

Maximum Power Point Tracking of Grid-connected Photovoltaic Arrays by Using Extremum Seeking Control

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Abstract: This paper focuses on the control of grid-connected photovoltaic arrays, which are required to provide the maximum of power irrespective of the solar irradiance conditions. The energy provided by the arrays is sent to the single-phased utility grid by means of a two-stage conversion system, composed of a DC-DC boost converter and a DC-AC inverter. The whole system is controlled through a two-level structure: the upper layer establishes the global scope, *i.e.*, the desired operating regime, which is effectively implemented by the low control layer, *i.e.*, by low-level controlling the two power electronics converters. Thus, the operating regime of the PV arrays is imposed by controlling the DC-DC converter, whereas the inverter is in charge with ensuring the power transfer to the grid. In this case, the global scope of tracking the maximum power point under variable conditions of irradiance is achieved by using a simple and robust extremum seeking control scheme. MATLAB[®]/Simulink[®] numerical simulations are presented and discussed in order to prove the effectiveness of the approach.

Keywords: renewable energy systems, optimal power flow, hierarchical control, extremum seeking control.

1. INTRODUCTION

The actual continuously changing economical and political environment requires new ways of obtaining energy cheaply and safely. The renewable energy sources, clean and practically inexhaustible, are being paid growing attention and efforts are made in order to sustain the improvement of the existing conversion technologies and the development of new ones (PROGRESS, 2008; Carrasco *et al.*, 2006).

The photovoltaic (PV) installations are an already familiar class of renewable energy sources, being encountered either as small (less than 5 kW) residential stand-alone or even grid-connected, or as larger (hundreds of kW), building integrated or not. They can also be parts of hybrid power systems, together with other renewable energy sources (Rajendra Prasad and Natarajan, 2006; Jemei *et al.*, 2006). A lot of research effort is oriented to rendering the PV systems more adequate to the wide use with respect to power, efficiency, grid compliancy, reliability and service time, safety and security, *etc.* (Meyer and van Dyk, 2004; Fernández-Infantes *et al.*, 2006; Shi *et al.*, 2007). The PV system design is a quite complex industrial engineering optimization problem, with objective functions embedding various and sometimes contradictory criteria, whose solution represents the best trade-off in the context of a specific application.

The exploitation practice of PV systems has shown that methods of automatic control and signal processing are necessary in order to optimize its dynamic performance, reactivity to the variability of the primary energy source, *i.e.*, the solar irradiance, and robustness to any kind of disturbances. Depending on the application, the PV systems

may be required either to supply isolated loads or (weak) micro-grids, or even various energy storage systems (*e.g.*, batteries), or to inject the harvested power into a utility (strong) grid. The control goals are defined accordingly; thus, islanded applications will require to keep constant the supplied voltage value and frequency, whereas grid applications will require active and reactive power control, as well as ensuring the proper quality of the energy provided.

One of the most important problems of PV grid applications is how to achieve the *maximum power point tracking* (MPPT), aiming at maximizing the extracted energy irrespective of the irradiance conditions [9]. In the literature one can find a lot of works investigating simple, efficient and minimal-knowledge-demanding methods of MPPT, among which one can find the parasitic capacitance method, the incremental conductance method, the constant voltage method *etc.* (Salas *et al.*, 2006; Xiao *et al.*, 2007; Rodriguez and Amaratunga, 2007; D'Souza *et al.*, 2005; Hohm and Ropp, 2000). From these, the quite successful so-called *perturb-and-observe* (P&O) method is of interest in this paper, having good potential of being widely used. The P&O method is in fact a whole class of methods, consisting in injecting high-frequency small-amplitude (usually harmonic) perturbations in the system aiming at detecting the sign of the power gradient (Chung *et al.*, 2003; Tse *et al.*, 2004; Femia *et al.*, 2005).

One can remark that the MPPT is practically solved in the case of PV modules that have unimodal power characteristics. But in the case of systems composed of many series and parallel connections of PV modules, it may happen that the global power characteristic to exhibit multiple

maxima when the modules receive sensibly different levels of solar irradiance (Karatepe *et al.*, 2007; Shimitsu *et al.*, 2001). One of such particular topology in a single-phased grid application makes the object of this paper, where the energy conversion is performed in two stages, namely by a DC-DC boost converter in charge with imposing the desired operating regime, *i.e.*, the MPPT, and a DC-AC converter (inverter) required to ensure the proper power transfer to the grid. A simple and robust version of P&O method called *extremum seeking control* (ESC) is applied in order to achieve the MPPT under strongly variable irradiance conditions.

This paper is structured as follows. In the next section the structure of the considered PV system is presented and the associated control goals are formulated. The two-level global control structure is also presented, where the upper level control objective of imposing the MPPT operating regime is effectively implemented by the low-level control loops of the power electronics devices. The third section explains how the ESC method can be applied for MPPT of PV generators having unimodal power characteristics. In the fourth section one can find details about the design of basic (low-level)

control loops. Simulation results of the controlled PV system under different relevant irradiance scenarios are discussed in the fifth section. Some concluding remarks and future work are presented in the last section, the sixth.

2. PROBLEM FORMULATION. GLOBAL CONTROL STRUCTURE

The block structure of the PV conversion system together with its general control structure is given in Fig. 1. The PV conversion system considered here is composed of an array of PV modules whose captured energy is sent to the single-phased utility grid after being converted into electrical energy by means of a two-stage power electronics system: a DC-DC converter and a DC-AC converter (inverter) connected through a DC-link. The PV array is composed of n series connections connected in parallel, each of which is composed of m PV modules. It is supposed that, in general, each module undertakes its own irradiance conditions, Irr_{ij} , $i=1,2,\dots,n$, $j=1,2,\dots,m$. The PV array output current is I_{PVa} and its output voltage is V_{PVa} .

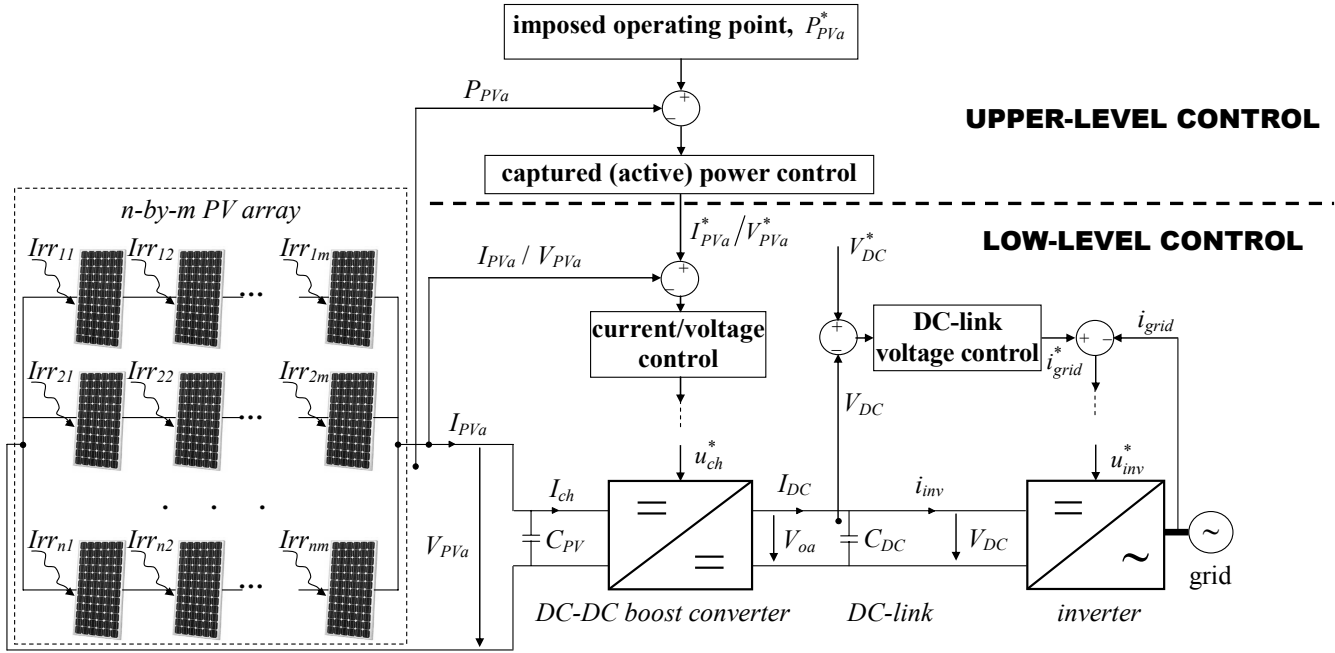


Fig. 1. Grid-connected PV energy conversion system and the associated two-level control structure

The control system has a two-level general structure. The desired operating regime is decided in the upper level – the low-level control effectively implements the decision taken at the upper level. In the case of grid-connected systems, imposing a certain operating point is equivalent with imposing a certain level of the power provided, P_{PVa}^* . The DC-DC converter is used to boost the voltage level in the DC-link; it is controlled in the sense of tracking either a current or a voltage reference, I_{PVa}^* or V_{PVa}^* , corresponding to the operating point imposed by the superior decision level (see also the static power characteristics from Fig. 2). The inverter output current, i_{grid} , is controlled such that an imposed voltage value, V_{DC}^* , be maintained in the DC-link.

Grid-connected PV systems are generally required to harvest the maximum power available. Therefore, the desired operating regime is the one that ensures the maximum power point tracking irrespective of the solar irradiance conditions. In this case, the upper-level control structure from Fig. 1 becomes an optimization control loop, required to track the maximum power operating point – which is in general not precisely known and varies with the irradiance level – instead of tracking an imposed power setpoint. The static power characteristics of singular PV modules are generally unimodal curves, as it is well known (Messenger and Ventre, 2003). In the case of PV arrays, if the irradiance levels received by the individual modules are not significantly imbalanced, these characteristics can remain unimodal – as

shown in Fig. 2a – but in the case of very large imbalance (e.g., when more than a half are shaded) they can exhibit multiple maxima – as Fig. 2b shows.

If the power characteristics are unimodal, then the MPPT of PV arrays can be achieved with the same methods like in the case of singular modules, as briefly reviewed in the previous section. If this is not the case, then the problem is to find a robust, sufficiently simple and as less demanding as possible control method which guarantees the convergence to the global maximum. In Shimitsu *et al.* (2001) the power optimization of a series connection of PV modules from which ones are partially shaded is achieved by means of a so-called Generation Control Circuit (GCC). In this paper the extremum seeking control method is proposed in order to implement the MPPT of a PV array under irradiance conditions that are time varying, as well as variable from a module to another. The aim is to study by numerical simulation the performance of this control method in both cases: of a unimodal power curve and of a power curve with multiple maxima.

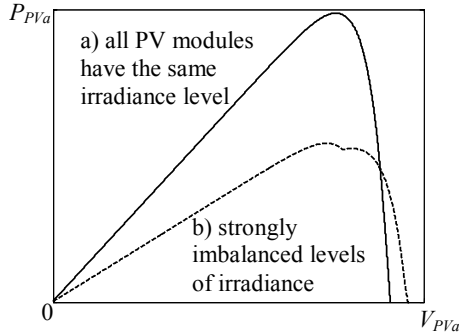


Fig. 2. Global static power characteristic of a PV array exhibiting: a) a single maximum; b) multiple maxima under certain irradiance conditions

3. EXTREMUM SEEKING CONTROL USED FOR MPPT OF SINGULAR PV MODULES

The extremum seeking control (ESC) can be used when searching for the extremum of some unimodal dynamics,

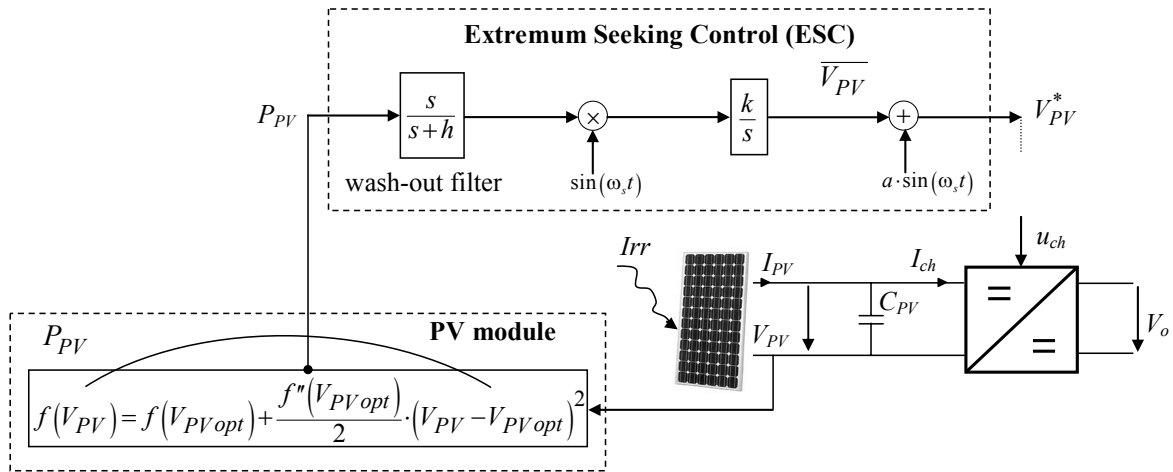


Fig. 3. The extremum seeking control (ESC) method applied in the case of singular PV modules by controlling the voltage of the associated DC-DC converter

usually difficult to model. Successful applications of ESC in the case of multiple maxima have also been reported (Tan *et al.*, 2006), however its effectiveness in finding the global maximum has not yet been theoretically guaranteed. This method is based on feeding the plant with sinusoidal probing signals (Åström and Wittenmark, 1995; Krstić and Wang, 2000; Ariyur and Krstić, 2003).

Fig. 3 illustrates the principle of this control method (Åström and Wittenmark, 1995): the controller performs a modulation/demodulation operation, outputting a harmonic component called the *probe signal*. The controller habitually contains a so-called washout filter, a demodulator, a low-pass filter and an integrator for obtaining the average component of the control input, as well as a summation with the probe signal block.

Let us consider a PV generator having a unimodal power characteristic connected to the grid through a two-stage conversion system like the one in Fig. 1. It is modelled by a generic power function, $P_{PV}(V_{PV})$, having an unique maximum at V_{PVopt} , whose argument has two components: an average one, $\overline{V_{PV}}$, and a harmonic probing one, of amplitude a (Fig. 3). This function is approximated by its two-term Taylor's series around its maximum, $P_{PV}(V_{PVopt})$. Let $\widetilde{V_{PV}} = V_{PVopt} - \overline{V_{PV}}$ be the searching error. Because constants k and a are positive and $P_{PV}''(V_{PVopt})$ is negative, it results that the searching error gradient is negative also (Ariyur and Krstić, 2003):

$$\dot{\widetilde{V_{PV}}} = 0.25 \cdot k \cdot a^2 \cdot P_{PV}''(V_{PVopt}) \cdot \widetilde{V_{PV}} < 0$$

In this way a convergent searching process is achieved. The stability of the closed loop system is ensured by a sufficiently large excitation frequency, ω_s , which the washout filter parameter, h , depends on (Ariyur and Krstić, 2003).

If a PV module is fed with a ω frequency sinusoidal voltage variation having a sufficiently small amplitude a , its output power variation will be sinusoidal, in phase with the voltage variation if the operating point is on the rising part of the voltage-power curve and with a phase lag of π for the falling part (see Fig. 2a). The integrator input, $d\overline{V_{PV}}/dt$, will toggle its sign following the excursion of the operating point from a side to the other of the maximum. Assuming equal slopes of the $P_{PV}(V_{PV})$ curve, the following value is integrated:

$$d\overline{V_{PV}}/dt = \pm k \cdot b \cdot \sin^2(\omega_s t),$$

where b is the amplitude of the induced sinusoidal power variation. Hence, the operating point moves to the optimal position with a speed of convergence depending proportionally on k , a and $1/\omega_s$ (Ariyur and Krstić, 2003). In this paper, the presented control method is employed in order

to impose the maximum power operating point to the PV array by means of controlling the DC-DC converter. Fig. 3 also details the corresponding block diagram, where the MPPT is achieved by controlling the DC-DC converter input voltage. Thus, the duty cycle u_{ch} results within a voltage control loop, whose reference V_{PV}^* comes from an ESC-based MPP tracker using the measured PV module power, P_{PV} .

3. DESIGN OF LOW-LEVEL CONTROL LOOPS

In this section basic control loops of the different stages of the conversion system are described. Modelling of the interaction between the PV array and the chopper on a hand, and of the interaction between the DC-link and the inverter on the other hand must be considered for control purposes. To these interactions correspond the two low-level control loops from Fig. 1. The electrical scheme of the conversion system is given in Fig. 4.

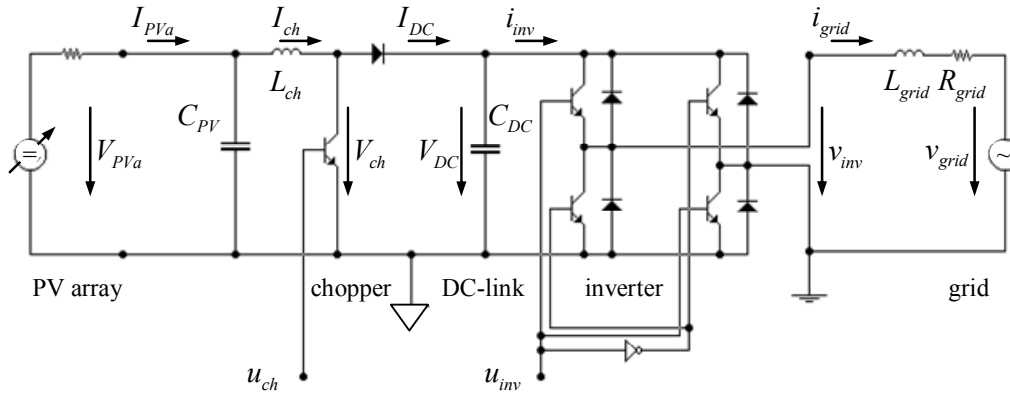


Fig. 4. Electrical scheme of the two-stage PV conversion system

In the following, notations introduced in Fig. 4 will be used.

The interaction between the PV array and the chopper takes place in the sense that the difference between current I_{PVa} and chopper's current, I_{ch} , determines the capacity C_{PV} being charged; thus, using notation introduced in Fig. 1 and Laplace notation, one can write:

$$V_{PVa} = \frac{1}{sC_{PV}}(I_{PVa} - I_{ch}) \quad (1)$$

The variation of the PV array's current, I_{PVa} , versus its voltage, V_{PVa} , is nonlinear, having the same shape as the analogue curve of a single module, strictly decreasing and concave (Messenger and Ventre, 2003). For sake of simplicity, this curve is usually used in control design as linearized around a suitably chosen steady-state operating point. Thus, the exact nonlinear function $I_{PVa}(V_{PVa})$ can be replaced by a linear one:

$$I_{PVa} = -C \cdot V_{PVa}, \quad (2)$$

where coefficient $C > 0$ varies with the operating point. Taking into account that in this paper the desired operating regime is the maximum power point tracking and assuming that this regime is ensured by the upper-level control loop, one can also assume a constant value of C when designing the low-level control loops. From (1) and (2) results:

$$sC_{PV}V_{PVa} + C \cdot V_{PVa} = -I_{ch} \quad (3)$$

The interaction between the boost chopper and the DC-link is governed by power conservation equations:

$$\begin{cases} V_{ch} = V_{DC}(1 - u_{ch}) \\ I_{ch}(1 - u_{ch}) = I_{DC} \end{cases} \quad (4)$$

and by the electromagnetic energy variation in the inductance L_{ch} (the diode voltage drop is neglected):

$$I_{DC} = \frac{1}{sL_{ch}}(V_{PVa} - V_{DC}) \quad (5)$$

Note that relation (4) denotes an average model. From (4) and (5) one can deduce:

$$I_{ch} = \frac{1}{sL_{ch}} \left(\frac{V_{PVa}}{1-u_{ch}} - V_{DC} \right), \quad (6)$$

where the DC-link voltage, V_{DC} , is constant, as it is maintained by the inverter. The chopper is controlled such that to impose a certain operating point, that is, a desired

value of the array output voltage, V_{PVa}^* . To this end, one can use, for example, a PI controller that provides the corresponding reference of the chopper's current, I_{ch}^* (Fig. 5). This controller is tuned by using the plant model (3). I_{ch}^* serves as reference for an inner current control loop, which is faster. The current loop uses the hysteretic control for model (6) and further provides the necessary duty cycle, u_{ch}^* , which is sent to the chopper as PWM signal. The control diagram of the chopper is presented in Fig. 5.

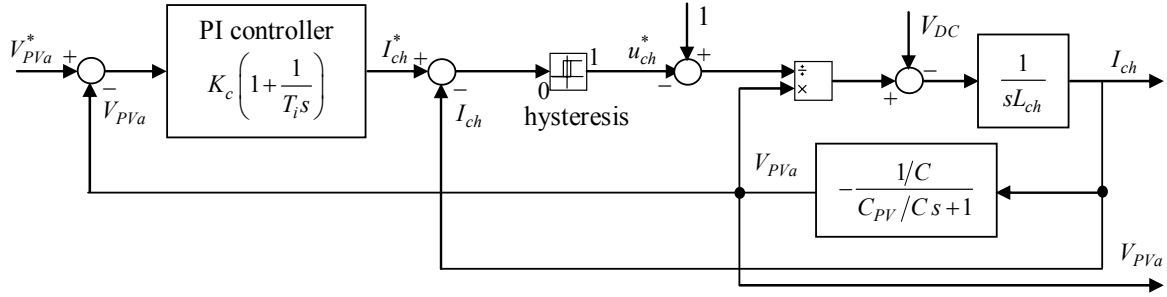


Fig. 5. Control of the boost chopper: imposing of the desired input voltage, V_{PVa}^* , corresponding to the desired PV array's operating point

One can aim at imposing a desired current, I_{PVa}^* , in a similar manner. Note also that, no matter how it is implemented – either as voltage or as current control loop – the reference of the chopper's control loop is provided by the upper control level, which consists finally in requiring a certain level of power (see also Fig. 1). In the second conversion stage, the inverter transforms the DC-link voltage into AC single-phased voltage in order to achieve the grid connection. The inverter control goal is to inject sinusoidal current into the grid, meanwhile maintaining the DC-link voltage constant. Thus, using notations in Fig. 4, the following relations hold:

$$sC_{DC}V_{DC} = I_{DC} - i_{inv}, \quad (7)$$

$$i_{grid} \cdot (sL_{grid} + R_{grid}) + v_{grid} = v_{inv}, \quad (8)$$

$$\begin{cases} v_{inv} = u_{inv} \cdot V_{DC} \\ i_{inv} = u_{inv} \cdot i_{grid} \end{cases}, \quad (9)$$

where u_{inv} is the commutation function of the inverter, having three components: the fundamental of the grid voltage, higher-frequency harmonics due to the system dynamics and a high-frequency component due to voltage switching. The high-frequency components are not concerned by the control (they are filtered by a conveniently sized value of inductance L_{grid}), therefore, u_{inv} is a variable-amplitude 50-Hz-sinusoidal signal. By replacing $u_{inv} = U_{inv} \cos(\theta)$ and $i_{grid} = I_{grid} \cos(\theta)$, with the capital-letter variables denoting the amplitudes and $\theta = \omega t$ being the grid electrical angle, in the second equation from (9), one obtains (switching frequency omitted):

$$i_{inv} = U_{inv} I_{grid} / 2 + U_{inv} I_{grid} / 2 \cdot \cos(2\omega t) \quad (10)$$

Equation (10) shows that the current drawn by the inverter from the DC-link, i_{inv} , is a sum of a DC component, noted by:

$$I_{inv} = U_{inv} I_{grid} / 2, \quad (11)$$

and a double-grid-frequency (100 Hz) sinusoidal component, whose amplitude depends on the delivered current, I_{grid} . i_{inv} cannot be measured and it cannot be used as feedback signal in control – the grid current, i_{grid} , is used instead, because it depends of i_{inv} , but it is smoothed by L_{grid} .

The inverter is controlled by means of two loops: an outer voltage loop, regulating the DC-link voltage at an imposed value, V_{DC}^* , and imposing the grid current reference, i_{grid}^* , to an inner current loop. Besides this aspect, the current loop is sufficiently fast so that the voltage V_{DC} can be taken as constant and the i_{grid} generation model is considered linear.

A commonly used solution in this case is based on a hysteretic nonlinear controller inside the current loop (Bose, 2002). The reference i_{grid}^* must be sinusoidal; it is obtained by multiplying the required amplitude I_{grid} with a synchronization signal provided by a phase-locked loop (PLL). The inverter control diagram is presented in Fig. 6.

Disturbances induced in V_{DC} by the variations of current I_{DC} are rejected by using a PI controller (see (6)). Note also that the PI voltage controller must be tuned as it could further impose i_{inv}^* . In fact, using the relation that exists between i_{grid} and i_{inv} in DC components, which is implemented by the block called “compensation law” in the diagram at Fig. 6, the PI controller imposes the amplitude of i_{grid} , I_{grid}^* .

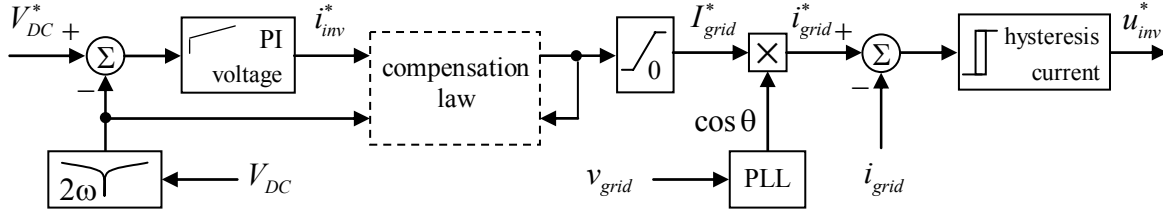


Fig. 6. Control of the grid-side inverter: maintaining the imposed DC-link voltage, V_{DC}^*

In order to deduce the compensation law, one must start from (8) also holding for 50 Hz-amplitudes at the grid side (the effect of L_{grid} on 50 Hz-signals is neglected):

$$I_{grid} \cdot R_{grid} + V_{grid} = V_{inv} \quad (12)$$

In (12) one can replace $V_{inv} = U_{inv} \cdot V_{DC}$, according to the first equation from (9), then use (11) to finally obtain:

$$I_{grid} (I_{grid} R_{grid} + V_{grid}) = 2V_{DC} I_{inv}, \quad (13)$$

which is the compensation law sought for, allowing for imposing I_{grid}^* that corresponds to a required I_{inv}^* . However, one can omit this compensation law when designing the control, but the closed-loop overall gain will depend on the grid current amplitude, I_{grid} .

Because the plant control input is quite particular, having intrinsic 2ω variations, the V_{DC} voltage will also be affected depending on the values of C_{DC} and I_{grid} . In Fig. 6 one can

note the presence of a notch filter on the measured DC-link voltage, to eliminate its 2ω variations not useful for control purpose.

5. NUMERICAL SIMULATION RESULTS

The effectiveness of the proposed control laws has been tested by MATLAB®/Simulink® numerical simulations on the PV conversion system whose features and control parameters are given in the Appendix. The following two sections are dedicated to respectively illustrate the performance of the low-level control loops and the performance of the ESC law employed for the MPPT.

5.1 Performance of low-level control loops

The simulation results corresponding to the chopper control are presented in Fig. 7. Fig. 7a₁ shows the responses in PV voltage and in PV current, respectively, at step changes of voltage reference – from 45 V to 40 V and back to 45 V – whereas Fig. 7a₂ shows how the chopper duty cycle varies in the same case.

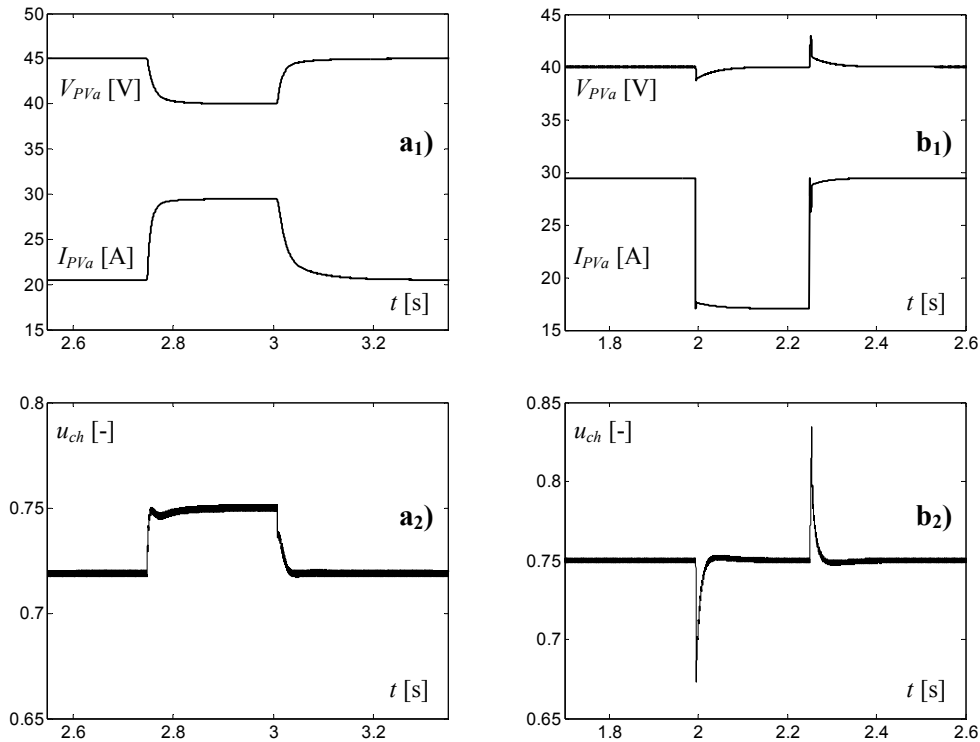


Fig. 7. Performance of the chopper low-level control: a) response to step variation of the input voltage reference; b) rejection of step variations of the irradiance level (from 1000 W/m^2 to 500 W/m^2 and back to 1000 W/m^2)

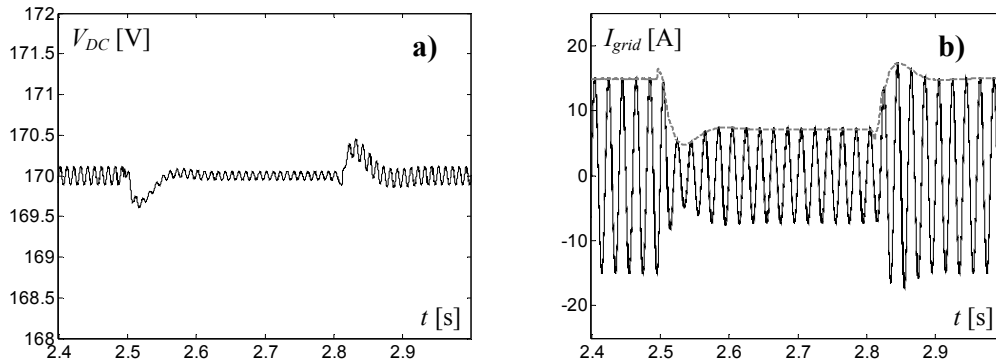


Fig. 8. Performance of the inverter low-level control – effect of irradiance step changes (from 1000 W/m² to 500 W/m² and back to 1000 W/m²) a) over the DC-link voltage, V_{DC} , and b) on the current injected to grid, I_{grid}

Fig. 7b₁ illustrates the rejection of a step variation of irradiance when the voltage setpoint is 40 V; Fig. 7b₂ presents the variation of the duty cycle in the same conditions. Note that the transients are shorter than 0.1 s.

Fig. 8 contains simulation results associated to the inverter basic control loops, namely the effect of an irradiance step variation. Fig. 8a shows the rejection of this step as a disturbance by the DC-link voltage control loop, whereas Fig. 8b presents the variation of the grid current under the same conditions. One can remark the transient response of the grid current's amplitude.

5.2 Performance of MPPT by ESC

Two aspects have been studied about the performance of the ESC law used for MPPT: the first one concerns the dynamic performance of tracking unimodal power curves depending on how is set the ESC controller parameter, k (Fig. 3), while the second aspect is focused on the capability of tracking multimodal power curves. These two aspects are illustrated by the simulation results shown in Fig. 9 and in Fig. 10, respectively. Remember that, if all the modules of the PV array receive the same irradiance level, then global unimodal power curves are obtained.

At its turn, Fig. 9 contains two types of simulation results: Fig. 9a refers to the case when the common level of irradiance is affected by step changes (from 900 W/m² to 600 W/m², and then back to 900 W/m²). The system is set to start from the imposed voltage of $V_{pva}=43$ V at 900 W/m² irradiance, which does not correspond to the maximum power point. Thus, the first power transient shows how the system performs the MPPT and reaches the maximum power operating point. Three time evolutions of the power are presented, namely for three different values of the ESC controller parameter, k . One can note that, the larger the value of k is, the better the tracking quality. However, the value of $k_3=50$ denotes controller over-tuning, as it corresponds to a longer and more turbulent transient.

The other figures, that is, Fig. 9b,c,d illustrate the dynamic behaviour under strongly variable irradiance conditions, that is, when the irradiance varies stochastically. Regarding the

dynamic model of the irradiance, as the literature is very poor in references, one can make an analogy with the dynamic modelling of another irregular renewable energy source, the wind speed (Munteanu *et al.*, 2008). Thus, here it is supposed that the irradiance dynamic behaviour can be modelled by a two-spectral-component model, containing an average component and a turbulent component. Intuitively, as the light is however more regular than the wind, the frequency of variations would be smaller than in the case of wind. Also, the turbulent component of the irradiance would depend inversely of its average – the irradiance turbulence is greater on cloudy days – unlike the wind, where the turbulence level of the wind speed depends directly on the average wind speed (Munteanu *et al.*, 2008). The following irradiance model has been used in simulations:

$$Irr(t) = \overline{Irr} + \left(Irr_{max} / \overline{Irr} \right)^3 \cdot f_t(t), \quad (13)$$

where $f_t(t)$ is a band-limited white noise passed through a suitably chosen low-pass filter having the gain proportional with the desired turbulence variance. In this case, variation speed has been set around 1 s, which corresponds to faster variations than habitually occurring.

The irradiance stochastic signal can be viewed in Fig. 9b with dashed line; indeed, it exhibits quite fast variations in relation to the usual natural behaviour, but this emphasizes even more the robustness of the MPPT by ESC. The corresponding variation of the maximum power is given in the same figure with solid line, showing a direct relation between the irradiance and the maximum power. The ESC controller has been tuned thusly: the integrator constant, $k=30$, the washout filter parameter, $h=50$, the sinusoidal disturbance of amplitude $a=0.1$ and frequency $\omega=100$ Hz.

Fig. 9c and 9d presents the time evolutions of the PV array voltage and of the current injected to the grid, respectively. One can note that, as expected, the PV array voltage around the maximum power point is almost constant. The amplitude of the grid current, I_{grid} , depends proportionally of the irradiance level.

The capability of the proposed control law of tracking

multimodal power curves is analyzed by means of the simulation results from Fig. 10. The ESC is tuned like for the case described in Fig. 9b,c,d. A scenario supposing that 8 of the 10 PV modules are practically covered (35 W/m^2 level of irradiance) and the 2 remainder are maximally irradiated (1000 W/m^2) has been implemented; such a scenario leads to multimodal power curves like the one represented with dashed line in Fig. 2. For the PV conversion system considered, the two local power maxima are 244 W and

236 W, respectively. Fig. 10a presents the dynamic performance of the ESC law when the system is set to begin the MPPT from voltage $V_{PVa}=45 \text{ V}$ – it converges to the power level of 236 W. Simulations have also shown that, starting from a point characterized by a lower voltage level, the algorithm converges to the other local power maximum, 244 W. This result suggests that the ESC law in its original form will always find the closest local maximum from the initial point.

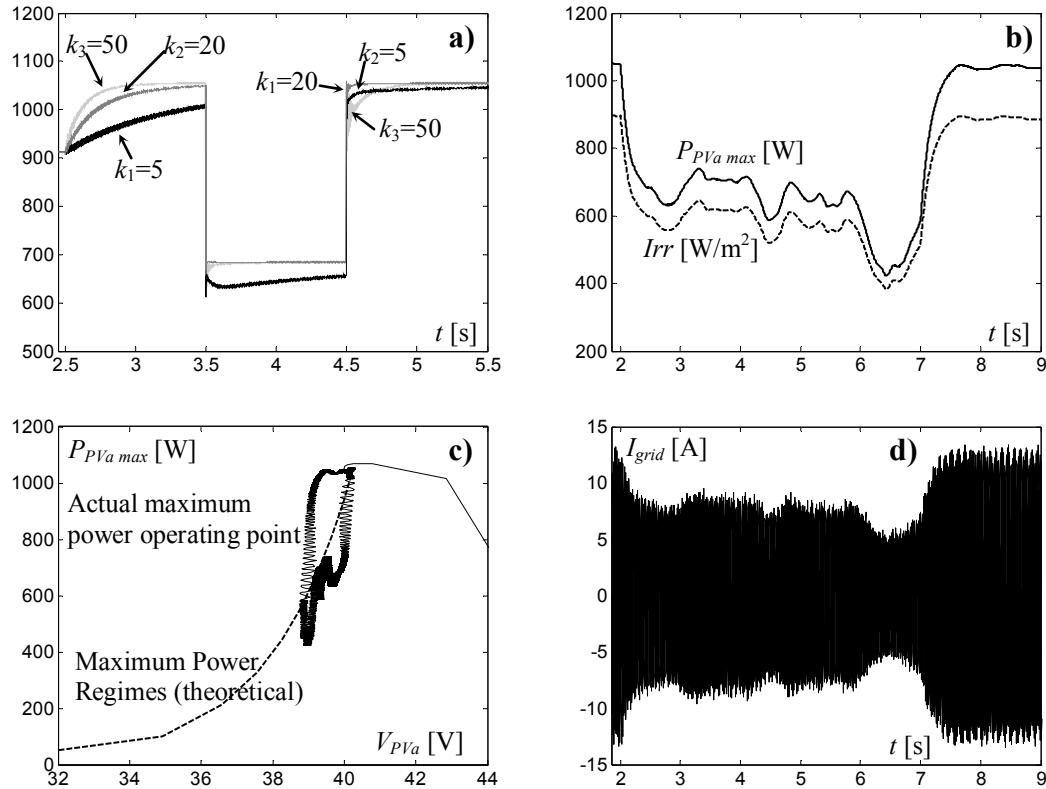


Fig. 9. Performance of the ESC in tracking the maximum of unimodal PV power curves under changes of irradiance: a) power responses at step changes of irradiance versus maximum power for different values of the ESC controller, k ; b) stochastic profile of irradiance and corresponding variation of the maximum power; c) excursion of the operating point in the power-voltage plane and d) grid current under the irradiance profile from b)

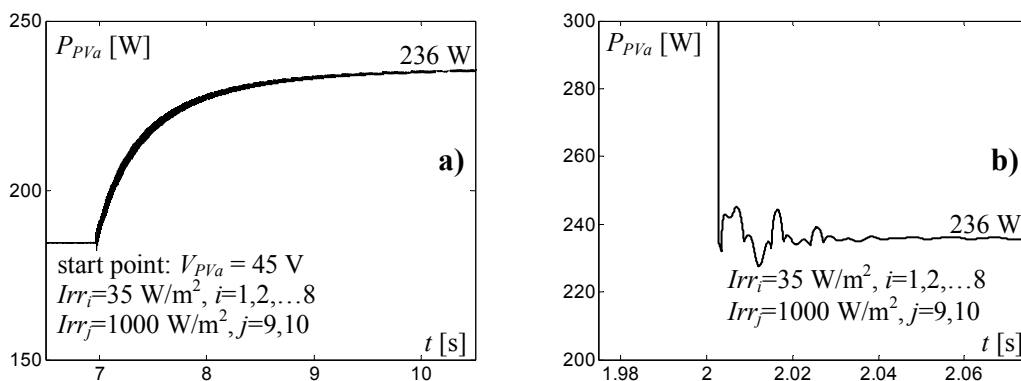


Fig. 10. Performance of the ESC in tracking the maxima of multimodal PV power curves – dependence of the initial state (initial voltage)

Fig. 10b shows the dynamic behaviour of the power when the irradiance varies abruptly from 1000 W/m^2 for all modules to

the above described situation (more than a half of modules practically covered). One can see the transient power regime

that passes eventually around the level of 244 W – which is the global maximum power in this case – but finally the steady-state power is again 236 W.

6. CONCLUSION

The control problem of grid-connected photovoltaic arrays is stated as to provide the maximum of power irrespective of the solar irradiance conditions. The conversion energy system analyzed in this paper is composed of two stages, that is, from a DC-DC boost converter and a DC-AC inverter, respectively. This system is controlled through a two-level structure: the desired operating regime, as imposed by the upper layer, is effectively implemented by low-level controlling the two power electronics converters. In this case, the desired operating regime is the maximum power point tracking (MPPT), whereas the low-level control layer consists essentially of basic voltage and current control loops. This paper has been focused on the performance of a control method based upon extremum seeking control (ESC), which belongs to the larger class of perturb-and-observe methods widely used for the MPPT of PV arrays. The MATLAB®/Simulink® numerical simulations have shown that the MPPT by ESC is quite effective at tracking strongly variable irradiance conditions. Two cases have been analyzed: when all the modules of a PV array receive the same level of irradiance and when the modules are significantly imbalanced irradiated. In the first case the power curve is unimodal and the ESC method performs very well, exhibiting robust behaviour at various disturbances, both exogenous, as well as parametric. In the second case, it may happen that the power curve to have multiple maxima – in this case, the performance of the ESC method of tracking the global maximum is affected by the initial state. The ESC capability of finding the global extremum is not guaranteed theoretically. In practice, the method can be forced to escape from local maxima by increasing the amplitude of the searching signal, but there are some limitations to meet. Further work will aim at studying this possibility in the context of a thorough study of the system's structural properties (stability and attractiveness of local extrema). Another interesting issue to further study is to solve the same problem in the case of a single-stage PV conversion system, that is, where the power is converted and transferred to the grid only by means of an inverter.

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Appendix. NUMERICAL FEATURES OF THE PV SYSTEM

Plant:

PV array: $n=10$ modules in parallel ($m=1$), global power 1100W, global voltage 48V

Chopper type: boost, $L_{ch}=10$ mH, $C_{PI}=4700$ μ F

DC-link: $V_{DC}=170$ V, $C_{DC}=10000$ μ F

$L_{grid}=1$ mH, $R_{grid}=0.17$ Ω , $V_{grid}=110$ V RMS, 50 Hz

IGBT-based power electronics, 10 KHz

Control laws:

Low-level control loops:

Current hysteresis bands: 0.25 A

Chopper PI control: $K_c=10$, $T_i=0.4$ s

Inverter PI control: $K_c=7.5$, $T_i=0.15$ s

Upper-level control loop:

MPPT probing signal: 100 Hz, 0.1V

Integrator parameter: $k=30$