Experimental test of seven widely-adopted MPPT algorithms

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***Abstract*—In these years the technology progress has allowed to increase renewable energies utilization and in the same time has contributed to raise large scale distributed generation applications. In particular the solar generation is growing and in the next future it will be always more considerable. Therefore it is important to optimize its production under different conditions (for example climatic situations), because the output characteristic of photovoltaic generators is nonlinear and changes with solar irradiation and cell's temperature. This paper presents a comparative study of seven widely-adopted MPPT algorithms; their performance is experimentally evaluated in presence of solar irradiance variations.**

***Index Terms*—Maximum power point (MPP), maximum power point tracking (MPPT), photovoltaic (PV).**

I. INTRODUCTION

SOLAR energy is one of the most important renewable energy sources. As opposed to conventional not renewable resources such as gasoline, coal, etc..., solar energy is clean, inexhaustible and free. The main applications of photovoltaic (PV) systems are in either stand-alone (water pumping, domestic and street lighting, electric vehicles, military and space applications) [1] or grid-connected configurations (hybrid systems, power plants) [2].

Unfortunately, PV generation systems have two major problems: the conversion efficiency of electric power generation is low (in general less than 17%, especially under low irradiation conditions), and the amount of electric power generated by solar arrays changes continuously with weather conditions.

Moreover, the solar cell V-I characteristic is nonlinear and varies with irradiation and temperature. In general, there is a unique point on the V-I or V-P curve, called the Maximum Power Point (MPP), at which the entire PV system (array, converter, etc…) operates with maximum efficiency and produces its maximum output power. The location of the MPP is not known, but can be located, either through calculation models or by search algorithms. Therefore Maximum Power Point Tracking (MPPT) techniques are needed to maintain the PV array's operating point at its MPP.

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Many MPPT techniques have been proposed in the literature; examples are the Perturb and Observe (P&O) methods [3]-[6], the Incremental Conductance (IC) methods [3]-[7], the Artificial Neural Network method [8], the Fuzzy Logic method [9], etc…. These techniques vary between them in many aspects, including simplicity, convergence speed, hardware implementation, sensors required, cost, range of effectiveness and need for parameterization. The P&O and IC techniques, as well as their variants, are the most widely used.

Because of the large number of methods for MPPT, in the last years researchers and practitioners in PV systems have presented survey or comparative analysis of MPPT techniques. As a matter of fact, some papers present comparative study among only few methods [5], [6] and one paper presents a survey and a discussion of several MPPT methods [10]. Another paper [11] presents a ranking of ten widely adopted MPPT algorithms (P&O, modified P&O, Three Point Weight Comparison [12], Constant Voltage, IC, IC and CV combined [13], Short Current Pulse [14], Open Circuit Voltage [15], the Temperature Method and methods derived from it [16]), based on simulations, under the energy production point of view. The MPPT techniques are evaluated considering different types of insolation and solar irradiance variations and calculating the energy supplied by a complete PV array.

In this paper the attention will be focused on experimental comparisons between some of these techniques, considering several irradiation conditions. Therefore the aim of this work is to compare several widely adopted MPPT algorithms between them in order to understand which technique has the best performance. The evaluation of algorithms' performance is based on the power and the total energy produced by the panel during the same test cycle. In this work, respect to the MPPT algorithm compared by simulations, the methods that need temperature or irradiance measurements are not considered for sake of simplicity. Indeed, as described in [11], these techniques do not have very high performance and they are too expensive. In the simulations, the considered MPPT techniques has been implemented strictly following the description indicated in the references: no MPPT algorithm is preferred and no MPPT techniques have been realized with more attention respect to the others.

In particular, without lack of generality, we will focus our attention on a stand-alone photovoltaic system constructed by connecting the dc-dc converter between the solar panel and the dc load.

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II. Experimental System

The comparison among the different MPPT techniques has been performed in an experimental way realizing the whole system in the power quality laboratory of Department of Energy at the Politecnico di Milano.

The experimental system is constituted by three main elements (Fig. 1): the dc-dc converter, the PV-panels and the solar simulator.

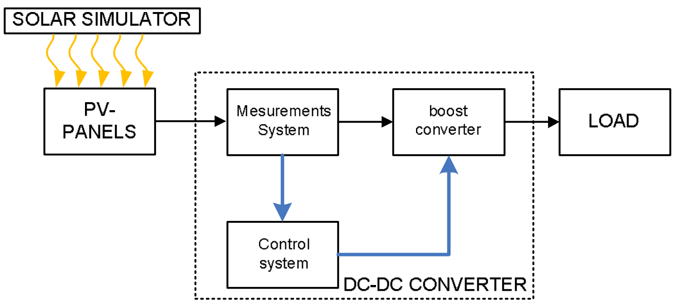


Fig. 1. Block diagram of the whole experimental system.

A. The dc-dc converter

In order to obtain comparable results, it has been realized a single device constituted by a dc-dc converter [17] and other components able to implement all the different MPPT techniques here analyzed, including Open Circuit Voltage (OV) [14] and Short Current Pulse (SC) [13] which required to insert further static switches to open the circuit or to create the short-circuit condition. All the MPPT techniques here described are easily obtained changing the software compiled on the microcontroller. In this way the differences in the measured energy load depend mainly on the software used for the implementation of the particular MPPT technique.

The choice of a stand-alone system, and hence the choice of using a dc-dc converter, reflects some industrial configurations composed by a first dc-dc conversion stage, in which usually the control of MPPT techniques is implemented, a second filter stage, and eventually a dc-ac conversion stage.

The dc-dc converter includes the control and power boards as shown in Fig. 2.

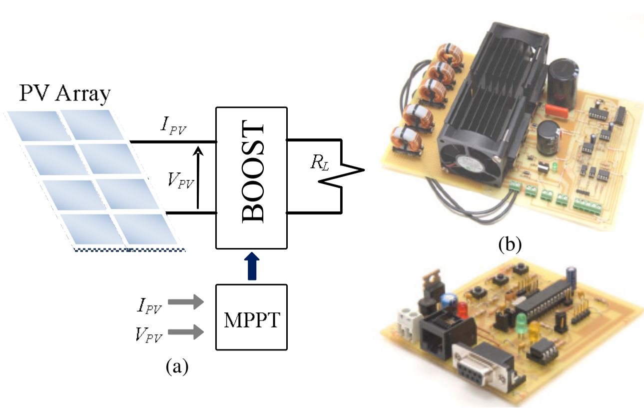


Fig. 2. (a) Stand-alone PV system analyzed. Dc-dc converter's (b) power and (c) control boards.

The control board is constituted by all the components that need for the implementation of the various MPPT algorithms already illustrated in [10]-[16]. The microcontroller, in this case a Microchip dsPIC30f4012, is the core of the control board.

The command connection to the power board is provided by means of driver circuits which allow the valves commutation.

The interface between control and power circuits is realized with optoinsulators and Hall effect transducers to guarantee the necessary metallic insulation required between these boards. Such connection allows not only to drive the valve in PWM mode and hence to implement the different MPPT techniques without modifying the power components, but also to acquire the PV voltage and current signals.

In particular, the voltage and current measurements are made by Hall effect transducers; they are perfectly suitable for this application indeed they are able to detect continuous components, furthermore they can guarantee very low losses during the measurement and insulation between the control board and the power one, and finally they have a wide enough bandwidth.

To reduce the white noise effects and to remove all the oscillation with fundamental frequency of 100 Hz into the signals, the control performs a mean value computation among 10ms.

There are a lot of dc-dc conversion circuits. In the present work the boost configuration is chosen. It is very spread thanks to its high reliability respect to other more complex configurations, to the reduced number of components and also to the high-minded experience in its operation.

The complete power device scheme is shown in Fig. 3.

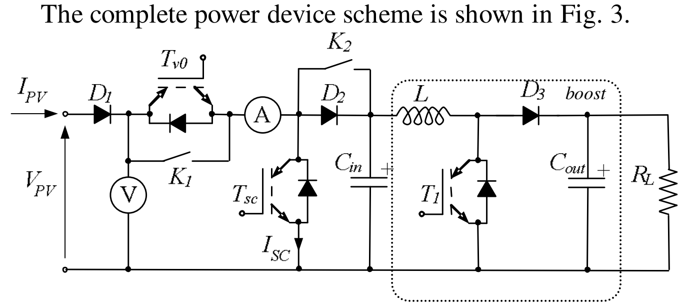


Fig. 3. Scheme of the power device.

The boost section is realized by the two accumulation units, L and C_{out}, by the T_1 static switch and by the D_3 diode.

Moreover, diode D_1 is put into the circuit to protect the PV-panel against negative current which could damage it.

The measures of the PV-panel voltage, V_{PV}, and current, I_{PV}, are obtained by inserting the voltage transducer V and the current one A in the circuit as reported in Fig. 3.

Fig. 3 shows the circuit elements T_{v0}, T_{sc}, K_1, K_2, C_{in} and D_2, that have been inserted to:

- measure the PV-panel open circuit voltage, that is necessary in OV technique, through the opening of T_{v0} valve, in this case D_2 is short-circuited through K_2;
- measure the PV-panel short-circuit current, that is necessary in the SC technique, through the closure of T_{sc} valve, in this case T_{v0} is short-circuited through K_1.

During the tests of other MPPT techniques, the valve T_{sc} is kept open, while T_{v0} and D_2 are short-circuited, respectively through K_1 and K_2 switches, to increase converter efficiency removing their power losses even if this not affect the MPPT algorithms because the voltage and current measurements are evaluated before this group of valves.

It is important to note that in the SC MPPT technique it is necessary to insert the D_2 diode to avoid, during the short-circuit test, the discharging of C_{in} placed at boost input. Such capacitor is always inserted in each techniques analysed to limit the high frequency harmonic components.

The prototype converter has been sized for the voltage of 3 in-series modules and the current of 3 in-parallel modules. In particular, in correspondence of the Standard Test Condition (STC), therefore at 1000 W/m^2 and 298 K, we have:

- a maximum open circuit voltage equal to 21.8 V and a maximum short-circuit current equal to 13.05 A with the modules in parallel configuration;
- a maximum open circuit voltage equal to 65.4 V and a maximum short-circuit current equal to 4.35 A with the modules in series configuration.

The dc-dc converter is designed to work at the MPP with a duty cycle of 25%. The dc-dc converter sizing, with a security margin, leads to the following data: switching frequency of 20 kHz, nominal current of 15 A, and nominal voltage of 150 V.

The IGBT IRG4PC30KD electronic valves are chosen. These components have integrated a ultrafast recycling diode and present small switching losses also in presence of high switching frequency.

B. PV panel

The PV panels here considered are the poly-crystalline 70 W PV-module by Helios Technology. Its main specifications are shown in Table I.

TABLE I.
ELECTRICAL CHARACTERISTICS OF PV PANEL IN STC

Symbol	Quantity	Value
P_{MPP}	Maximum Power	70 W
V_{MPP}	Voltage at P_{MPP}	17 V
I_{MPP}	Voltage at I_{MPP}	4.11 A
I_{SC}	Short-Circuit Current	4.35 A
V_{OV}	Open-Circuit Voltage	21.8 V
NOCT	Nominal Operating Cell Temperature	43±2 °C

C. Solar simulator

The sunlight simulator have to guarantee low spatial non-uniformity and temporal instability of irradiance, moreover it have to permit a significant power output from PV-system and finally it have to allow different irradiance levels on the PV-panel.

The solar simulator used in the present tests is realized by using incandescent and halogen lamps. The maximum power of the solar simulator is 2.8 kW and its size is 1200 mm long and 600 mm wide.

Combining the lamps, it is possible to have four different irradiation levels equal to 0 W/m^2, 272 W/m^2, 441 W/m^2 and 587 W/m^2.

III. NUMERICAL RESULTS

The measurements have been performed several times in order to cut off deviations caused by interferences and/or environmental factors in this system. The most important environmental factor, that hardly influence the PV-panel behaviour, is its temperature. In order to maintain the PV-panel temperature equal in all tests and to preserve this parameter into a little range during tests, all experiments are made starting from the same PV-panel's temperature, and the duration of tests has been reduced as short as possible avoiding overheating.

The test campaign involved a single module as the ones described in Table I, due to energy absorbed from the network and available space constraints, but especially due to economic constraints associated to the dimensions of the solar simulator.

The compared MPPT techniques are: classical P&O (P&Oa), modified P&O (P&Ob), three point weight comparison (P&Oc), Constant Voltage (CV), incremental conductance (IC), open circuit voltage (OV) and short-current pulse (SC).

In order to realize a precise analysis of the performance of the different MPPT techniques, they are experimentally compared taking into account two different irradiation diagrams. The first one, Case 1 (Fig. 4), is characterized by medium and medium-high irradiation levels of 441 W/m^2 and 587 W/m^2 with a time of 180 s and the second one, Case 2 (Fig. 5), with low, low-medium, medium-high irradiation levels of 0 W/m^2, 272 W/m^2, 441 W/m^2 and 587 W/m^2, with a time of 160 s (Case 2 include a 10 s interval without irradiation).

Every MPPT technique analysis starts when the initial steady state condition of each case are reached.

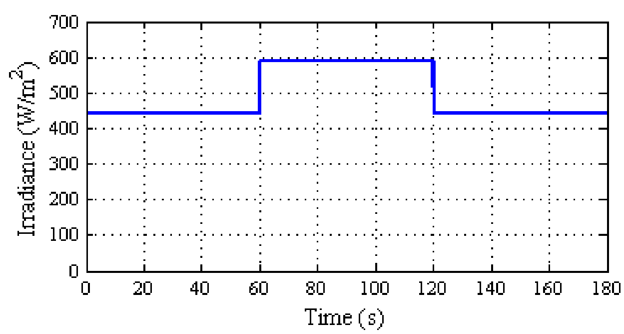


Fig. 4. Irradiation diagram of Case 1.

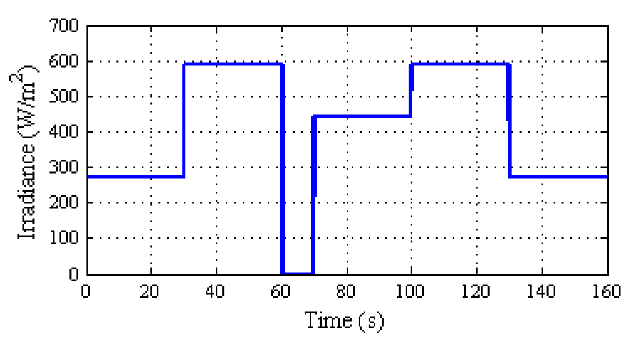


Fig. 5. Irradiation diagram of Case 2.

The P&Oa technique used in this comparison increases or decreases the duty-cycle of $\Delta\delta$=1.6% each 200 ms. It performs very well with low radiance values: in this condition the P-V curve is very smooth near the maximum and hence the 1.6% duty-cycle variations do not imply significant output power reduction under steady state condition. In case of higher radiance values, instead, oscillations are more evident. To reduce the oscillations it is necessary to reduce the $\Delta\delta$, but this implies a reduction of the technique's speed during the variations. The chosen $\Delta\delta$ value is a compromise between the reduction of steady state oscillations and the dynamic behavior of this technique.

Also in the case of P&Ob technique, the algorithm increases or decreases the duty-cycle with the same logic of P&Oa, and performs an iteration every 200 ms. In this technique the amplitude of duty-cycle (increase or decrease) is proportional to the ratio dP/dV and it ranges from 0.5% to 2.7%. The P&Ob logic with variable step is able to reduce steady state oscillations and, at the same time, to provide higher response speeds at medium-high irradiance level with respect to the P&Oa approach with fixed $\Delta\delta$. This technique is very slow in reaching MPP when irradiance level is low because dP/dV is small.

The P&Oc technique compare the power of three different working points. The first one is taken as reference, the second one is obtained increasing the duty-cycle of $\Delta\delta$ (equal to 1.6%) with respect to the reference and the third one is obtained decreasing duty-cycle of $\Delta\delta$ with respect to the reference. The algorithm modifies the duty-cycle, in function of the obtained results, to reach the MPP value as described in [12]. The amplitude of the duty-cycle's increment (or decrement) is constant and the algorithm performs an iteration every 200 ms.

The IC technique performs the test on the incremental conductance every 200 ms. This algorithm should run faster, but in this comparison is enforced to have the same duty-cycle variation speed and $\Delta\delta$ to the other algorithms. With this variation speed the performance is different until to arrive in steady state conditions. Case 2 shows the main disadvantage of the IC technique: for low radiance values the technique works on a P-V curve with a derivative close to zero in a large interval around the maximum value, therefore it is not able to properly identify the MPP. It results in oscillations around the MPP with a reduced output energy value.

The CV technique performs PV voltage regulation every 200 ms and is optimized for a single radiance value; the performance of this technique is strongly related with the voltage set point. As in IC technique, this algorithm should run faster, but in this comparison its speed and $\Delta\delta$ are forced to be the same of the other algorithms. It provides satisfying results, but they aren't as good as the ones provided by P&O and IC techniques.

Further considerations may regard OV and SC techniques. They require additional valves for, respectively, the measurement of the PV open circuit voltage and of the short-circuit current.

Concerning the OV technique, the voltage drop on T_{v0} is equal to about 1.5V, which implies a significant reduction of the load voltage, and hence of the output power. This is a significant feature in the evaluation of the converter efficiency. This technique performs voltage regulation every 200 ms and refresh the voltage reference value every 3 s through the open voltage measurement (for this measurement is necessary 10 ms without power generation). The ratio of the open voltage and the MPP voltage is not strictly constant with temperature, and the technique can be optimized only for a single temperature value. For this reason the converter performance with OV technique is in general better than CV, but is not as good as the ones provided by P&O and IC techniques because of the voltage drop on T_{v0} and the necessary measurement time.

Analogous considerations regard the SC technique. In this case the voltage drop that reduces converter's output power is due to the D_2 valve and it is about 0.6 V. This technique performs current regulation every 200 ms and it refresh the reference current value every 3 s through the short-circuit current measurement (for this measurement is necessary 10 ms without power generation). The voltage applied to the PV-panel during the measurement step is the voltage drop across T_{sc}. In this condition the measured current can be approximated to the real short-circuit current.

Fig. 6 shows the power generated from the PV-panel with the same converter configuration and different MPPT techniques in the two cases. The diagrams also show the ideal power, obtained by using an ideal MPPT technique that is equal to the maximum power that the PV-panel can produce. These values are measured directly on the PV-panel under test in STC. For this reason MPPT ideal curve must be considered only as a qualitative reference to compare tests' results.

It is important to observe that the uncertain in the PV voltage and current measurements and the small difference in the environmental conditions between each tests suggest that the results cannot be a good reference to calculate the efficiency of the single MPPT algorithm. In these conditions, even an uncertain of 0.5% in the measurements could produce an uncertain in the relative power losses that could be more than 10%.

Table II summarizes the performances of the different techniques in the two considered cases.

TABLE II.
ENERGY GENERATED AS A FUNCTION OF MPPT TECHNIQUE AND IRRADIANCE INPUT

MPPT Technique	Case 1		Case 2	
	Energy [J]	Rank	Energy [J]	Rank
P&Oa	4222	3	3119	2
P&Ob	4330	1	3197	1
P&Oc	4261	2	3104	3
IC	4175	4	3035	5
CV	4086	6	2984	6
OV	4145	5	3038	4
SC	4059	7	2970	7

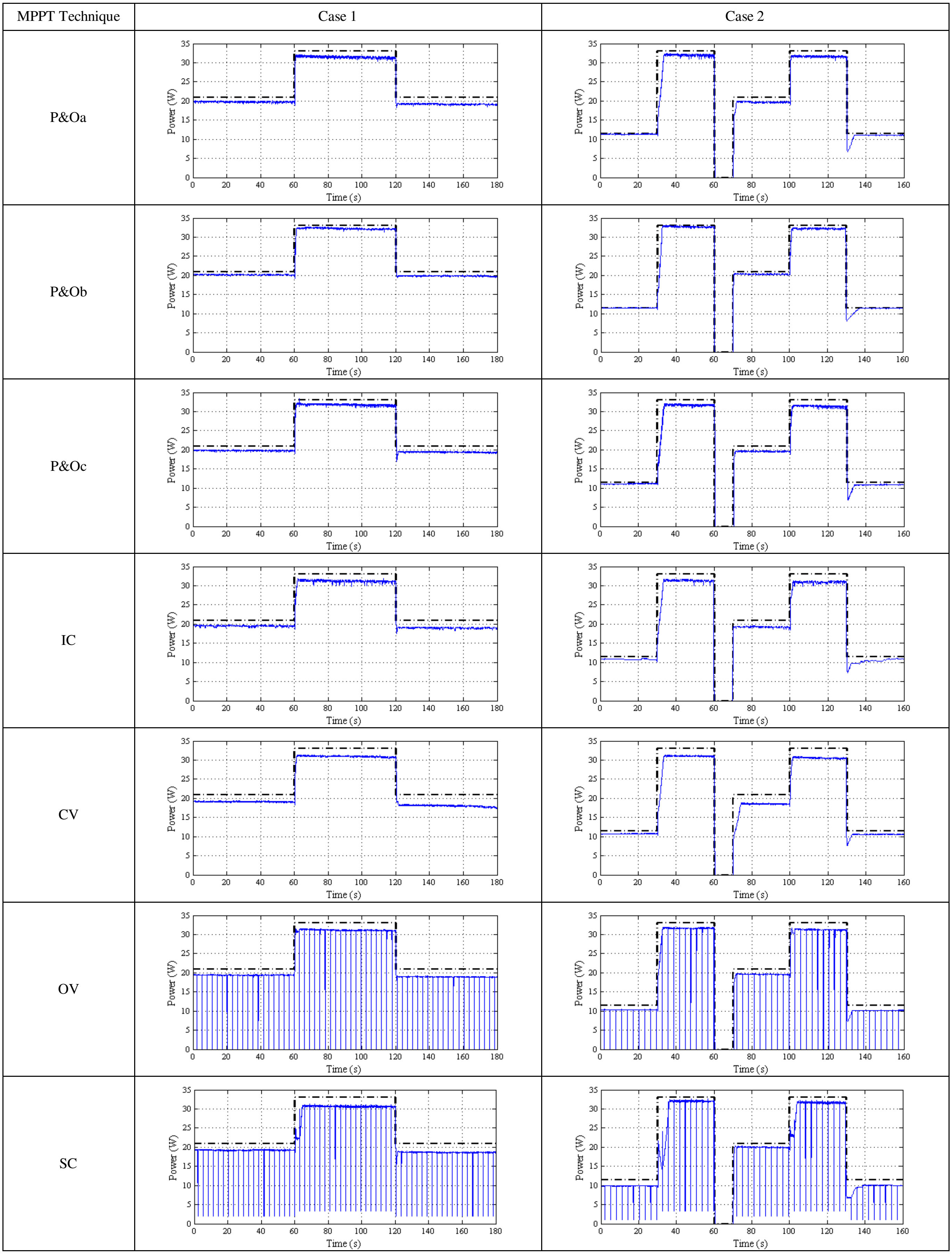


Fig. 6. Power generated by the PV array in the Case 1 and Case 2 by different MPPT methods (solid line) and ideal (dot-dashed line) MPPT method.

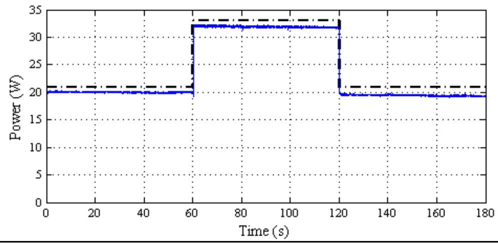
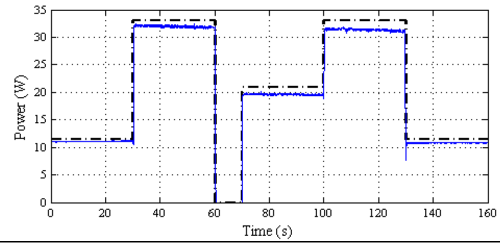
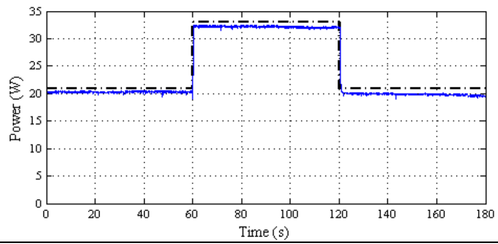
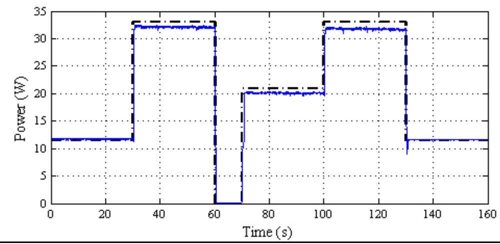
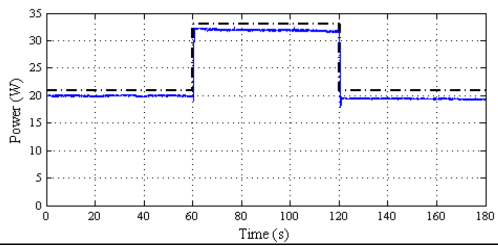
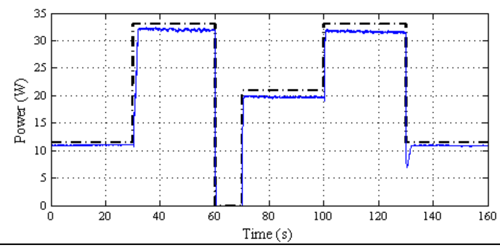
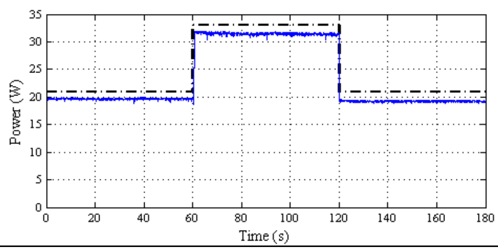
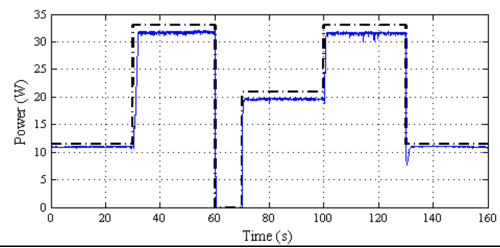
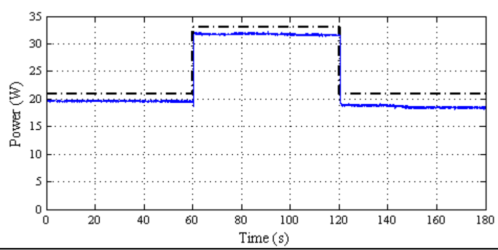
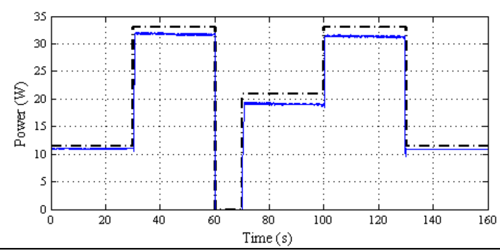
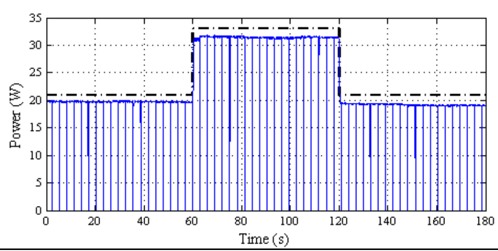
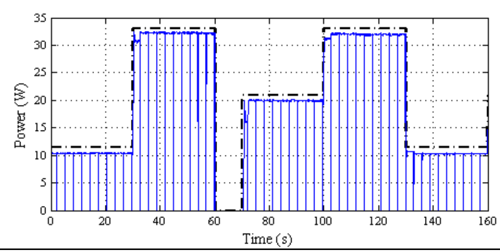
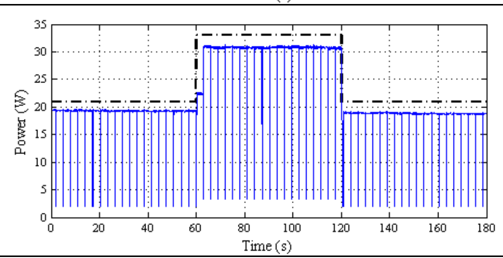
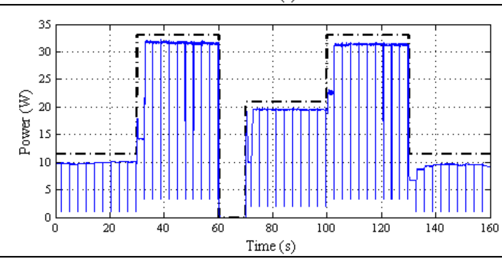
MPPT Technique	Case 1	Case 2
P&Oa		
P&Ob		
P&Oc		
IC		
CV		
OV		
SC		

Fig. 7. Power generated by the PV array in the Case 1 and Case 2 by different optimized MPPT methods (solid line) and ideal (dot-dashed line) MPPT method.

IV. Numerical Results – Optimized MPPT Algorithm

The results previously described, and summarized in Fig. 6 and Table II, are made with the same mean speed of the duty cycle variation, that is equal to $\Delta\delta=\pm1.6\%$ every 200 ms. To evaluate the maximum dynamic performance of these algorithms a second test campaign was made, reducing the time interval between two iterations of the MPPT logic and decreasing the amount of duty-cycle variation.

A couple of samples of voltage and current is available every 10 ms, and P&Oa, P&Ob, IC, CV, OV and SC algorithms can perform an iteration for each couple of values; only P&Oc needs 3 measurement of power instead of 1.

Duty-cycle variation amplitude $\Delta\delta$ is 0.5% for all techniques except P&Ob, in witch $\Delta\delta$ is the same adopted to the previous paragraph. A reduced duty-cycle variation value decreases the speed of the algorithm dynamic behaviour but it increases the precision in reaching MPP. Therefore the reduction of the time interval between two iterations, from 200 ms to 10 ms (except P&Oc that perform an iteration every 30 ms), and the reduction of duty-cycle variation amplitude give both better accuracy and fastest dynamic response.

The optimized techniques increase the energy extracted form PV-panel because they are faster in reaching the MPP after a variation of irradiance and they are more accurate in tracking the MPP value.

Fig. 7 shows the power generated from the PV-panel with the same converter configuration and different MPPT techniques in the same two cases. Table III summarizes the performances of the different techniques in the two cases and compare the results to the ones obtained in Table II.

All optimized techniques show better performance than the non-optimized ones, except for the SC. This is due to the fact that in presence of irradiance variation this technique firstly moves the duty-cycle in the worst direction till a new short-circuit measurement. For this reason high regulation speed in SC technique, especially in presence of high fast and continuous irradiance variation, can produce worst results than that a lower regulation speed will generate.

Table III.
Energy Generated as a Function of MPPT Technique and Irradiance Input

MPPT Technique	Case 1			Case 2		
	Energy [J]	Rank	Delta Energy	Energy [J]	Rank	Delta Energy
P&Oa	4282	2	+1,4%	3144	2	+0,8%
P&Ob	4346	1	+0,4%	3212	1	+0,5%
P&Oc	4278	3	+0,4%	3135	3	+1,0%
IC	4215	4	+1,0%	3117	4	+2,7%
CV	4201	5	+2,8%	3100	6	+3,9%
OV	4200	6	+1,3%	3104	5	+2,1%
SC	4088	7	+0,8%	2942	7	-0,9%

V. Conclusions

This paper has presented a comparison among some of the more diffused Maximum Power Point Tracking techniques in relation to their energy performance. In particular, different types of solar insolation characterized by low and medium irradiation level are considered, and the energy supplied by a complete PV array is experimentally evaluated. The whole system – including the dc-dc converter and the lighting system – is arranged in the power quality laboratory of Department of Energy of the Politecnico di Milano. The different MPPT techniques have been implemented following the directions indicates in the papers listed in the references; no one has been preferred or better improved respect to the others.

The results show that the best MPPT technique is the modified P&O (P&Ob). The logic turned out to be effective in both the situations here considered, providing always the highest efficiency. P&Ob technique shows its limit in the response to the irradiance variation at low irradiance level.

The IC technique has an efficiency lower than the P&O techniques, but its response time is quite independent to the irradiation values and its efficiency increase with the irradiance level. This technique can be a good alternative to the P&O techniques in applications characterized by high, fast and continuous radiance variations, e.g. the PV applications in transportation.

The two techniques are also equivalent concerning the costs and the software complexity; in particular both the techniques require a microcontroller with medium/higher performances than the ones required by other techniques, due to the necessity of high computation capability.

Among the other hill climbing techniques, the P&Oa method presents acceptable results: this algorithm can be a good alternative to the two previous techniques. Instead the P&Oc method, even if characterized by output energy values analogous to the P&Oa, has a more complex algorithm and a lower reactivity, with no benefit in terms of performances. Furthermore, given the features required by the controller, the P&Ob technique is better than the P&Oc one.

The P&Oa technique requires a microcontroller which has lower computational capability constraints with respect to the best technique here considered. It is therefore necessary to evaluate if the cost gap between the two microcontrollers is justified by lower performances of the technique.

It is necessary to underline that the maximum irradiance level obtained from solar simulator is about half than the real irradiance from the sun. In these conditions the performance of IC are quite less than the P&O techniques ones because the MPP in the PV power characteristic has a derivative close to zero for a quite large voltage variation.

In the present analysis the CV, OV and SC techniques turned out to be the worst ones. Their performances are lower than the ones obtained with P&Ob techniques especially in case of conditions very different from the radiance and temperature values in correspondence of which these techniques have been modeled. Moreover OV and SC techniques requires additional valves in the converter that decrease its efficiency and the output power.

The CV technique is still a very simple logic which provides a very good efficiency for radiance values closed to 700 W/m^2, with low costs. Hence, generally this technique can be selected only if there is the necessity to minimize the control system cost.

However the cost of a microcontroller currently low, so that the implementation of the P&O type techniques is anyway preferred.

VI. References

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VII. Biographies

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