of the centralized and decentralized stand-alone photovoltaic system, respectively, considering that both systems are submitted to a uniform radiation equal to 1000W/m^2 over all panels which compose the PV array. It can be observed that both systems delivered virtually the same power to the bus.

On the other hand, when is considered the second condition, shown in figure 6, in which half of the PV panels are under a solar radiation of 700W/m^2, characterizing a shading/failure/aging of these panels, a meaningful difference over the power delivered to the bus by the systems is observed. The results demonstrate that the decentralized stand-alone photovoltaic system is able of delivering to the DC bus a higher power when compared with the centralized stand-alone photovoltaic system (in the case studied, the increase was of 17%).



(a)



(b)

Fig. 5. Power delivered to the DC bus from both the studied topologies, under uniform radiation of 1000W/m^2. (a) Centralized, (b) Proposed.

This is due to the fact that in the centralized configuration the generated power is limited by the current from the shaded/defective/aged panels. This condition does not occur for the proposed decentralized system, where each PV string delivers its maximum power capability to the DC bus, considering the solar radiation under it.

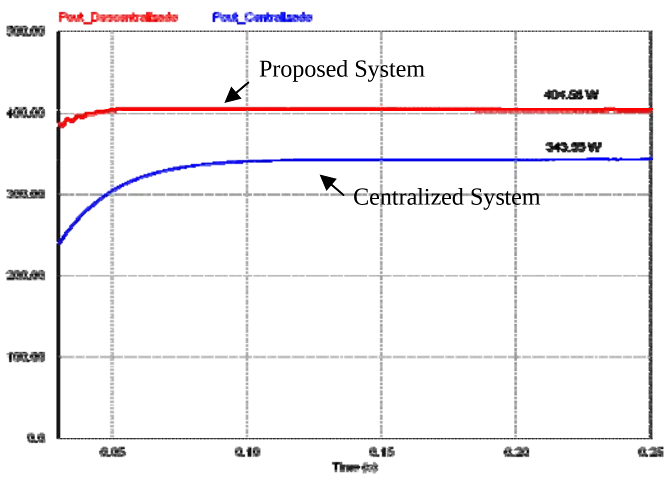


Fig. 6. Power delivered to the DC bus from both the studied topologies, considering half of the photovoltaic panels under a solar radiation of 700W/m^2.

VI. EXPERIMENTAL RESULTS

In order to validate experimentally the gain in the delivered energy to DC bus by decentralized stand-alone photovoltaic system, were implemented prototypes of the input stage for both, centralized and decentralized stand-alone photovoltaic systems, as shown in Figure 7. The systems were designed to operate with an array composed of six panels of 80Wp each. The PV array of the centralized system is composed of six series-connected panels and a boost DC-DC converter. The main specifications of this system are presented in Table I.

Table I
Specifications of the Centralized System

P_{MPPT}*	**483W**	**S_1**	**MOSFET IRFP360LC**
V_{MPPT}*	109.20V	D_1	DIODE RHRP870
I_{MPPT}*	4.43A	C_O	100µF/400V
f	30kHz	L_1	1,5mH - EE-65/26
V_{out}	200V		

* Radiation 1000W/m^2, Temperature 25ºC

On the other hand, the proposed decentralized system is composed of two PV arrays, each one with 3 series-connected panels of 80Wp. Each array is connected to a boost DC-DC converter of 240W, enabling the achievement of the maximum power point for each PV array as shown in Figure 7.

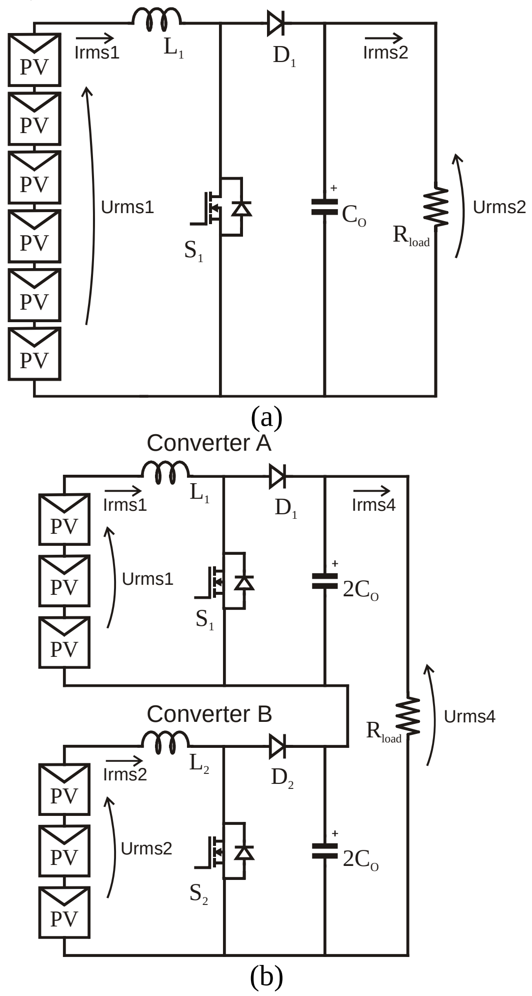


Fig. 7. (a) Implemented Centralized System (b) Implemented Proposed System

The main specifications of each one of the converters employed in the proposed system are presented in Table II.

Table II
Specifications of the Decentralized System

P_{MPPT}*	**241.83W**	**S_1, S_2**	**MOSFET IRFP360LC**
V_{MPPT}*	54.60V	D_1, D_2	DIODE RHRP870
I_{MPPT}*	4.43A	C_O	100µF/400V
f	30kHz	L_1, L_2	767µH - EE-55/21
V_{out}	100V		

*Radiation 1000W/m^2, Temperature 25ºC

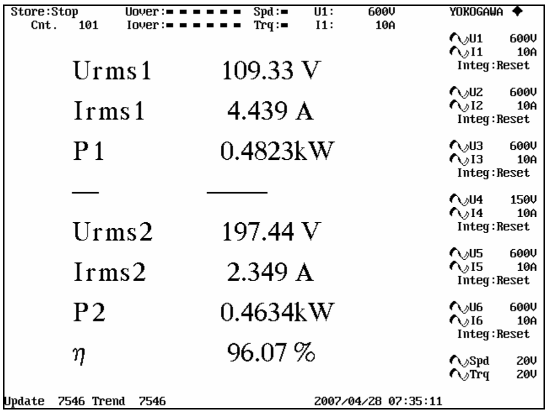
Both systems were submitted to the same operation conditions as mentioned in the previous section: i.) both systems are under uniform radiation over all the PV panels; ii.) half of the PV panels which compose the arrays are submitted to a reduced solar radiation, characterizing shading/failure/aging of such panels.

Table III shows the theoretical voltage and current values onto the maximum power point of the solar panel arrays for each of the analyzed situations.

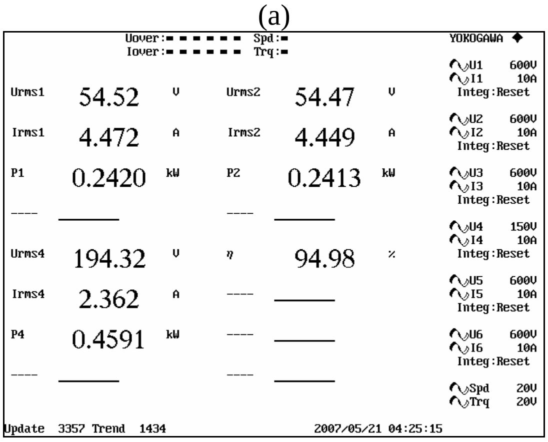
Table III
Specifications of the solar panel array

Centralized System			
Radiation of 1000W/m^2		Radiation of 1000/700W/m^2	
Parameter	Value	Parameter	Value
V_{MPP}	109,19 V	V_{MPP}	111,23 V
I_{MPP}	4,43A	I_{MPP}	3,09 A
Decentralized System			
Radiation of 1000 W/m^2		Radiation of 700 W/m^2	
Parameter	Value	Parameter	Value
V_{MPP}	54,60 V	V_{MPP}	53,09 V
I_{MPP}	4,43A	I_{MPP}	3,09 A

Figure 8 shows the results obtained for both topologies, through a digital power meter (Yokogawa®, model WT16000) operating under uniform solar radiation of 1000W/m^2.



(a)



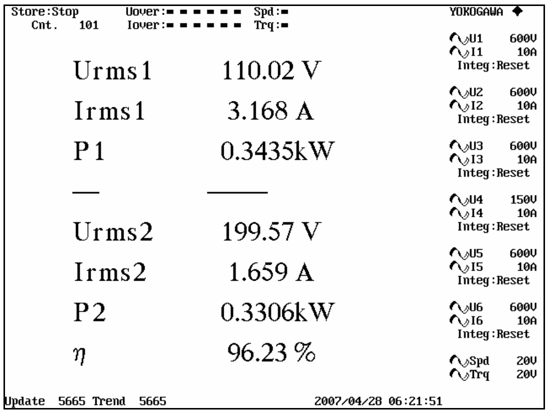
(b)

Fig. 8. Results obtained under solar radiation of 1000W/m^2, (a) for the centralized system, where η=P2/P1; and (b) for the proposed system, where η=P4/(P1+P2).

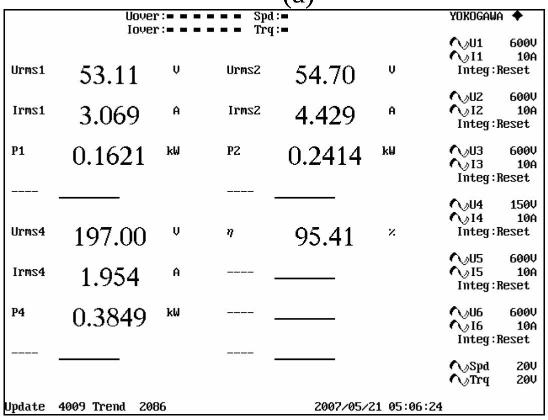
From experimental results shown in figure 8(a), it is possible to deduce that the decentralized system operate close to the maximum power point, which is defined in Table III. Likewise, through the input values, U_{rms1} and I_{rms1}, from converter A and, U_{rms2} and I_{rms2}, from converter B, shown in Figure 8(b), it is verified that the proposed centralized system also operates close to the maximum power point of both PV arrays. Due to the fact that the decentralized system has more semiconductors and components to process the energy, its output power (P_4 in figure 8(b)) is lightly lower to that obtained in the centralized system (P_2 in figure 8(a)).

However, when is considered the second condition, i.e., half of the PV panels which compose the arrays are submitted to a reduced solar radiation, characterizing shading/failure/aging of such panels, the results are more favorable for the decentralized system. Figure 9 shows the results obtained for both topologies in this second condition, where half of the panels of the PV array are under solar radiation of 1000W/m^2 and the others under a solar radiation of 700W/m^2.

As mentioned in the previous section, in a centralized system, the small current that flow through in one of the PV panels, define the current flow through the PV array, thus reducing the energy generation capability of the system. This drawback of the centralized system is greatly reduced in the proposed decentralized system, once each PV string delivers its maximum power capability to the DC bus, considering the solar radiation under it.



(a)



(b)

Fig.9. Results obtained (a) for the centralized system, where η=P2/P1 and (b) for the proposed system, considering half of the panels under solar radiation 700W/m^2, where η=P4/(P1+P2).

Comparing the values of Table III with the values of U_{rms2} and I_{rms2}, which represent the input voltage and current of the converter connected to the non-shaded PV array, in Figure 9(b), it is verified that this array operates over the maximum power point. In despite of having one of the arrays shaded and a slightly lesser efficiency in comparison to the centralized system, the decentralized system presents an energy gain of 16% delivered to the DC bus.

VII. SUMMARY

The commercial stand-alone PV systems are traditionally based on centralized structures. In these cases, when one or more photovoltaic panels are shaded or damaged, the system cannot deliver the maximum generated energy. Additionally, they also have an energy storage management system of poor quality, due to the fact that the battery bank is connected in series with the power flow.

This paper proposes a new stand-alone photovoltaic system, based on decentralized structures, which employ a DC-DC converter dedicated to a reduced number of PV panels, enabling deliver a higher energy to DC bus. In the experimental comparison, the decentralized system can deliver an energy gain of 16% to the DC bus, when compared to centralized systems.

Moreover, in the proposed decentralized system, the battery bank is placed out of the main power flow, and it is connected to the system by a converter, with bi-directional power flow control, which disconnects the battery bank when it is not necessary. So, this topology avoids unwanted charge and discharge of battery bank, enabling a prolonge life cycle of the energy storage system.

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