Online ISSN 1848-3380, Print ISSN 0005-1144
ATKAFF 53(2), 128–141(2012)

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Distributed Maximum Power Point Tracking: Challenges and Commercial Solutions

DOI 10.7305/automatika.53-2.181
UDK 621.383.51
IFAC 4.2; 4.3.2.4

Original scientific paper

In this paper the state of the art of distributed maximum power point techniques for photovoltaic systems is discussed. Modern applications of photovoltaic systems in urban context and to sustainable mobility require the proper facing of drawbacks due to partial shading and different orientations of the cells the photovoltaic source is made of. The latest architectures proposed in literature are reviewed and their points of strength and weakness are discussed. Finally, the products that are currently available on the market are presented and their fields of application and features are overviewed.

Key words: Maximum power point tracking, Photovoltaic systems

Distribuirano slijeđenje točke maksimalne snage: izazovi i komercijalna rješenja. U ovom članku opisane su suvremene napredne tehnike za distribuirano postizanje maksimalne snage fotonaponskih sustava. Moderne aplikacije fotonaponskih sustava u urbanom smislu i održivoj mobilnosti zahtijevaju pravilno suočavanje s nedostacima uslijed djelomičnog zasjenjenja i različitih orijentacija ćelija fotonaponskog izvora. Razmatraju se najnovije arhitekture predložene u literaturi te su objašnjene njihove prednosti i nedostaci. Naposljetku, izloženi su trenutno dostupni proizvodi na tržištu te je dan pregled njihovih karakteristika i područja primjene.

Ključne riječi: slijeđenje točke najveće snage, fotonaponski sustavi

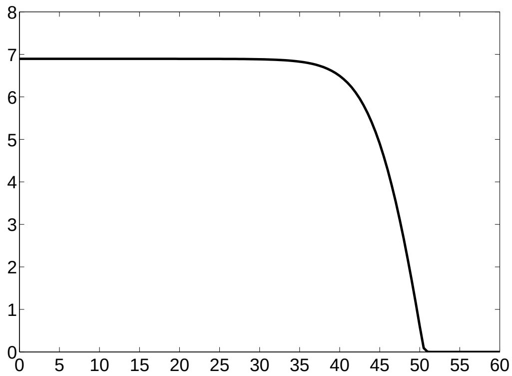
1 INTRODUCTION

Up to few years ago, large-scale power plants represented the majority of the Photovoltaic (PV) systems installed all around the world. Such plants were able to generate hundreds of kilowatts or even some megawatts because they paved large even grounds with thousands of panels, all of the same type and with the same orientation towards the Sun. This kind of installation required specific solutions for power conversion, so that the effort was concentrated in developing high performance inverters, usually equipped with only one DC input at which the Maximum Power Point Tracking (MPPT) algorithm operated. The latter did not have to face uncommon problems: the central inverter was easily able to draw the PV strings and the whole field towards the Maximum Power Point (MPP) of a power vs. voltage curve that was a scaled-up version of that one of any PV panel of the field. This quiet condition was due to the fact that all the panels received the same irradiation level and were equally oriented. Effects due to clouds, determining a partial shading of the PV field, were neglected, especially when the occurrence of such a condition was not frequent and when the clouds transition was expected to be very fast. Possible different orientation of the PV panels, due to ground unevenness and mistakes in the installation, was considered as a minor issue. Additionally, theft problems and issues related to the monitoring of the power production of the PV field were not afforded systematically, with significant consequences on the plant productivity. In fact, some stops in the energy production of the whole plant, or of a part of it, were required for maintenance or repairing. Last, but not least, issues related to safety were a minor problem, because the access to the area of the PV plant was open to authorized and skilled personnel only.

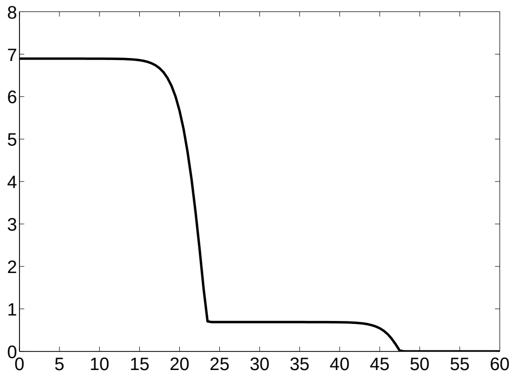
More recently, multi-string inverters have been proposed on the market, their main feature being two or more DC inputs, each one equipped with its own MPPT controller. Such a feature allowed to divide the PV field in subsections, each one potentially working in different operating conditions, and to ensure the maximum power from each one of them. In case of shadowing, or installation with a different orientation with respect to the Sun of some panels, a power drop affected only the string in which such panels were connected, without any effect on the parts of the PV field connected to the other DC inputs of the inverter. Such a solution also allowed to have different sections of the PV field made of different types of panels, the only forethought being the series connection in the same string of panels of the same peak power and open circuit voltage.

Fig. 1 qualitatively shows the effects of the series connection of PV modules subjected to different irradiances. With the same working conditions, the current vs. voltage curve of the string is a scaled up version, in terms of voltages, of the curve of a single module. Instead, the series connection of modules working in different conditions gives rise to multiple variations in the slope of the curve and, consequently, in multiple peaks of different heights in the power vs. voltage curve of the array. Details about the possible modifications in the curve shape can be found in [1] and references cited therein.

Multi-string inverters have mitigated the effect of the so-called "mismatching" events in the case of large PV fields



(a)



(b)

Fig. 1. String of two series connected Kyocera KC120 modules. a) both modules receive the same irradiation level, b) one module receive one tenth of the irradiation received by the other one. Horizontal axis = voltage [V], vertical axis = current [A].

but not in the case of small power installations. Moreover, they have not been helpful in solving the problem of substituting few damaged PV panels, after some years of operation, in the plant building. The unavailability of panels with characteristics that are close to those ones of the original panels in the PV field determines the stop in the power production of the power plant, or at least of a part of it; in fact the substitution of the damaged panels with similar, but not exactly the same panels, determines a mismatching effect, in the string including different types of panels, even if they all operate under the same irradiation level.

An increased need of flexibility in the electrical design of the PV field has been also required by the increased interest in PV applications in urban contexts. These require a relatively small number of panels, but they may have many different orientations with respect to the Sun and/or shadowing effects can irregularly affect them. Last but not least, because of convection effects due to wind or different installation supports, they can work at more or less different temperatures. Such a mismatch is due to the installation of the panels on more than one façade of a building and to the shadows produced by obstacles, trees, chimneys, poles and so on. Since the use of any multi-string inverter would require too many series connected panels per each DC input, because some hundreds of volts must be reached, the mismatching effect would be unacceptable.

The solution that has been recently proposed in literature and, slightly after, put on the market by some producers is the so-called Distributed MPPT (DMPPT). Such a term was firstly introduced in [2] and nowadays it is the synonym of MPPT control dedicated to a single PV panel. This goal can be obtained by means of two different tools. The first, and older, one is the adoption of one DC/DC converter per PV module, so that the dedicated converter, whose output terminals are connected in series or in parallel with those ones of the converters dedicated to the other panels, runs the MPPT. This solution requires a careful choice of the DC/DC converter topology and control, depending on the chosen electrical connection and on the maximum stresses the switching devices can be subjected to.

The second solution is especially aimed at grid connected PV systems and it is based on the adoption of a DC/AC converter (micro-inverter) per PV panel. In this case the micro-inverter output terminals are straightforwardly connected to the grid, so that the circuit has to take charge for the significant boosting of the low DC voltage at the panel terminals up to the peak voltage value at the AC mains. In many cases, and especially when the DC/AC converter involves a DC link followed by a PWM inverting stage, a DC/DC converter with a high voltage conversion ratio is needed for boosting up the PV panel voltage by 10-15 times. Up to now, any DC/DC converter having such a feature has the drawback of a low efficiency, so that the main limitation of the most flexible DMPPT solution, that is the panel dedicated inverter, is the quite low conversion efficiency.

Another solution to the mismatching effect is currently available on the market, but it is not reviewed in this paper because it does not perform literally a DMPPT. It consists of a switching box that takes at its input the couples of cables coming from each PV module in the field. The couple of its own output terminals is connected at the inverter input port. The switching box [3] performs a periodic reconfiguration of the PV field by arranging the PV modules connection in order to maximize the power produced by the whole field. The switching box consists of a large number of power switches, realized in a proper way so that a high reliability is ensured, and a digital control unit that takes the decisions about the reconfiguration. A similar approach is presented in [4].

All the mentioned solutions have among the main features the increased safety in case of fire, because of the capability of reducing the risk of hazards for firemen. The automatic module shutdown is included in many products. Firefighters shut off power but this means that the central inverter is shut off. Unfortunately, the DC of hundreds of volts is still present and this poses risks to firefighters, especially when they cut through roofs and walls because it could result in chopping through live wires [5]-[7].

In this paper the main solutions for DMPPT are overviewed. In section 2 architectures, topologies and control techniques are compared and the advantages and limitations of different solutions based on the use of the so-called "power optimizers" are discussed.

Section 3 is dedicated to the design of micro inverters. Different solutions proposed in literature are compared, both in terms of efficiency and reliability.

Finally, in section 4 the DMPPT solutions available on the market are compared each other.

2 DMPPT BY MEANS OF POWER OPTIMIZERS

The first grid-connected PV systems put in service were made of strings of PV modules which were connected in parallel and fed a central DC/AC inverter (Fig. 2). The function of such a central inverter, besides that one of converting DC power to grid-compliant AC power, was also that one of carrying out the tracking of the MPP of the Power vs. Voltage (P-V) characteristic of the whole field. In other words, the central inverter was responsible of the Field Maximum Power Point Tracking (FMPPT). It is well known that, in case of mismatch (due to clouds, shadows, dirtiness, manufacturing tolerances, aging, different orientation of parts of the PV field in the so called Building Integrated Photovoltaic Systems etc.), the P-V characteristic of the PV field exhibits more than one peak, due to the presence of bypass diodes, and MPPT algorithms can fail [8]-[17]. The failure of such MPPT algorithms is due to the fact that they are not able to avoid that the operating point of the PV source may remain trapped in the neighborhood of a relative maximum power point instead that close to the absolute maximum power point. Moreover, even when FMPPT is able to catch the absolute maximum power of the mismatched PV field, such a power is lower than the sum of the available maximum powers that the mismatched modules are able to provide. Distributed Maximum Power Point Tracking (DMPPT) allows to overcome the drawbacks associated to mismatching phenomena. Two different DMPPT approaches can be adopted. The first one is based on the adoption of one microinverter per PV module converting DC power to grid-compliant AC power. Such an approach will be discussed in Section 3 of this paper. The second approach adopted is instead based on the use of a module dedicated DC/DC converter carrying out the MPPT for each module (Fig. 3) and central inverters [18]-[30]. In this section, such an approach will be analyzed in detail. Examples of commercial devices developed with reference to the architecture shown in Fig. 3 are the SolarEdge Power Box, the Tigo Energy Module Maximizers, the Xandex SunMizers. The main technical characteristics of such commercial devices are presented and discussed in detail in Section 4.

The DMPPT architecture shown in Fig. 4 instead requires DC/DC converters characterized by two contrasting

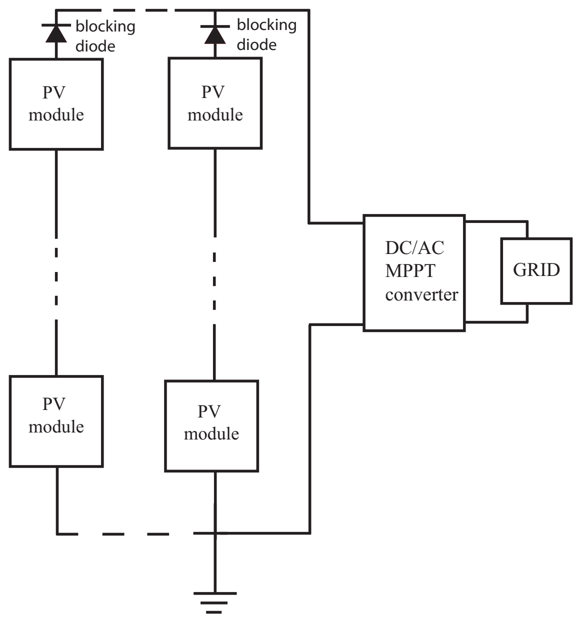


Fig. 2. Grid-connected PV system with FMPPT.

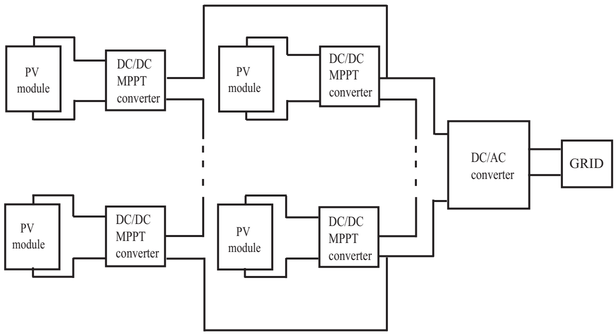


Fig. 3. Grid-connected PV system with DMPPT. Approach based on the adoption of MPPT DC/DC converters with the output ports connected in series.

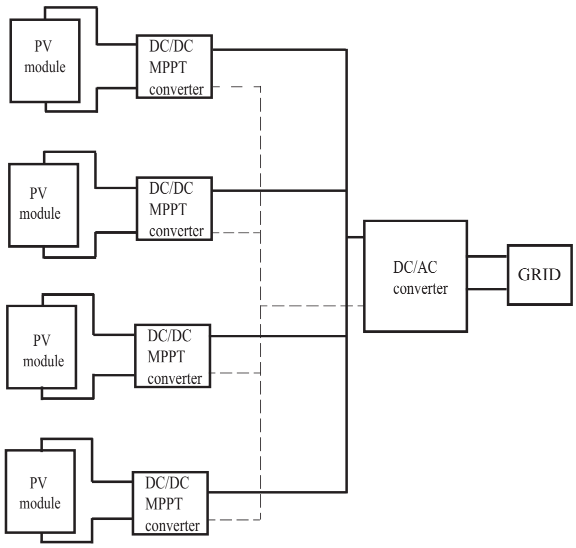


Fig. 4. Grid-connected PV system with DMPPT. Approach based on the adoption of MPPT DC/DC converters with the output ports connected in parallel.

requirements: a high voltage conversion ratio (e.g. from 20-30 V to 350-450 V) and a high conversion efficiency. Up to now, only one company, the eIQ Energy, markets a device (Parallux Vboost) which has been developed for such a kind of architecture. In the following, PV systems adopting the architecture shown in Fig. 3 will be discussed and analyzed in detail. A system composed by a PV module with a dedicated DC/DC converter will be called Self Controlled PV module (SCPVM).

The first important consideration to underline is the following one. Usually, in commercial PV modules, each bypass diode is connected in parallel to a string of up to 18-20 PV cells. Therefore, since a PV module is equipped with more than one bypass diode, if the module is not uniformly shadowed but, as an example, only one cell is covered by snow or dirt, then the power versus voltage characteristic of the whole PV module may exhibit multiple peaks. In such a case, the MPPT controller of the dc/dc converter associated to such a PV module can lead to a suboptimal operating condition since no MPPT technique is able to correctly face the presence of multiple peaks in the power versus voltage PV characteristic [8]-[17]. Therefore, it is worth noting that DMPPT is fully effective only if each PV module is equipped with as many dc/dc converters as bypass diodes. In particular, one dc/dc converter should be inserted in place of each bypass diode. However, in order to grant the functionality of the rest of the PV system also when a dc/dc converter is turned off or damaged, a bypass diode should be connected at the output of each dc/dc converter. Indeed, depending on the adopted dc/dc converter topology and on the type of chosen switching components, the addition of a bypass diode at the output of each dc/dc converter may not be necessary. As an example, if the standard boost topology is chosen and the active switch of the boost converter is a MOSFET, the bypass function is ensured by the presence of the boost output diode and of the body diode of the MOSFET itself. Instead, if the synchronous version of the boost topology is chosen, the bypass function is ensured by the presence of the body diodes of the two MOSFETS or by the presence of the external diode which is generally added in antiparallel to each MOSFET in order to increase the overall efficiency of the power stage.

Another important aspect to discuss is indeed just related to the power stage efficiency. In fact, one drawback of DMPPT applications is represented by the fact that DMPPT is able to ensure higher energy efficiency than FMPPT, in presence of mismatching phenomena, only if the efficiency of the power stage of MPPT DC/DC converters is enough high [31].

In fact, in ideal, uniform operating conditions, the overall efficiency of a PV system with FMPPT is expected to be greater than that one of the same system operating with DMPPT since this last includes additional dc/dc conversion stages. Indeed, DMPPT does not necessarily require two dc-dc stages; e.g., in the case of the commercial device SolarEdge, the strategy of the company is based on the adoption of a dc/dc stage dedicated to each PV module and on the use of a single dc/ac stage for the whole array. Nevertheless, if a commercial PV inverter is adopted, it usually contains two conversion stages: a dc/dc and a dc/ac stage. In such a case DMPPT requires the flow of energy from the PV modules to the grid through three different conversion stages: two dc/dc stages and one dc/ac stage.

Therefore high efficiency is a mandatory requirement for the dc/dc converters to be adopted in DMPPT PV applications; indeed efficiency is the starting point of the design process of the power stage of the SCPVMs. Such a design involves not only decisions concerning the topology of the dc/dc converter, the type of power components, the value of the output voltage, the value of the switching frequency but also, the time varying characteristics of the PV sources. In fact, the peculiarity of DMPPT PV applications is just represented by the fact that the operating point of the SCPVMs is not constant but it is continuously changing. So that it is not possible to identify a single reference operating condition to be taken into account in the design process. In particular the profile of the efficiency of the dc/dc MPPT converter must be optimized on the basis of the power profile of the PV source which in turn depends on the weather conditions characterizing the installation site [31].

In addition, it is worth noting that the set of design constraints characterizing grid-connected and stand alone DMPPT PV applications are not coincident. In particular the optimization of a dc/dc converter dedicated to stand alone DMPPT PV applications requires to keep into account, in addition to what has been already listed above, also the efficiency of the charge/discharge processes of the batteries, their lifetime, and the shape of the profile of the power required by the load.

The second drawback of DMPPT PV applications is represented by the fact that conditions exist in which also the DMPPT approach does not allow the working of each PV module of the field in its MPP. This is due to constraints associated to the more or less limited voltage conversion ratio of the adopted DC/DC converters, to the finite voltage and current ratings of devices used in the power stage of SCPVMs and/or due to a non optimal value of the bulk inverter voltage [2] [25] [32].

In the following, without loss of generality we will refer only to a step up topology (boost) and to a step up/down topology (buckboost). The set of constraints to be fulfilled in the case of a string of N SCPVMs with the output ports connected in series is:

$$\mathrm{M_{min}} < \mathrm{M_k} < \mathrm{M_{max}} \tag{1a}$$

$$\mathrm{V_{offk}} < \mathrm{V_{ds\ max}} \tag{1b}$$

$$\mathrm{I_{onk}} < \mathrm{I_{ds\ max}} \tag{1c}$$

$\mathrm{M_k}$ is the voltage conversion ratio of the k-th converter and $\mathrm{M_{min}}$ and $\mathrm{M_{max}}$ are the corresponding minimum and maximum values ($\mathrm{M_{min}} = 1$ and $\mathrm{M_{max}} \to \infty$ for the ideal boost converter, $\mathrm{M_{min}} = 0$ and $\mathrm{M_{max}} \to \infty$ for the ideal buckboost converter). $\mathrm{V_{offk}}$ is the value of the voltage across the switches of the converter when they are in the OFF state and $\mathrm{V_{ds\ max}}$ is the corresponding maximum allowed value which depends on the voltage rating of the adopted devices. $\mathrm{I_{onk}}$ is the peak value of the current in the switches of the converter when they are in the ON state and $\mathrm{I_{ds\ max}}$ is the corresponding maximum allowed value which also depends on the ratings of the adopted devices.

It is worth noting that, in the boost topology, the voltage across the output capacitor and the active switch, during its OFF subinterval, is equal to the output voltage [32]. In the case of the buckboost topology, the voltage across the active switch, during its OFF subinterval, is equal to the sum of the input and output voltages [32]. Due to the series connection of the output ports of the SCPVMs, the output voltage $\mathrm{V_{outk}}$ of the k-th SCPVM is equal to the bulk inverter voltage times the ratio between its output power and the total output power:

$$\mathrm{V_{outk}} = \frac{\mathrm{P_{pank}}}{\mathrm{I_{outk}}} = \frac{\mathrm{V_b}}{\sum_{\mathrm{k=1}}^{\mathrm{N}} \mathrm{P_{pank}}} \mathrm{P_{pank}} \tag{2}$$

where $\mathrm{P_{pank}}$ is the power extracted from the k-th PV module, $\mathrm{V_{outk}}$ and $\mathrm{I_{outk}}$ respectively are the output voltage and current of the k-th SCPVM, $\mathrm{V_b}$ is the inverter DC input voltage. On the basis of eq. (2), the output voltage of a SCPVM can vary in a wide range due to possible imbalances among powers delivered by modules. In mismatching conditions, the output voltage of the SCPVMs providing higher powers can become very large, causing dangerous, potentially destroying, switch stresses. In order to avoid that the voltage stress of devices belonging to one or more SCPVMs exceeds a given maximum value $\mathrm{V_{ds\ max}}$, an output voltage limitation technique needs to be adopted [2]. In the case of the buck-boost topology, in addition to output overvoltage protection circuitries, also switch current limitation techniques need to be adopted [32]. In fact, in the case of the buckboost converter, when the value of the duty-cycle D decreases, then the peak value of the switches currents increase since the peak value of the switches currents is equal to the PV current divided by D. So that, especially when the buckboost converter steps down the output voltage with respect to the input voltage (D $<$ 0.5), the currents in the switches may exceed the safety threshold $\mathrm{I_{ds\ max}}$.

In the following the symbol η_{DMPPT} (η_{FMPPT}) will identify the ratio between the PV power which can be extracted by adopting DMPPT (FMPPT) and the maximum available power. In the case of an ideal lossless boost converter made with devices characterized by unlimited voltage and current ratings, if $V \geq \mathrm{V_{MPP}}$ than the I-V characteristic of the SCPVM is an hyperbole of equation $\mathrm{V} \cdot \mathrm{I} = \mathrm{P_{MPP}}$, where V is the output voltage, I is the output current of the SCPVM and $\mathrm{P_{MPP}}$ is the maximum power which can be provided by the adopted PV module in the considered atmospheric conditions [20][25]. Instead, if $V \leq \mathrm{V_{MPP}}$ then I-V characteristic of the SCPVM is coincident with that one of the adopted PV module in the considered atmospheric conditions [20][25]. If the boost converter is lossless but is characterized by a finite value of $V_{ds\ max}$, the I-V characteristic of the SCPVM is truncated at $V_{ds\ max}$. In Fig. 5 the I-V characteristic of a SW225 PV module ($V_{oc} = 36.8$ V, $I_{sc} = 8.17$ A, $V_{MPP} = 29.5$ V, $I_{MMP} = 7.63$ A, NOCT = 46 °C) at an irradiance value $S = 1000$ W/m^2 and an ambient temperature $T_{ambient} = 25$°C is reported together with the corresponding I-V characteristic of the associated boost based SCPVM. In the case of an ideal lossless buckboost converter made with devices characterized by unlimited voltage and current ratings the I-V characteristic of the SCPVM is an hyperbole of equation $V \cdot I = P_{MPP}$ (in the buckboost case V is the absolute value of the output voltage of the SCPVM) [15][20]. If finite voltage and current ratings are taken into account the I-V characteristic is modified as shown in Fig. 6 ($V_{ds\ max} = 60$ V, $I_{ds\ max} = 16$ A) [20][25]. In order to obtain the I-V equivalent characteristic of N SCPVMs connected in series, for each value of the current the corresponding value of the voltage can be evaluated by summing the N voltages obtained by the N characteristics of the SCPVMs in correspondence of the considered value of the current. From the I-V equivalent characteristic is then simple to get the P-V equivalent characteristic. In the following, without any loss of generality with reference to the conclusions which will be highlighted, a string made of NH SCPVMs operating under irradiance level S_H and of NL SCPVMs operating under irradiance level S_L will be considered. It is NH + NL = N. Fig. 7 refers to the case of N = 11 boost based lossless SCPVMs with $S_H = 1000$ W/m^2; $S_L = 200$ W/m^2; $T_{ambient} = 25$°C; $V_{ds\ max} = 70$ V.

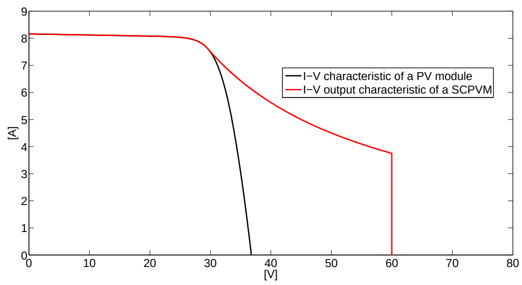


Fig. 5. $S = 1000$ *W/m*^{2}*,* $T_{ambient} = 25$°*C; boost based SCPVM* ($V_{ds\ max} = 60$ *V).*

Each red curve represents the P-V characteristic of a string of SCPVMs obtained by adopting a given value of NH ($1 \le NH \le 11$) as indicated by the arrow pointing in the direction of NH growing from 1 to 11. Each black curve represents instead the P-V characteristic of a string of PV modules. The maximum value obtainable for η_{DMPPT} is equal to 1 only in the trivial case NH = 11; but, of course, also η_{FMPPT} is equal to 1 for NH = 11, in fact when

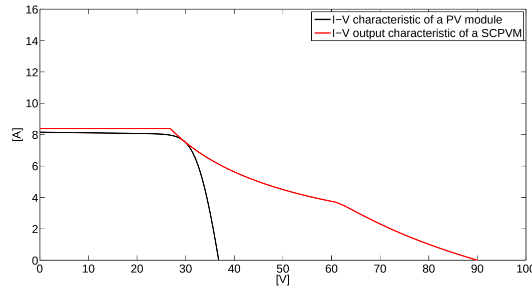


Fig. 6. $S = 1000$ *W/m*^{2}*,* $T_{ambient} = 25$°*C; buck-boost based SCPVMs* ($V_{ds\ max} = 90$ *V,* $I_{ds\ max} = 16$ *A).*

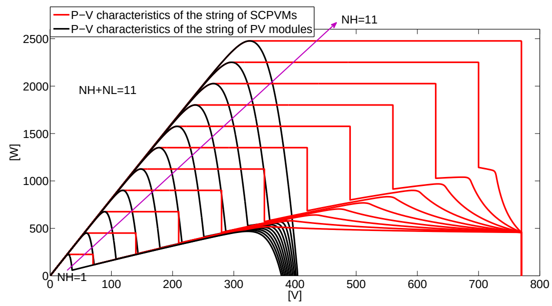


Fig. 7. $S_H = 1000$ *W/m*^{2}*,* $S_L = 200$ *W/m*^{2}*,* $T_{ambient} = 25$°*C; boost based SCPVMs* ($V_{ds\ max} = 70$ *V).*

NH = 11 there is no mismatching.

It is worth noting that, only in the cases NH = 1 and NH = 2, the maximum value of η_{DMPPT} is higher than the corresponding maximum value of η_{FMPPT}. In all the other cases such maximum values are equal and lower than one since, of course, η_{FMPPT} is lower than one in mismatching conditions. Moreover, the equality between the maximum value of η_{DMPPT} and the maximum value of η_{FMPPT} is fulfilled only if the bulk inverter voltage belongs to an optimal range whose position and amplitude changes case by case. If the bulk voltage does not belong to the above optimal range η_{DMPPT} can be much lower than η_{FMPPT}.

As an example, $V_b = 500$ V belongs to the optimal operating range only for the cases NH = 11, NH = 10, NH = 9, NH = 8, NH = 1 and NH = 2. In all the remaining cases, at $V_b = 500$ V, η_{DMPPT} is lower than η_{FMPPT}.

Fig. 8 refers instead to the case of NH = 11 boost based lossless SCPVMs with $S_H = 1000$ W/m^2; $S_L = 500$ W/m^2; $T_{ambient} = 25$°C; $V_{ds\ max} = 70$ V. In this case, the maximum value obtainable for η_{DMPPT} is always equal to one and, of course, it is higher than the maximum value obtainable for η_{FMPPT}. Also in this case an optimal range for the bulk inverter voltage exists and it changes case by case.

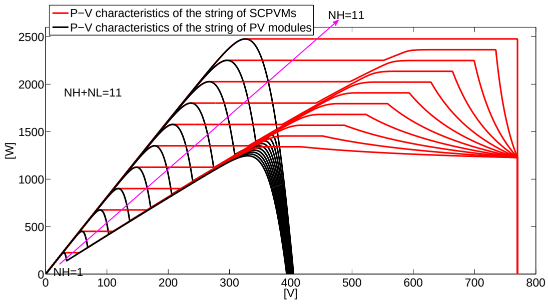


Fig. 8. $S_H = 1000\,W/m^2$*,* $S_L = 500\,W/m^2$*,* $T_{ambient} = 25°C$*; boost based SCPVMs (*$V_{ds\ max} = 70\,V$*).*

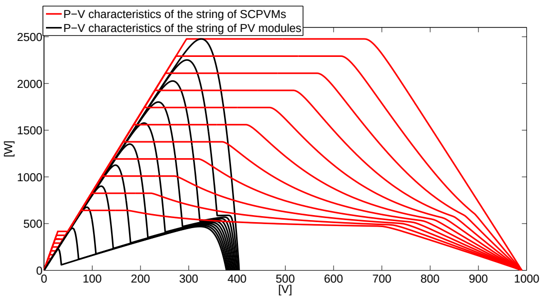


Fig. 9. $S_H = 1000\,W/m^2$*,* $S_L = 200\,W/m^2$*,* $T_{ambient} = 25°C$*; buck-boost based SCPVMs (*$V_{ds\ max} = 70\,V$*,* $I_{ds\ max} = 16\,A$*).*

Fig. 9 refers instead to the case of $N = 11$ buck-boost based lossless SCPVMs with $S_H = 1000\,W/m^2$; $S_L = 200\,W/m^2$; $T_{ambient} = 25°C$; $V_{ds\ max} = 70\,V$; $I_{ds\ max} = 16\,A$.

While Fig. 10 refers to the case of buckboost based lossless SCPVMs with $S_H = 1000\,W/m^2$; $S_L = 500\,W/m^2$; $T_{ambient} = 25°C$; $V_{ds\ max} = 90\,V$; $I_{ds\ max} = 16\,A$. In both cases of Fig. 7 and 8 the maximum value obtainable for η_{DMPPT} is always equal to one and it is always higher than the maximum value obtainable for η_{FMPPT}. Referring, as an example, to the case $NH = 1$ and $NL = 10$ shown in Fig. 8, the optimal range for the bulk inverter voltage in order to get $\eta_{FMPPT} = 1$ is [77 V, 115 V]. Figs 7-10 clearly show that, in order to be able to get the maximum value of η_{DMPPT}, the bulk inverter voltage must belong to an optimal range; the position and amplitude of such an optimal range are not fixed but they depend on the number of SCPVMs in the string, on the atmospheric operating conditions characterizing each PV module (irradiance and temperature values), on the voltage and current ratings of the physical devices the power stages of the SCPVMs are made of and on the adopted DC/DC converter topology. From this point of view, this means that, in order to get profit from DMPPT, the inverter MPPT input voltage range should be as large as possible.

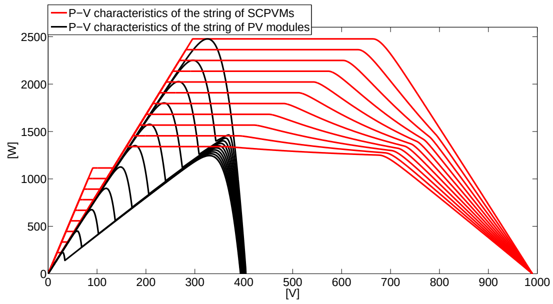


Fig. 10. $S_H = 1000\,W/m^2$*,* $S_L = 500\,W/m^2$*,* $T_{ambient} = 25°C$*; buck-boost based SCPVMs (*$V_{ds\ max} = 90\,V$*,* $I_{ds\ max} = 16\,A$*).*

A final additional aspect to take into account is represented by the impact of system parameters on effectiveness and stability of the DMPPT technique. The approach described in [2] allows to effectively analyze modules interaction and stability of a string of SCPVMs provided that the dynamics of the MPPT block in each SCPVM is slow enough for the closed-loop DC/DC converter to reach steady-state operation after each perturbation driven by the MPPT controller. Nonlinear systems stability criteria or small-signal double control loop design techniques should be adopted in cases in which MPPT techniques involving faster dynamics or nonlinear functions are used.

3 DMPPT BY MEANS OF MICRO-INVERTERS

The DMPPT architecture based on Module Integrated Inverter (MII) has the objective of making the PV module a “plug and play” system, thus being directly connected to the grid without any additional device and usable by persons without any knowledge of electrical installations. Moreover, in terms of safety, MII systems are less affected by electric arcs and nearby lightning by reducing the installation cost because no DC-specific equipments (e.g., DC cabling, connectors, fuses) are necessary. Furthermore, only conventional AC installation is required, and system planning is made easier due to the high level of modularity.

Even if those features are very attractive, especially from a commercial point of view, because they stimulate the installation of low power residential PV systems, the commercial success of a PV-MII highly depends on its reliability and efficiency.

Unfortunately, as for the case of the parallel connection of the output ports of DC/DC converter discussed previously, the PV-MII requires a high voltage-amplification that may reduce the overall efficiency and increases the price per watt, because of more complex circuit topologies. On the other side, SiC semiconductor technology, which is one of the most significant developments in power electronics in recent years, might be used for making very competitive the PV-MII. Indeed, such a technology can work at higher switching frequencies thus allowing the decrease of inductance and capacitance values and consequently the size of power electronic converters. The heat-sink can also be made smaller given the superior thermal capabilities of SiC, so that a further decrease of weight and cost could be achieved. A fairly high conversion efficiency of up to 97% has been recently reached in PV-MII by combining different technologies for semiconductors devices [33]. The power stage topology is another hot point in the development of PV-MII. It is usually based on a multistage architecture, in which the first stage is used to perform the MPPT and to step up the PV voltage, the second one to perform the dc-ac conversion. Capacitors placed in parallel with the PV modules and/or in the DC link between the two stages are used as "power decouplers" for balancing the DC power coming from the PV module and the AC instantaneous power injected in to the grid. The choice of the capacitors plays a fundamental role for the PV-MII reliability. In [34][35] it has been shown that it is not completely true that the main limiting factor of the system lifetime is related to the high percentage of failure of electrolytic capacitors. New generation of power converters are designed in order to keep the bulk and the PV capacitances as small as possible, so that the use of film capacitors is allowed. The DC/DC stage is designed and controlled for obtaining a fixed DC voltage or for producing an output current modulated to follow a rectified sine wave. Consequently, in the first case, the DC/AC stage regulates the sinusoidal profile of grid current by means of pulsewidth modulation (PWM) or bang-bang operation. In the second one, the DC/AC stage switches at line frequency, "unfolding" the rectified current to a full-wave sine. Different combinations of these two basic approaches might be performed: in Fig. 11 only some architectures, used in commercial products, have been shown. A complete overview of PV-MII topologies is reported in [36]-[38] and references cited therein.

Fig. 11 a) shows a typical configuration of dc-dc stage based on flyback converter; it is very compact and requires a low number of components. The driving signal of transistor S0 is properly modulated in order to obtain a fully rectified sine wave profile for the current in D1. The S1-S4 full bridge topology is used as an unfolding inverter. By adding the C2 capacitor to the flyback transformer, a quasi-resonant converter is achieved. This lowers the switching losses and therefore increases the efficiency.

DC/DC conversion based on resonant converters (Fig. 11-b) offers the advantage that the HF transformer is more effectively used and it can therefore be smaller. These topologies can be modulated on the primary side for having a constant DC voltage or a rectified sine wave output

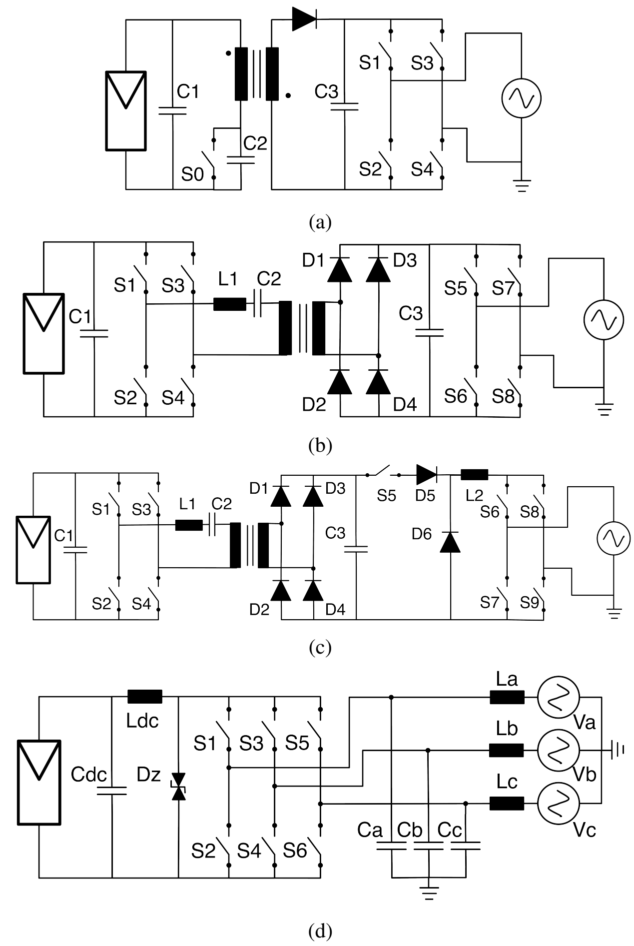


Fig. 11. PV-MII multistage architectures: a) Inverter with quasi-resonant flyback converter (Enphase topology), b) Inverter with resonantly controlled HF transformer (OKE 4 topology), c) Inverter with HF transformer buck converter and line frequency full bridge (Enecsys topology), d) three phase solution.

current, consequently the DC/AC stage might be a PWM inverter or an unfolding inverter. These converters achieve a quite high efficiency.

The circuit in (Fig. 11 c) is not sine wave modulated on the primary side. The sine wave modulation is carried out by using the third stage, which is a buck converter consisting of transistor S5, diode D6 and inductor L2. The transistors S6 to S9 of the full bridge flip the sign of the output current only. In this circuit, the capacitor C3 can be driven with a large voltage ripple, thus reducing the required capacitance.

An additional configuration that deserves to be cited has been described in [33], it is based on a transformer-less three-phase inverter and it is particularly suitable for PV modules, which are capable of providing an output voltage of several hundred volts, e.g. thin-film PV modules. The proposed topology is a current source inverter, features a single-stage power conversion system that directly feeds into the three-phase grid, as shown in Fig. 11.d).

Due to a three-phase grid connection, a continuous power is required at the inverter input and flowing from the module to the grid, thus energy storage at the dc link can be drastically reduced. Hence, the use of electrolytic capacitors can be avoided.

Of course this advantage can be exploited also for the low-voltage PV modules, which may be interfaced to the three-phase inverter through a step up dc-dc converter by obtaining a two-stage configuration similar to those ones described before.

The three-phase PWM CSI is composed of a bridge with six reverse blocking switches (S1–S6), which are composed of a transistor and a series diode each. The dc link contains an inductor as the main energy storage component, and, at the output, there is a CL filter, which smoothens the pulsed phase currents from the dc link.

Diode Dz provides a "freewheeling" path in the event of an unintended open circuit of the bridge.

Although the CSI exhibits higher conduction losses when compared to voltage source inverter this should be well traded off by lower switching stress and specifically smaller passive components. In [33] a 97% European efficiency has been reached.

As for whichever PV inverter, MIIs have to fulfill a set of standards related to the power quality, the islanding conditions and the dc current component injected into the grid, thus the development of a suitable control technique is a not trivial task. Those aspects make the MII less competitive than the DC-DC converters in terms of cost and complexity.

An interesting MII solution is also the one based on multilevel topologies [39][40]. Indeed cascaded multilevel inverters are becoming an alternative to perform DMPPT by means of a series connection of AC inverter outputs.

If compared with the two-level topologies, the multilevel architectures offer advantages such as the operation at lower switching frequency, the rejection of the common mode perturbations and the harmonic content reduction of the current injected in to the grid. Unfortunately the multilevel approach requires the synchronization among the H-bridges so that it is effective only when the PV string is fractioned in few subsections and the H-bridges are physically placed in a single central unit. This means that the level of granularity of this architecture up today is not yet mature for performing the DMPPT at the PV panel level.

4 COMMERCIAL PRODUCTS FOR DMPPT

In the last five years some producers have put on the market solutions dedicated to the DMPPT function. Some forerunners developed and commercialized micro inverters even before, but without success because at that time the PV market was not so mature as in the last few years.

Solutions based on power optimizers can, in many cases, be used in conjunction with any existing PV inverter, but some producers propose the whole system, also including a dedicated string inverter having special features. Almost all the companies, both for DC/DC and DC/AC solutions, propose software systems for monitoring the performances of the PV field equipped with their products. This market seems to be in an exponential growth and a large number of players is accessing the field of PV plants performance monitoring. This is also confirmed by the fact that companies who early developed effective, reliable and complete monitoring systems have been subject of the interest of other important actors. This is the case, for instance, of Power-One Renewable Energy Solutions LLC who acquired the assets of National Semiconductor's SolarMagic monitoring business [41]-[42].

4.1 Power optimizers

Table 1 resumes the main characteristics of the power optimizers available on the market. In this table, one of the pioneers in this field has not been included. In the middle of the last decade, National Semiconductor Corporation proposed the Solar Magic power optimizer, pushed by a strong marketing activity. Such a product opened the market and was helpful in transferring to the installers the idea of module-dedicated electronics. Solar Magic has not had a relevant success and afterwards, due to strategic reasons, National Semiconductor Corporation, now owned by Texas Instruments, decided to change its asset in this market area by producing integrated circuits, and not switching converters, for photovoltaic applications. The catalog includes integrated circuits for different functions needed in PV applications, referred both to power optimizers and micro-inverters: MPPT controllers and sensors, voltage regulators and drivers are available [39]. Nowadays such integrated circuits are the core of power optimizers and micro inverters sold by leading players in the field of power converters.

Table 1 also does not include the products of another important player, ST Microelectronics, which offers integrated circuits for PV applications [43]. They are two integrated devices including the semiconductor part of the dc/dc switching converter, but needing the external connection of passive components. The SPV1020 allows to develop a four phases interleaved topology of a DC-DC converter by avoiding the use of electrolytic capacitors. Its operating range is 0-45 V and reaches a 98% efficiency. SPV1040, instead, is a 95% efficiency battery charger with a 0.3-5.5 V input voltage range, thus suitable for controlling an even small number of series connected PV cells.

Table 1. Main characteristics of some power optimizers available on the market.

Producer		Power [W]	Input voltage [V]	Output voltage [V]	η_{max} [%]	η_{EU} [%]	Connection	Warranty [yrs]
Xandex [42]		250	48	-	98	-	Series	20
		350	80			-		
Power-One [43]		300	20-60	20-60	98	98	Series	-
SolarEdge [44]	OP250	250	5-55	5-60	99.5	98.8	Series	25
	OP300	300	5-75					
	OP400MV	400	5-75					
	OP400EV	400	15-125					
	350-TFI	350	10-95		98.6	97.7		
Tigo [45]	ES	300	16-48 30-89 30-140	variable	99	-	Series	20
		350	30-65					
	EP	200	28-42	375		-	Series (isolated)	
			39-54					
			53-60					
EIQ Energy [46]		250	20-50	250-350	97-98	-	Parallel	25
		350	30-100			-		

In this case, a small number of passive components must be added to this integrated device in order to realize the synchronous dc/dc converter.

Table 1 put into evidence that the choice of almost all the producers is to develop devices made for the series connection at their output terminals. Only one of them is devoted to the parallel-connected architecture. Some versions are dedicated to thin film solar modules. A generally high value of the efficiency is obtained. The peak one is even incredibly high, but this is due to the fact that in some cases the DC/DC converter has a “pass through” operation mode, when the required output voltage is close to that one corresponding to the maximum power point of the source. The switching operation is then temporarily suspended and this explains the high efficiency value in those conditions, the other side of the coin being the right detection of the source/load conditions requiring the wake up of the converter’s switching operation mode.

Topologies used for developing some products in Table 1 are shown in [36].

4.2 Micro Inverters

Table 2 provides an overview of the main micro inverters which are nowadays available on the market. As expected, the average efficiency is lower than the one ensured by the power optimizers, this being due to the significant voltage gain micro inverters must ensure.

SMA is also going to access the market of micro-inverters with the Sunny Boy 240 in the early 2012. According to [44], SMA device uses 60% lower number of components than the competitors, thus having an increased reliability.

Despite of the choice of other producers, who decided to avoid the use of electrolytic capacitors in order to improve the reliability of its micro-inverter, SMA follows the same line of the leading producer, Enphase Energy, who openly declares that the reliability bottleneck is not in the use of such components, because their appropriate use does not affect the converter’s lifetime more than other components. This point is quite controversial: Enphase Energy proposes some documents on this in which it is explained why the four parallel Nichicon electrolytic capacitors, 2200 μF, 63 V, are not a weakness point for Enphase micro-inverter. In fact, Enphase independent experts assess that, during normal operation, the capacitor is subjected to 65°C external temperature so that, according to data provided by the capacitors’ manufacturer, this results in a 50 years lifetime. They also declare that no indication of corrosion affecting the capacitors has been detected during the tests and that the peak voltage is well below the limit indicated by the manufacturer [34][35].

Some other manufacturers have the opposite opinion about the electrolytic capacitors: this is the case of Enecsys, which openly declares that this kind of components is not used in its micro-inverter. In fact, Enecsys does not employ electrolytic capacitors neither at the PV module terminals, nor as storage element at the dc bus. In fact, a multiple stage topology is used [45] which has the drawback of a slightly lower efficiency with respect to the com-

Table 2. Main characteristics of some microinverters available on the market.

Producer	Model	Power [W]	Input voltage [V]	η_{max} [%]	η_{EU} [%]	Warranty [yrs]	Galvanic Isol.
Power-One [43]		265	20-50	96	95.5	-	Yes (HF)
		320	30-50	96.3	95.5		
Enphase [47]	M215	190-260	22-36	96.3	96	25	Yes (HF)
	M190	230	22-40	95.5	95	15	
	M210	240	31-50	96	95.5	15	
Solarbridge [48]		250	48	95.5	94.5	25	Yes (HF)
			64				
Enecsys [49]		480	21-35	96	94	20	Yes (HF)
		360	29-42	95	93		
		280		94	92.5		
		240			92		
		200					
Direct Grid [50]	S460	480	53-65	93	92	20	-
	S250	250	24-32	92	91		
	S250	250	145-165	95	92		
	S400	400	145-165	94	92		
Petra Solar [51]		200	20-60	95	93	10	Yes (HF)

petitors.

Among the different models proposed nowadays, those ones produced by Direct Grid Technologies and dedicated to thin film modules deserve to be mentioned.

Some producers prefer to sell PV modules with the micro-inverter integrated on the backside, ready to be installed for different applications (house roofs, poles,...). This is the case of GreenRay, proposing the 200 W SunSine, of Petra Solar SunWave 200-240 W pole-mount solution and ExelTech, producing a 240 W module for the US market.

Looking at Table 2, it is evident that the efficiency level of a micro inverter is lower than the one of power optimizers. Almost all the models use a high frequency transformer for achieving the galvanic isolation and the voltage boost at the same time.

Topologies used by producers for developing some products in Table 1 are shown in [36][37][38][45].

5 CONCLUSIONS

In this paper an overview of the main challenges in distributed maximum power point tracking is given. The two main solutions, based on DC/DC and DC/AC converters, are discussed and the main characteristics of the devices available on the market have been listed and compared.

The paper puts into evidence that further work is needed for improving the smartness, efficiency, reliability and portability of such low power converters which can be the key for the widespread penetration of photovoltaics and for its best operation in extreme applications.

ACKNOWLEDGEMENTS

This paper has been partially supported by FARB and PRIN 2008 funds of the University of Salerno and by the PRIST funds of the Second University of Naples.

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Received: 2012-01-27
Accepted: 2012-04-04