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Control Laws to Improve Efficiency and Average Life Time of an Adaptive Multi-Phases Converter Dedicated to Photovoltaic Applications

A. Berasategi[1,2,3], Y. El Basri[1,2,3], C. Cabal[1], B. Estibals[1, 2], M. Vermeersch[3], C. Alonso[1, 2]
[1] CNRS; LAAS; 7 avenue du colonel Roche, F-31077 Toulouse, FRANCE.
[2] Université de Toulouse; UPS, INSA, INP, ISAE; LAAS ; F-31077 Toulouse, FRANCE.
[3]Dept. Solar & New Energies, TOTAL S.A, Tour Coupole -2, place Jean Miller- La Defense 6, 92400 Courbevoie, France
Phone number: +33 561336391
E-mail : aberasat@laas.fr

Abstract: In this paper, an Adaptive Multi-Phases Converter (AMPC) is used as an adaptation stage to improve the efficiency and reliability of a photovoltaic power conversion chain. We present a control law which guarantees high conversion efficiency, even in the presence of constantly changing operating point which is principal characteristic of the photovoltaic system . Another control law which consists in the rotations of phases of the converter is also presented. This rotation guarantees a homogeneous aging, increasing the average life time of the converter. Guidelines of these control laws are presented. An experimental prototype has been designed to evaluate the performances of this proposed adaptation stage.

Key words

Photovoltaic system, power converter, control, efficiency, life-time.

1. Introduction:

Photovoltaic converter must be designed considering the singular characteristics of the PV sources, such as its intermittence and above all its changeability. The solar array energy production is not constant and it changes depending on irradiation and temperature. These changes are directly dependant on the season of the year, the hour of the day and the weather.

The efficiency of a classical power converter presents a maximum value (η_{MAX}) to a given input power (nominal power, P_{nom}). The converter efficiency decrease when the input power is lower or higher than this nominal power value. In many power management applications, the design of the converter is made by referring to a fixed operating point (nominal power), set with the maximum efficiency. However, in photovoltaic systems it is not possible to fix an operating point, due to its constant power production changes. In this case, the maximum efficiency of the power converter is also obtained when the power supplied by the photovoltaic module is equal to the nominal power.

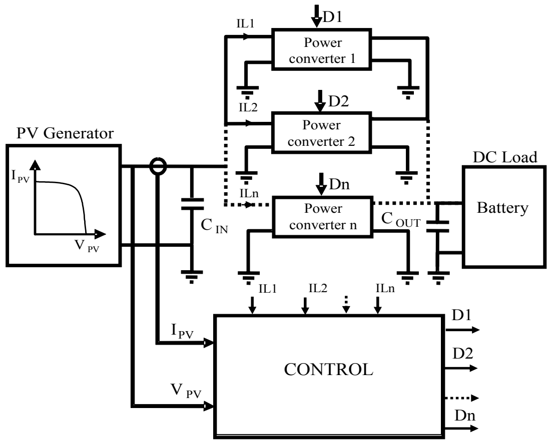


Fig. 1. Photovoltaic conversion chain realized with *n* power converters connected in parallel.

In this paper, the Adaptive Multi-Phases Converter (AMPC) solution is presented. The objective is to obtain a high efficiency of the power converter for a large power range. This solution is inspired in a well known technique used in high power applications. It consists in a parallel association of switching converters. This connection mode allows a uniform distribution of the global power among the dc-dc converters. This approach offers some advantages compared with a single high power converter. Paralleling mode increases the power processing capability and improves the reliability because stresses are better distributed and fault tolerance is guaranteed [1, 2].

This paper presents different control laws to improve the performances in term of efficiency and life-time of the AMPC. The first law guarantees that the converter works with a high efficiency every time. Moreover, in order to avoid the premature ageing of one phase, a control law consisting in the phase rotation of the converter is integrated.

2. Main function of the AMPC:

The AMPC is integrated by *n* converters in parallel as shown in figure 1. Each converter is designed to support the total power of the photovoltaic source. In this way, we can guarantee the operating of our system, even if one of the converters is faulty.

The AMPC integrates a control law adapting the number of active converters depending on the photovoltaic power production. This is set to permanently obtain the highest efficiency possible.

The number of converters inserted in the AMPC depends on the PV generator power and the efficiency curves evolution of the AMPC operating modes (1, 2… until n phases connected). Figure 2 represents the efficiency evolution of the AMPC designed to be connected to the PV module of 85 Wc. Here, the AMPC is constituted by three power converters of 100W. The intersection points of efficiency curves (P_1 and P_2) represent the power levels where the AMPC changes the configuration mode. For this example, we can see that just two converters are necessary to obtain the higher conversion efficiency of the AMPC. Indeed, the gain supplied by the connection of the third converter is obtained for the power higher than this PV module power.

The operating principle of the AMPC for *n* converters for a PV power production of a sunny day is represented in figure 3. In low power, only one phase will be activated. When the PV power increases, the second is activated. The following phases must activate with increasing power. The deactivation will be in the same progressive way, but with decreasing power. The algorithm of the converter adaptation law is reported in the figure 4 for *n* converters.

However, this mode of working could involve the premature aging of the phase number 1, which is active during all the different operating modes. In order to avoid this phenomenon, another control law has been integrated: the rotation of phases of the power converter.

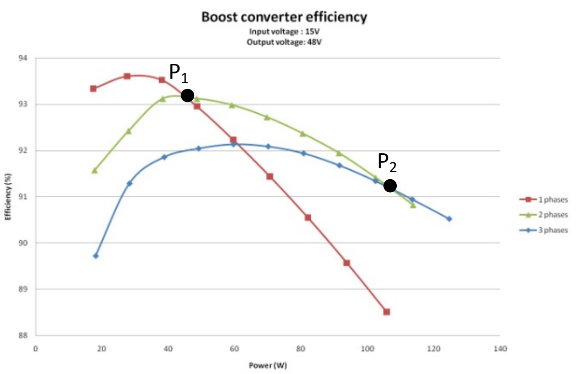


Fig. 2. Evolution of the conversion efficiency of the AMPC operating during different configurations

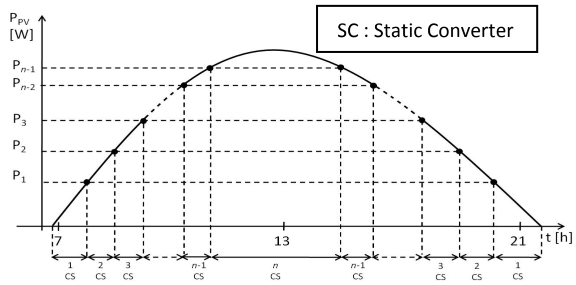


Fig. 3. Operating principle of Adaptive Multi-Phases Converter (AMPC).

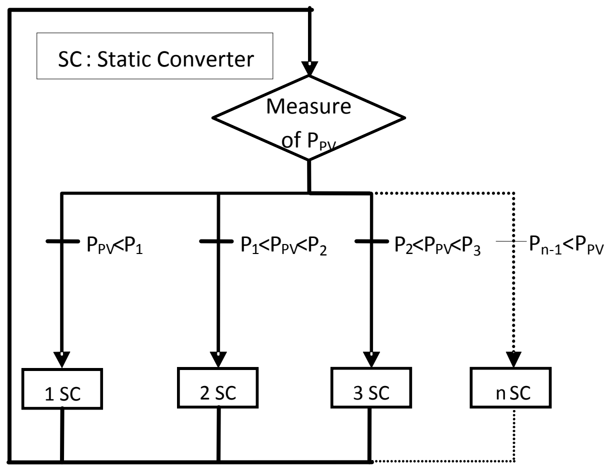


Fig. 4. Algorithm for the converters number activation.

3. Converter phase rotation

The rotation of converter phases has been incorporated to the system to homogenize working time of each phase. That will guarantee uniform aging in the phases and increased the average life time of the system, avoiding that one phase break down much faster than the other ones.

In order to perform the rotation of the converter, a control law has been implemented in the system. This control law is based in the assignation of priorities according to the total working time of each phase. The activation order of the phases will depend in this priority.

The algorithm consists in registering the total working time of each phase. Each 60 minutes this total time will be checked and the different phases will be assigned with respective priority levels. The converter that has worked less time will be assigned with the highest priority and the one that has worked more time with the lowest priority. Then, the phase or phases will be activated according to priority level. The algorithm of converter phases rotation must be in relation with the adaptive phase algorithm, explained in the previous section.

4. Description of the whole control system

The main functions of this system have been presented in the previews sections. However, they are not the only ones presents in the system.

Another function is incorporated in our system in order to prevent the possible failures of the power converters. Thus the different power converters are checked constantly in order to verify if their operating state is in accordance with the commanded state. The method to detect the default consists in measuring the currents through the different converters. In the case of the presence of current in a deactivated phase or the absence of current in an activated phase, the presence of a failure is detected. In this case, priority level of this broken phase will be set to null, disallowing the option of its activation. This monitoring mode is represented in the figure 5 by the security and fault blocks.

The simplified algorithm of all functions implemented in the system is represented in the figure 5.

After the system initialization, where the initial priorities will be defined in accordance with the total worked time of each converter, the activation of number of phases is carried out according to the PV power production and the priorities of the moment. Then the security test is carried out, as well as the verification of possible changes of static converter number due to a PV power evolution. These verifications are constantly carried out, and the same configuration mode is maintained, while there are no failure detected or power changes happened.

Each 60 minutes, the priority will be modified with the purpose of maintain the same operating time for all the phases and avoid the premature aging of one of them. This will carry on the activation or the deactivation of the phase or phases of the lower priority.

This system is dedicated to photovoltaic applications and due to its non lineal characteristic; the photovoltaic converters are normally associated to Maximum Power Point Tracking (MPPT) control which tracks permanently the maximum power point (MPP) of the panel. Many researches has been made about MPPT control; many kind of control has been studied and developed [3, 4]. In this system a MPPT control developed in our laboratory is used, which is based on the Perturb&Observe principle and carried out in digital way [5].

In the figure 6, the whole system has been represented: from the power processing part to the representation of the control laws and the interactions between all the system. Each part will be defined in the following lines:

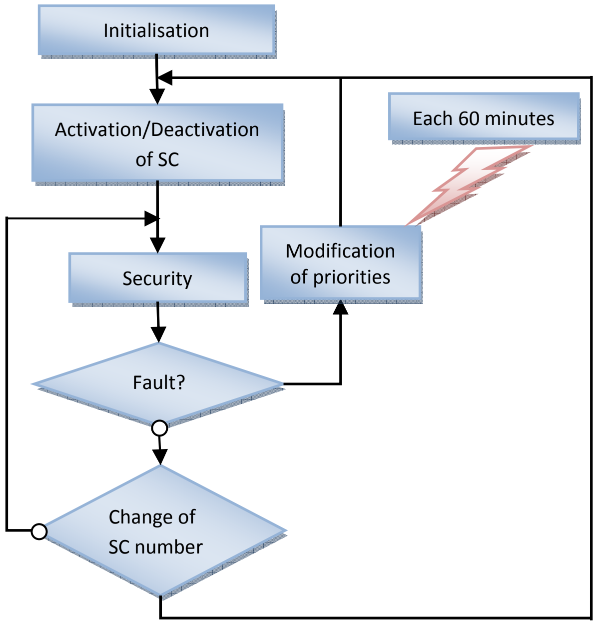


Fig. 5. Principle algorithm of the multi-phases converter.

Parts A, B and C represent the power processing part. The adaptation stage (A), which consists of a switching structure of three boost in parallel, transfers the power from photovoltaic array (B, source) to the battery (C, load).

All the part in D corresponds to the circuit representation of the control laws. All this controls are implemented in a FPGA. All the functions block interact between them, and the task are carried out in parallel.

A MPPT control identified by (1) in the figure 5 adjusts the duty cycle value (α) of the converter in order to permanently track the maximum power point.

In parallel, the phase adaptive algorithm, where is placed inside bloc number 2, will establish the number of phases to activate according to power of the photovoltaic array and the predefined power levels (P_1,P_2).

Block 3 represents the rotation algorithm, where the priority of the phases is defined. According of the signal with the information of number of phase to activated coming from (2), this block will set to 1 (on state) or reset to 0 (off state) the signals B1,B2 and B3, corresponding simultaneously to the working states of phase number 1, number 2 and number 3.

Security block (4) will recover the real state of phases by means of the current through each phase and will inform if they are faulty or not. This information will be send to the block (3), which will set to null the priority of the faulty phase, avoiding its activation.

Finally, the switching box (5), will define the duty cycle for each converter (d1, d2, d3) using the information received from the MPPT (1) and the signals B1, B2 and B3.

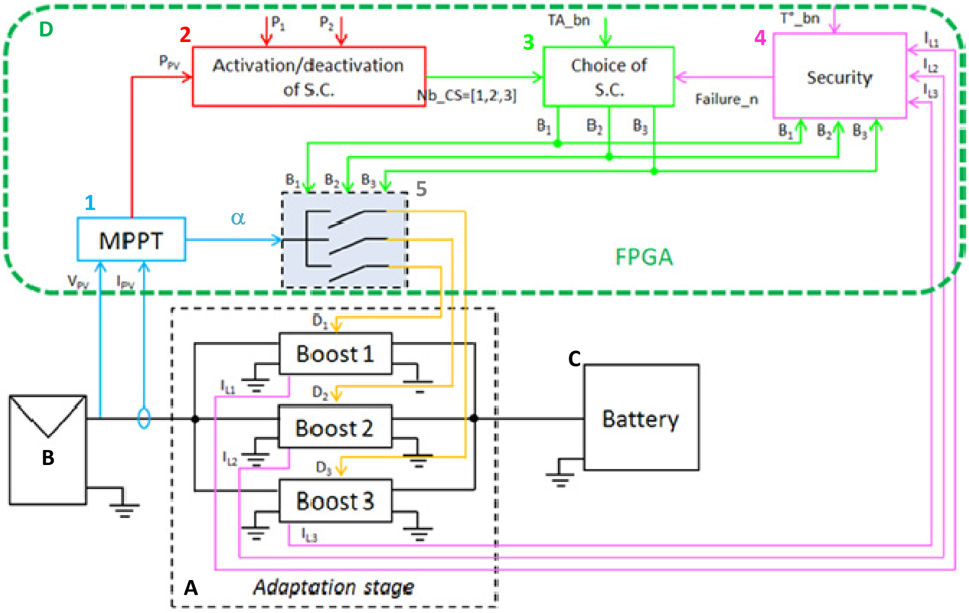


Fig. 6. Implementation of the function on the system for three static converters

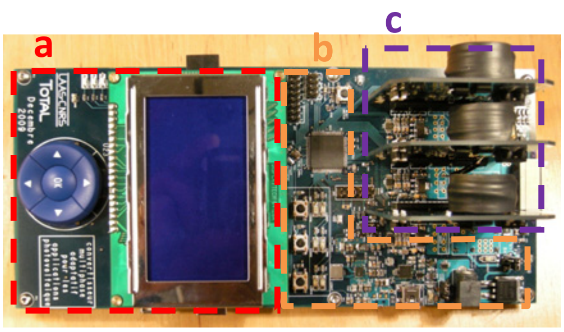


Fig. 7. Prototype of AMPC
a)User interface
b)Control
c) Power

5. Experimental prototype

A demonstrator of three dc-dc boost converters has been designed and implemented, as shown in figure 7. To validate the operating of our demonstrator, we have used a PV module of 85 W_C couple to a 48V battery. All the control laws are integrated in a FPGA AGLN250-VQG100 [6]. A set of supplementary function has been added to the system, as a date storage memory, an USB connection to a computer and a user interface. They allowed an easier analysis of the system and treatment of data.

6. Experimental results

Different tests have been carried out to validate all the functions of the AMPC converter.

The first tests have been carried out in order to validate the rotation algorithm and the phase adaptation function, as well as the stability of the system in the presence of the continuous changes in the state of the converter. At first time, we have made the tests without the MPPT control, using as source a constant DC supply. The figures 8 and 9 show these first tests. Figure 8 shows the results of the rotation algorithm tests for a constant input power corresponding to operating mode with two static converters. The signals 1, 2 and 3 represent the working state of three different phases, being the high state, the activated condition and the low state, the non-activated condition. We have reduced the rotation time to 30s in order to observe de signal in the oscilloscope and facilitate the analysis of the results, Each 30 seconds, the working phase will change. From t_1 to t_2, the phases number 1 and 2 work; from t_2 to t_3, the phase number 3 takes the place of the phase 2, in order to equilibrate the working time of all the phases.

In figure 9, the interaction of the rotation algorithm and the phase adaptation function is shown for an increasing and decreasing input power generate by a DC supplier. Like in figure 8, the signals 1, 2 and 3 represent the working states of the phases 1, 2 and 3 corresponding to the power evolution: from t_0 to t_1, only one phase is activated (phase 2). In t_1, as the power become higher than P_1, a second phase is activated (phase 3). From t_2, the phase rotation algorithm can be noticed: the phase 1 takes the place of the phase 2, to equilibrate the operating times of all the phases. In t_3, the limit of P_2 is passed and all the three phases are activated. In decreasing power, the deactivation of phases is carried out, following also the rotation of the converters. In t_4, the third phase is disconnected. In t_5, the rotation algorithm take place, deactivating the first phase and activating the third phase. In t_6, the power become lower than P_1 and the second phase is deactivate. Between t_6 and t_7, the phase number 3 is the only phase that is operating, to give place to the phase number one in t_7.

These two figures validate the functioning of the phase adaptation and the rotation algorithms.

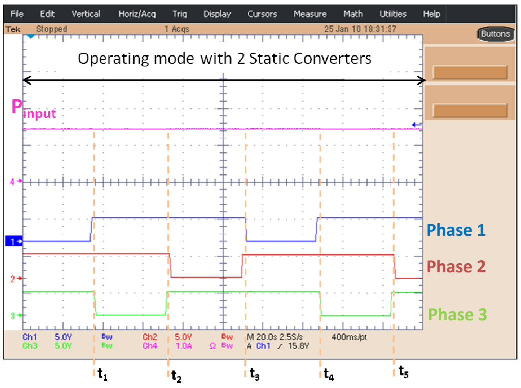


Fig. 8. Test of phase rotation algorithm

In a second time, as shown in figure 10, we test the compatibility of our system with the MPPT control. The AG E4360A [7] solar simulator of Agilent Technologies have been used to simulate the PV input and the PV power changes. The system reaches the maximum power point (MPP) and oscillates around this one. In figure 10.a., the system suffers a decreasing power change. Before the perturbation, we can see that the PV Current (I_{PV}) is uniformly shared between the converter 1 and 2 ($I_{L1}=I_{L2}=I_{PV}/2$.) The answer of our system to this change is fast and stable: it follows oscillating around the new MPP. Moreover, we can see that the first phase is deactivated, since the second phase current (I_{L2}) is equal to the PV current. Although the impact of this change is visible in the currents of the phases, it is invisible from the view of the input voltage and current. With the decreasing power change, the operating point has been changed from two to one active converter. In the figure 10.b., a increasing power change occurs. Previous to perturbation, only one phase is active as the phase number two takes all the PV current ($I_{L1}=I_{PV}$). We can also see that the system stay stable after the change, oscillating around the MPP and as in the falling change, the reponse is fast. In this case, we can distinguish the activation of the phase 2; as the power has passed the P_1 limit, a second phase is activated and the input current is distributed uniformly between both phases ($I_{L1}=I_{L2}=I_{PV}/2$).

In order to validate the gain in the produced energy provided by this new system (AMPC) in comparison to a classical structure, a set of indoor measurement has been made. The electrical features of 90W PV array are simulated with AG E4360A solar simulator in order to supply the same PV energy to both structures. The equivalent of one day solar power production has been simulated in 4 hours for both structures. The transferred energy to the load and the converter efficiency have been measured [8]. The results are shown in figure 11 and table I. This test has demonstrated the benefit of the AMPC structure with a gain in terms of power converter efficiency of 1,5%.

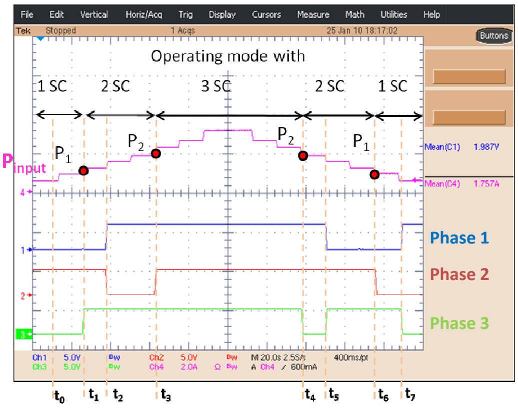
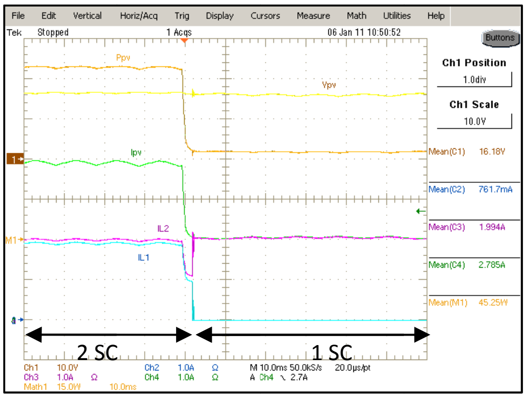
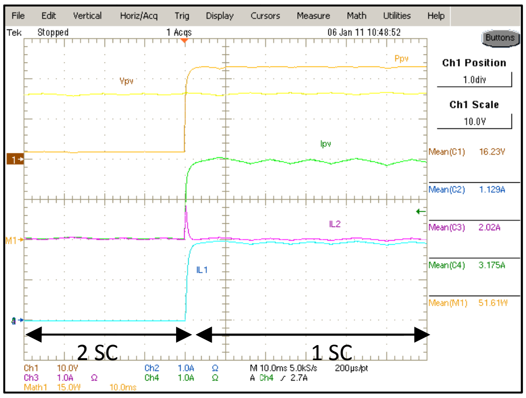


Fig. 9. Test of the algorithm for the converter number activation in interaction with the phase rotation algorithm.
(SC : Static Converter)



a)



b)

Fig. 10. Experimental results:
a) Phase adaptation in decreasing power: from 2 to 1 active phase
b) Phase adaptation in power: from 3 to 2 active phases

Finally, a set of outdoor tests has been carried out during several days. Our new structure has been compared to a classical structure during five days. Both structures have been connected to 85Wc identical solar panels and the energy supplied to the load has been measured. The figure 12 shows the obtained results. We can notice that the output energy of our structure is superior in comparison with a classical (table II). The energy production is 2.9% higher for the AMPC than for a single converter.

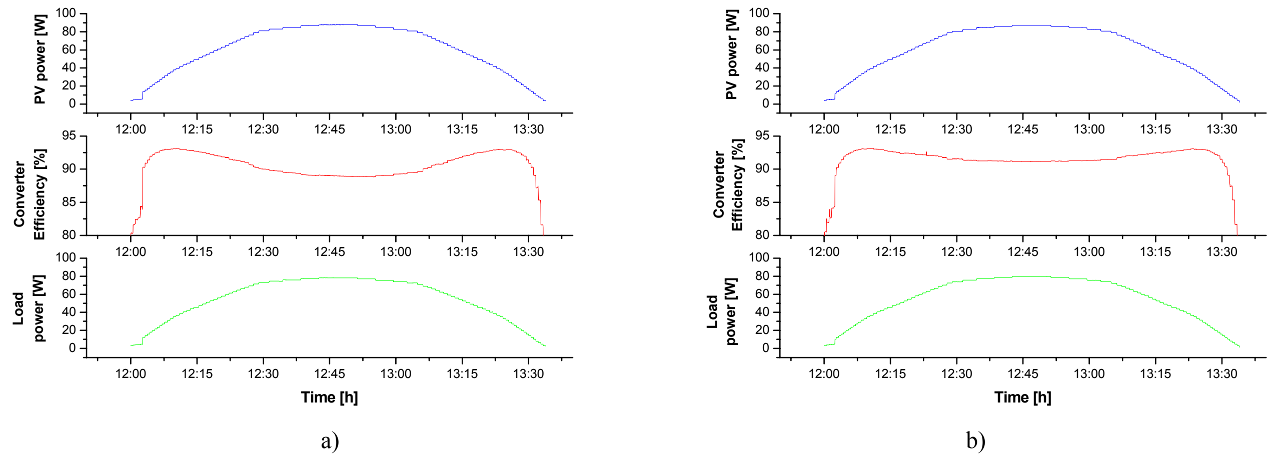


Fig. 11. Experimental results:
a) classical converter (1 phase),
b) adaptive multi-phases converter (2 phases)

TABLE I

Synthesis of the measures

	PV Energy E_{PV} [Wh]	Load Energy E_{LOAD} [Wh]	Converter efficiency [%]
Classical Structure	91.5	82.6	90.2
AMPC	91.1	83.6	91.7

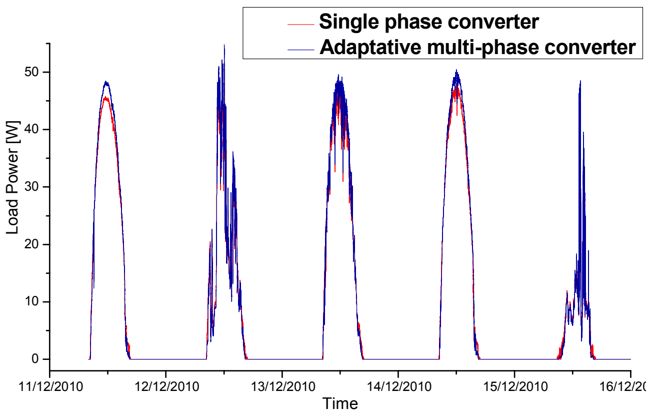


Fig. 12. Comparison of power production of a classical boost and our new converter

TABLE I
Energy production of 5 days

	Day 1	Day 2	Day 3	Day 4	Day 5	**Total**
Classical Structure	248 Wh	164.1Wh	238.4Wh	249.7Wh	66.4Wh	**966Wh**
AMPC	258.5Wh	166.1Wh	247Wh	259.66Wh	62.97Wh	**995Wh**

7. Conclusion

The AMPC converter has been presented in this paper. This converter allows improving the power production of a PV system. Moreover, the use of the rotation algorithm guarantees a longer life to the system. The implementation of all the function has been presented. Many tests have been carried out in order to demonstrate the adaptability of the system to new function. Finally, the comparative tests have demonstrated the gain of the new system in the energy production. However, the presented system is more complex and therefore, more expensive. Long run tests must be carried out in order to evaluate real life-time increase and global energy gain.

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