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Hardware Platform for Photovoltaic MPPT Algorithms Implementation and Validation

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***Abstract*—Photovoltaic panels energy generation depends on irradiation and cell temperature; the curve generated by the array presents a Maximum Power Point (MPP) corresponding to the maximum efficiency for these environment conditions. Appropriate Maximum Power Point Tracking (MPPT)algorithms must be utilized to track MPP. In the paper is described the design and realization of an hardware platform to implement and compare different MPPT algorithms. The platform is mainly constituted by a push-pull dc/dc converter with the driving circuit opportunely realized. The PV working point depends on the load, it has been demonstrated that by utilizing dc/dc converters is possible to dynamically vary the impedance seen from the PV panel acting on the converter duty-cycle, once fixed the load. The proposed design is based on the above considerations. Different MPPT techniques are implemented by means of the platform and experimental results are reported in the paper.**

I. Introduction

THE optimization of energy generation in a photovoltaic (PV) system is necessary to let the PV panels operate at the Maximum Power Point (MPP) corresponding to the maximum efficiency. Since the MPP varies, based on the irradiation and cell temperature, appropriate algorithms must be utilized to track the MPP. This is known as Maximum Power Point Tracking (MPPT).

The power generated by photovoltaic (PV) panels depends on the load seen from the panel itself. In the last decades, different algorithms have been proposed in the technical literature that are implemented on proper converters and are capable of letting the PV panels work at maximum power.

The MPPT techniques can be classified as Hill Climbing/Perturb & Observe, Incremental Conductance, Fractional Open-Circuit Voltage, Fractional Short-Circuit Current, Fuzzy Logic Control, Neural Network, Ripple Correlation Control, Current Sweep, Load Current Voltage Maximization, dP/dV or dP/dI Feedback Control [1].

Among these techniques particularly diffused are Hill Climbing and Perturb & Observe (P&O) methods. Hill Climbing involves a perturbation in the duty ratio of the power converter, and P&O a perturbation in the operating voltage of the PV array. In the case of a PV array connected to a power converter, the perturbation of the duty ratio of power converter changes the PV array current and consequently the array voltage.

The perturb and observe (P&O) technique is widely used, especially because of its low-cost and easy implementation [2-5]. It is based on the following criterion: if the operating voltage of the PV array is increased, and if the power drawn from the PV array increases, this means that the operating point has moved toward the MPP and, therefore, the operating voltage must be further perturbed in the same direction. Otherwise, if the power drawn from the PV array decreases, the operating point has moved away from the MPP and, therefore, the direction of the operating voltage perturbation must be reversed [6]. This method not only has a relatively simple control algorithm but also tracks the MPP of a PV-module well. However, when atmospheric conditions are constant or change slowly, the P&O method oscillates close to the MPP. Especially, when these change rapidly, this method fails to track the MPP and loses part of the available energy.

In the paper is described the design and realization of an hardware platform set up to implement and compare different MPPT control algorithms for PV panels, that can be experimentally validated. The platform is mainly constituted by a push-pull dc/dc converter with the driving circuit opportunely realized, capable of being interfaced via USB to a personal computer. By means of this connection the MPPT algorithms are implemented in MATLAB environment and are easily accessible through a user-friendly graphic interface properly set up for the considered application.

As well-known and reported in the recent technical literature, the PV working point depends on the load; it has been demonstrated that using dc/dc converters it is possible to dynamically vary the impedance seen from the PV panel acting on the converter duty-cycle, once fixed the load.

II. The Hardware Platform

The hardware platform proposed has been designed and constructed and can be utilized to do experimental tests on photovoltaic panels. In particular it allows the implementation of power control by means of MPPT algorithms and the analysis of the results comparing the performance in different working conditions. The platform is realized including the firmware and software.

The experimental validation of algorithms can be completely done by means of the platform avoiding any external instrumentation.

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The platform scheme and operation is quite simple as represented in fig. 1. PV panel, converter and load are the power section: the impedance that is seen by the panel changes by changing the converter duty-cycle, which varies the working point of the panel. The software implements the control algorithms that determine the converter duty-cycle.

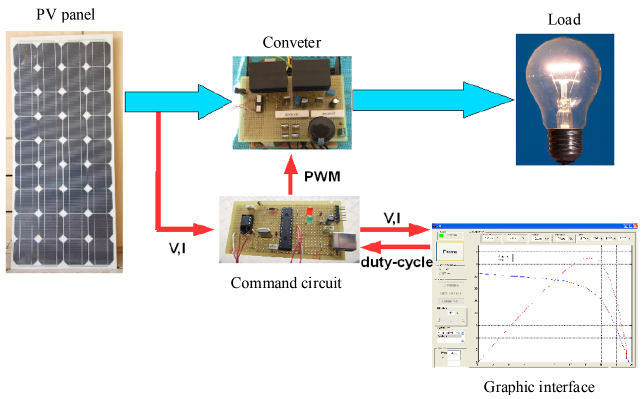

Fig. 1. Scheme of the hardware platform.

The hardware platform was designed and realized to do experimental tests on photovoltaic panels by means of MPPT control algorithms implementation.

It is known that the working point of a PV panel depends on the load seen from the panel, and by utilizing dc/dc converters it is possible to dynamically vary the impedance seen from the panel, this is done by changing the duty-cycle at a fixed load. The hardware platform design is based on an isolated dc/dc converter, push-pull type, controlled by means of a microcontroller which has multiple integrated functions that allow to simplify the realization of the circuit, reducing the number of needed components. Some of these functions are: hardware implementation of a proper PWM signal which produces the command of the converter switches, the possibility to have analog signal acquisition by an ADC 10 bit converter, USB connection interface able to operate in high-speed mode. These characteristics allow the connection of the hardware platform to a PC that is devoted to the control of the whole system.

The last part of the design was focused on the software development in order to implement the MPPT control and manage all the functions needed for laboratory tests.

In the following sections are described the main components of the platform: the converter and the command circuit.

III. Dual Inductor Push-Pull Converter

The converter that was designed and constructed to be embedded in the platform is an isolated dc/dc converter that is a variation of push-pull current-fed, proposed in the technical literature with the name Dual Inductor Push-Pull Converter (DIC).

The push-pull current-fed converter is widely used thanks to its operational characteristics that avoid unbalanced fluxes. On the other side there are some disadvantages by using this converter, such as an output voltage ripple that needs high filtering capacitances, high voltages on the main switches (double of output voltage referred to the primary) and the necessity to design the transformer considering high volt-ampere values.

It was proposed this alternative topology of Isolated Boost converter in order to overcome the above specified disadvantages, but having good performance.

This converter has the characteristics of the Isolated Boost but utilizes two input inductances instead of having only one inductance and has the insulation transformer with one primary winding.

The general scheme is shown in fig. 2, the most important characteristics that make this topology preferable respect to the Isolated Boost are [7]:

- voltage on the switches is reduced to the half;
- each input inductance is less stressed in current because the mean value is halved;
- the rms current in output capacitance is highly reduced because the current peak on the secondary of the transformer is halved;
- also the current ripple on the output capacitance is highly reduced, the same happens for the voltage ripple due to the absence of equivalent series resistance (ESR) of the capacitance;
- the sizing in volt-ampere terms of the transformer is half the case of Isolated Boost, obtaining then a total weight and dimension reduction;
- the input inductances are individually lower than one single inductance of the isolated boost.

The modality of discontinuous conduction mode of the current is not possible because of the presence of magnetizing inductance of the isolation transformer. Even in case of small loads the current in the inductance falls to zero but immediately increase with a linear trend, for the short-circuit of magnetizing inductance through a switch and a diode connected in anti-parallel to the other switch. The inductance current will always be in Continuous Current Mode (CCM), even if in case of small loads this current will be approximately zero. In this circumstance the converter has a behaviour different from the one of CCM and, to distinguish the two situations, is called Boundary Mode (BM) or Critical Mode (CM).

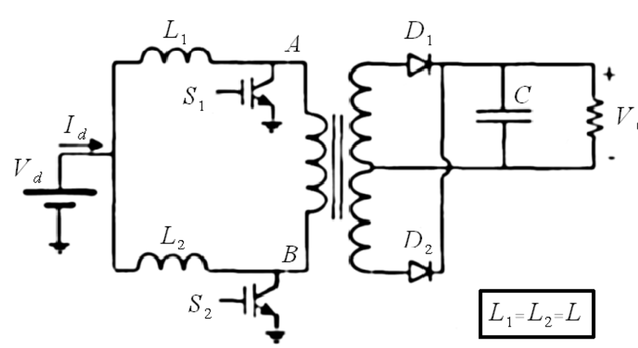

Fig. 2. Scheme of Dual Inductor Push-Pull Converter.

The operating phases that involve half the duty cycle of switch S_1, are described and represented in fig. 3:

- Phase 1: both the switches are closed, the primary winding is short-circuited and the current linearly increase in the input inductances, according to the ripple limit established in the design, the inductances store energy while the output filter capacitances supply the load.
- Phase 2: when the switch S_1 is turned off the current flows in the transformer primary winding that transfer the energy to the load through the diode at the secondary. The voltage on the switch is equal to the output voltage referred to the primary of the transformer. The driving pulse and the waveforms in CCM are shown in figs. 4 and 5.

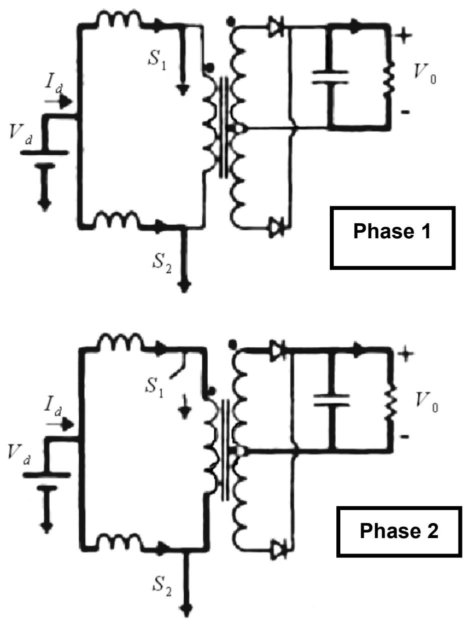

Fig. 3. Operation phases of the converter in CCM.

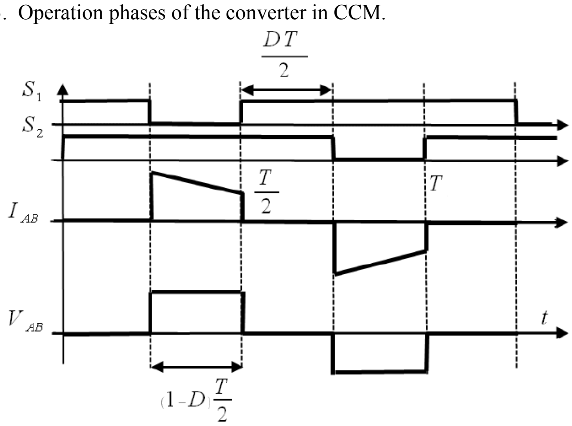

Fig. 4. Command signals of voltage and current in the primary of the transformer.

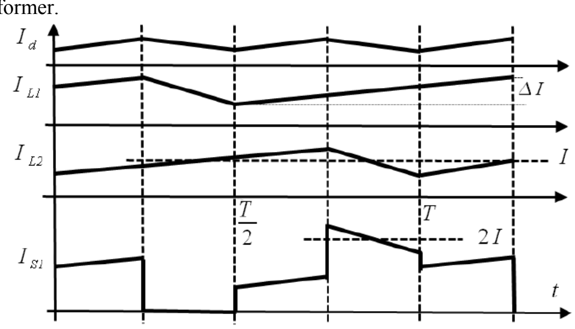

Fig. 5. Current in the circuit.

It is possible to consider some significant characteristics of the converter, i.e. if energy is the same in on and off mode of the inductance L_1, it yields:

$$V_d \cdot t_{ON} = \left(V_0 \frac{N_1}{N_2} - V_d \right) t_{OFF} \quad \Leftrightarrow \quad V_d \cdot DT_s = \left(V_0 \frac{N_1}{N_2} - V_d \right) (1-D) T_s$$

$$V_0 = \frac{N_2}{N_1} \frac{V_d}{1-D} \tag{1}$$

The above relation is valid only if $0.5 \le D \le 1$ and put in evidence an important characteristic of this topology of converter: even with a minimum duty-cycle (D = 0.5), the output/input voltage ratio V_0/V_d is two times the turn ratio, this makes the converter particularly suitable for all those applications that require an high voltage gain.

This type of converter was realized to be utilized in applications where is needed a voltage on the load much higher than the supply voltage, and capable of operating only for duty-cycle higher than 50%. On the other side, analysing the circuit it can be seen that to have a correct operation it is necessary that at least one of the two switches is always turned on to avoid high over-voltages that can damage the switches.

Among different operation modes of the converter it is also considered the case that the duty-cycle can be less than 50%, i.e. down to zero. This is the case i.e. when it is necessary to determine the characteristic of the photovoltaic panel, in this situation the duty-cycle must vary from zero up to 100% by small steps, in the way to acquire many working points and plot the diagram.

Another typical situation that can happen is that the maximum power point of the panel, for a fixed load, is in correspondence of a duty-cycle value less then 50%. In this circumstance, during MPPT control algorithm implementation, the converter will work in proximity of that duty-cycle value.

This converter topology is therefore not particularly good for the functionality of the hardware platform, but with some precautions, it is possible to adapt it avoiding fault conditions.

In the realization phase the switches have been protected from over-voltages by means of snubbers. This gives to the converter a safety margin to operate even in anomalous working conditions. Analysing by simulation what happens with short duty-cycles (less than 50%) it can be seen that the behaviour gradually diverges from the behaviour that is theoretically expected in case the duty-cycle is higher than 50%. Going under this threshold the current that in each cycle flows in the primary winding of the transformer decreases, while increases the leakage current in the snubbers.

Before constructing the designed DIC converter, it was simulated by means of a model realized in SPICE environment as represented in fig. 6. The correctness of the design was verified, with particular attention to mosfet voltages and power that must be tolerated by the devices. Once completed the construction it was compared the simulation behaviour to the one obtained by experimental tests.

The circuit scheme is reported in fig. 6, the command was given off-line using a couple of transistors in totem pole configuration driven by a generator of ideal pulses.

The analysis was done at steady-state, imposing an input voltage V_d=10 V, duty-cycle D=70%, load resistance R_{out}=30 Ω.

The converter performance can be summarized in:

$$P_{in} = V_d \cdot I_d = 243W, \quad P_{out} = \frac{V_{out}^2}{R_{out}} = \frac{70.5^2}{30} = 166W \quad (2)$$

Then the efficiency is 68%. In the considered working condition, with a power that is 80% of the maximum power considered in design, approximately 80 *W* are lost.

The majority of this power is lost in the mosftets (in simulation 29 *W* each). In figs. 7 and 8 voltage and current are shown.

With reference to the voltage, it may be noticed the influence of the snubber circuit, that is capable of limiting the voltage peak under dangerous values when opening the mosfet. The power dissipated in the snubber resistance is 5.6 *W*, that is within the design range (10 *W*).

Figures 9 and 10 show the input current ripple and the ripple of currents flowing in L_1 and L_2, the design limits are respected in this case too. In figures 11 and 12 are represented voltage and current of primary transformer winding.

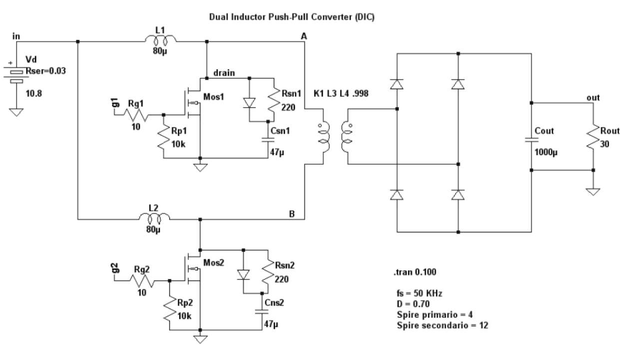

Fig. 6. Scheme of the converter model.

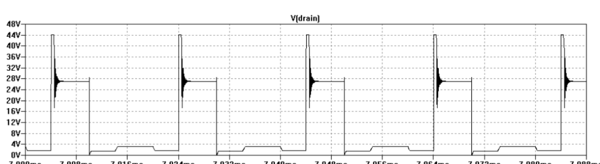

Fig. 7. Mosfet voltage V_{DS}.

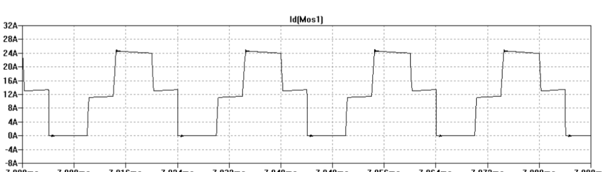

Fig. 8. Mosfet current I_D.

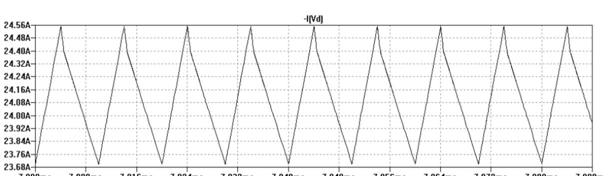

Fig. 9. Energy source current.

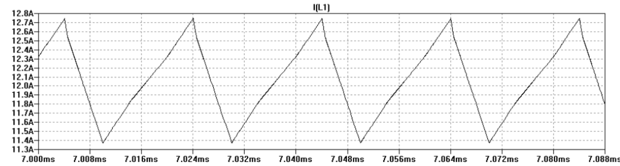

Fig. 10. Current in L_1.

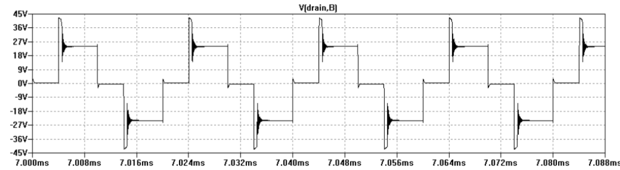

Fig. 11. Voltage on the primary winding of transformer.

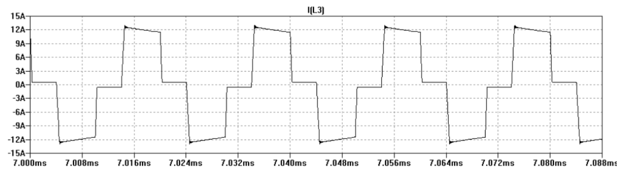

Fig. 12. Current in primary winding of transformer.

IV. COMMAND CIRCUIT

The command circuit was designed to realize the following operations:

- generation of PWM signals to properly drive the converter mosfets;
- small step variation of the duty cycle of PWM in range 0-100%;
- analogic acquisition of the output voltage and current values;
- implementation of a communication protocol with the PC;
- data exchange with the computer in real time, sending the ADC values and receiving duty cycle;
- system upgrade with new functions by simply programming the firmware.

Despite the apparent complexity of the many functions that must be executed by the command circuit, the realization was quite simple because all these operations are done by a single integrated circuit. It is a microcontroller PIC 18F4550 Microchip [8] connected in circuit serial programming (ICSP) mode. To realize an highly independent stage and allow the acquisition of analog signals through transducers with low output impedances it was used an integrated circuit with a couple of operational amplifiers in buffer configuration. In fig. 13 is shown the realized command circuit.

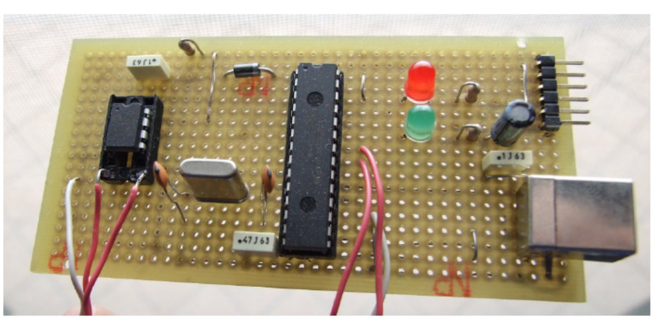

Fig. 13. Command circuit.

V. Experimental Validation

A test bench was set up with the hardware platform connected to the PC and to an irradiated photovoltaic panel (irradiation and temperature fixed). MATLAB was used for laboratory tests. This software can be easily utilized for specific applications, including new functions in the code just modifying the graphic interface. In fig. 14 is represented the implementation of an MPPT control algorithm as typical experimental experience with this software.

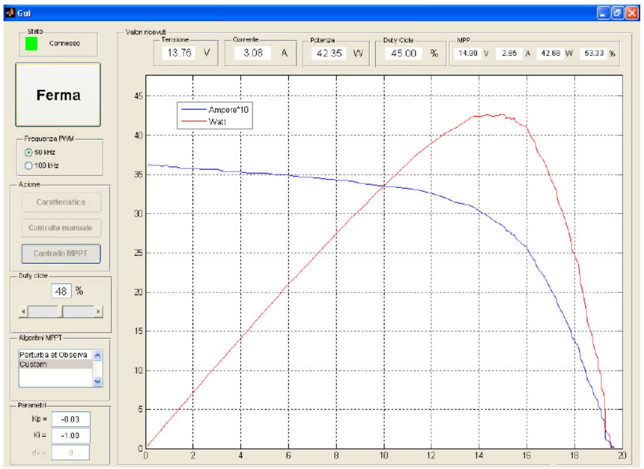

Fig. 14. Example of MPPT implementation.

First of all must be determined the characteristic of the panel for a fixed irradiation and temperature, it is then plotted and stored to be utilized for other elaborations. In this phase the maximum power point MPP is held to be assumed as a reference for the following MPPT algorithms implementation.
Other MPPT algorithms are then selected and implemented for an established time interval. After each implementation the values of voltage, current, power and duty-cycles acquired during the control cycle are saved in a file. This procedure can be repeated changing the algorithm parameters. Changing the operative conditions (irradiation and temperature) the tests can be repeated to evaluate the adaptation of the algorithms to different environmental conditions.

The last phase is the elaboration of data acquired during experimental tests. It is possible to obtain significant graphs like: current-voltage (*I*,*V*), power-voltage (*P*,*V*), power-time (*P*,*t*), energy-time (*E*,*t*), working point position on the (*P*,*V*) curve.

It is finally possible to analyze the characteristics of the panel and the effectiveness of the MPPT algorithms without any other laboratory instrument.

To validate the platform some experimental tests have been done, by means of the test bench, and the results are reported in the following.

The tests have been done irradiating a PV panel (with the technical characteristics shown in tab. I) by means of halogen lamps, fed by a variac voltage transformer. A Perturb & Observe algorithm was compared to an Adaptive Perturb algorithm. The main difference between the two algorithms is that in P&O there is a specific perturbation step, whereas in the adaptive algorithm the step change according to a suitable function. The P&O was validated with three different steps, at fixed values of irradiation and temperature.

TABLE I
Technical characteristics of the PV panel

Type	Aluminium-Tedlar 125M36
VOC	21.85 V
Rated input voltage	10 V
ISC	4.52 A
PMAX	69.03 W
VMP	17.74 V
IMP	3.89 A

In fig. 15 are reported the graphs representing current and power vs. voltage in different considered irradiations obtained in the laboratory at power highly reduced if compared to the rated power of the panel, the current results lightly distorted.

In fig. 16 is evidenced the different behavior of MPPT when starting the control: a bigger perturbation step allows a quicker response. The same situation is shown in fig. 17: the P&O algorithm with a step $2V$ immediately gives energy higher than other control algorithms. The analysis of fig. 18 shows that after an established interval there is a higher efficiency by utilizing an adaptive P&O with a reduced step. This is due to the power losses caused by high oscillations occurring in proximity of the MPP.

The same considerations can be done looking at figs. 19 and 20: it is evident the way of implementing different algorithms both in starting (or sudden change of) operative conditions and in steady working conditions.

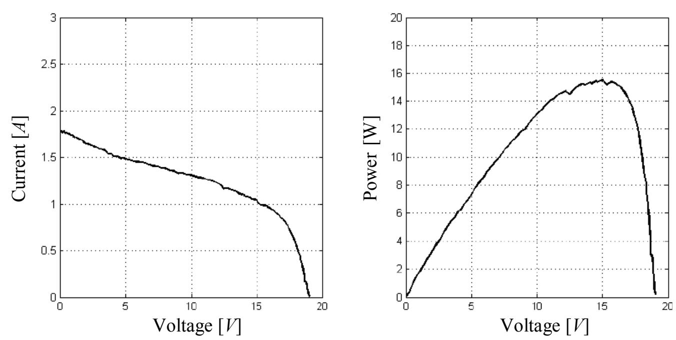

Fig. 15. Current and power vs. voltage.

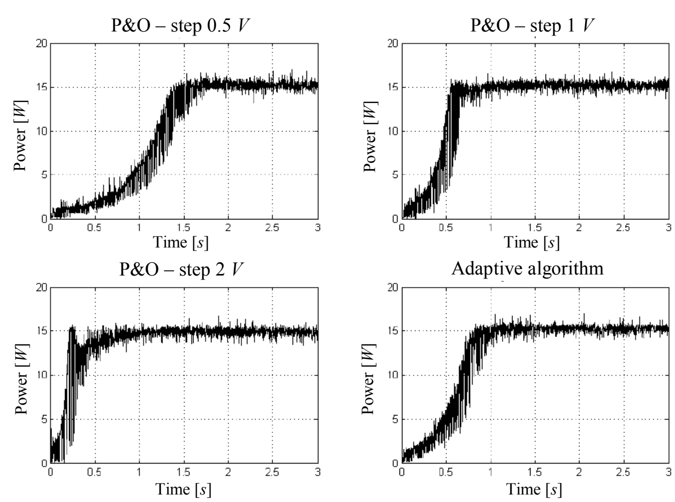

Fig. 16. Power in P&O and Adaptive algorithm.

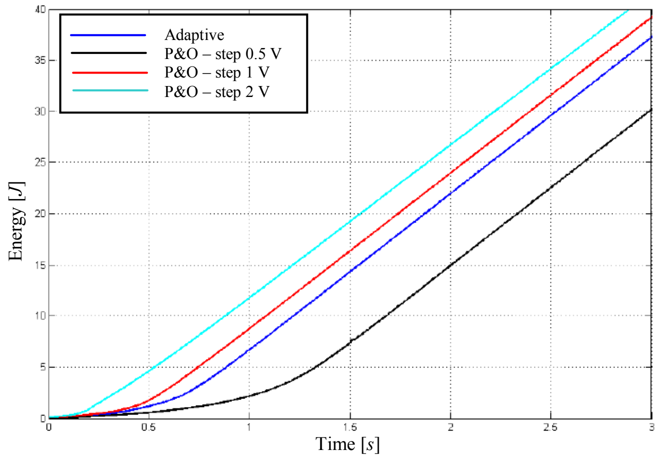

Fig. 17. Energy in time interval 0-3 seconds.

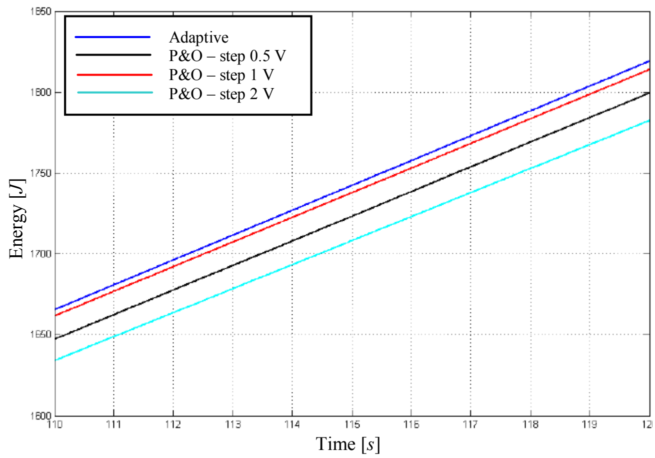

Fig. 18. Energy at steady-state.

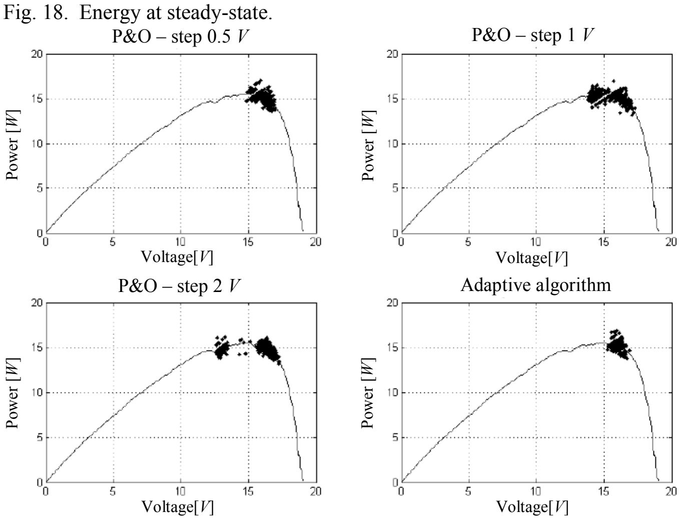

Fig. 19. Power curve at steady-state.

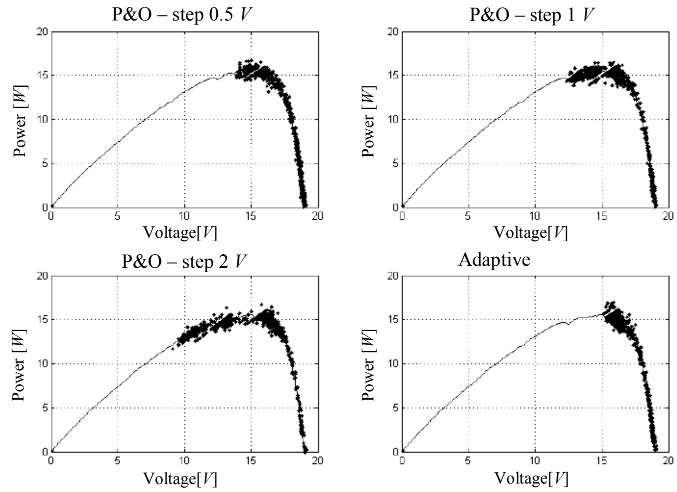

Fig. 20. Power curve in the starting operative conditions.

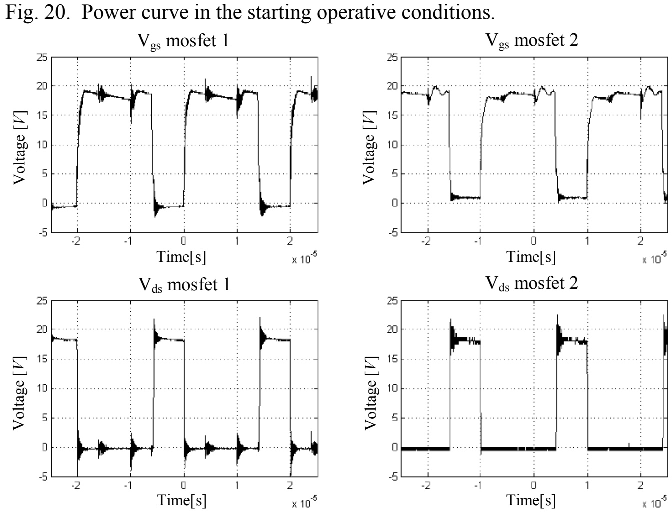

Fig. 21. V_{GS} and V_{DS} mosfet voltage.

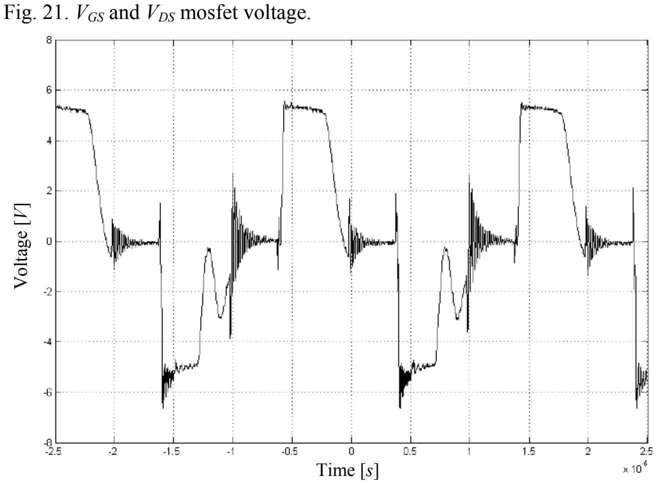

Fig. 22. Voltage on the primary of the transformer.

Some measurements have been done to check the characteristics of the converter. The feeding source was the photovoltaic panel irradiated by artificial light, with a duty-cycle 75%. In figs 21 and 22 are represented the experimental data (mosfet voltage and voltage on the primary winding of the transformer), the results can be compared to the expected ones. The power in this case is highly reduced (15*W*), corresponding to typical testing conditions that will be artificially reproduced in the laboratory.

VI. Conclusions

The design and realization of an hardware platform, including firmware and software, has been presented and experimental test of photovoltaic panels have been completed, in particular to implement the power control by means of different MPPT algorithms and compare them in different operative conditions.

The experimental validation results evidenced that the proposed system is particularly useful to test complex MPPT algorithms, evaluate their efficiency, and verify the economic convenience of photovoltaic systems.

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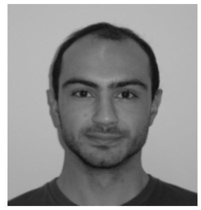
VIII. Biographies

Renato Rizzo (M'00, SM'06) was born in Naples, Italy. He studied at the University of Naples Federico II and received the Degree in Electrical Engineering. He is professor of Electromechanical Design, Basics of Electrical Drives, Electric Propulsion, Electric Machines Laboratory, at the Faculty of Engineering of University of Naples Federico II. Prof. Rizzo is professor honoris causa of the Technical University of Cluj-Napoca, Romania. He is an IEEE Senior Member, EAEEIE Member, treasurer of ANAE (the National Association of Electrical Drives in Italy). His researches are devoted to electrical machine and drives, and to their applications in transport systems, renewable energy sources. He published more than 100 scientific papers and 2 books and he participated to different research programs.

Prof. Rizzo is a Registered Professional Engineer in Italy.



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