An Improved Model-Based Maximum Power Point Tracker for Photovoltaic Panels

Loredana Cristaldi, *Senior Member, IEEE*, Marco Faifer, *Member, IEEE*
Marco Rossi, *Student Member, IEEE*, and Sergio Toscani, *Member, IEEE*

I. Introduction

CLIMATE change concerns, increasing prices of the fossil fuels as far as an increasing global demand for energy are stimulating the research focused on the exploitation of renewable energy sources. One of the most promising features seems to be the solar radiation, which can be directly converted into electricity because of the photovoltaic (PV) effect. Unfortunately, as for most of the so-called alternative sources, the cost of energy is substantially higher than that produced from fossil fuels. The diffusion of PV generation, however, has been encouraged through incentives issued by the local governments. Because of this economical support, in the last years, there has been a proliferation of PV plants and we have also experienced a dramatic reduction of their cost per watt as well as significant increase in the efficiency. In spite of this, the competitiveness with respect to nonrenewable sources still remains unfair without a strong public support. Substantial improvements should be achieved to make solar energy convenient even in the absence of local incentives.

Manuscript received November 30, 2012; revised May 2, 2013; accepted May 4, 2013. Date of publication August 28, 2013; date of current version December 5, 2013. The Associate Editor coordinating the review process was Dr. Jesus Urena.

The authors are with the Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Milano 20133, Italy (e-mail: loredana.cristaldi@polimi.it; marco.faifer@polimi.it; marco.rossi@rse-web.it; sergio.toscani@polimi.it).

Color versions of one or more of the figures in this paper are available online.

The cost effectiveness of a PV plant for given environmental conditions basically depends on two aspects. The first is the technology employed to build the PV cells; the second is the configuration and the control algorithms implemented in the switch mode power converters in which the PV panels are connected to. It is well known that the low-frequency behavior of an array of PV modules can be represented by a current–voltage characteristic, while the dynamics can be neglected in most of the applications. Its shape essentially depends on the temperature and on the solar irradiance. For given environmental conditions, there is an operating point on the V–I characteristics, called Maximum Power Point (MPP), where maximum power output is achieved, hence the efficiency is optimized. However, if each PV panel was connected to its own power converter hence known as Module Integrated Converter (MIC) controller, it would be possible to further enhance the system efficiency. In fact, the panel-level Maximum Power Point Tracker (MPPT) control allows a huge reduction of the losses because of the mismatch between panels, which can be serious in partially shaded conditions. Furthermore, the employment of MICs allows eliminating the panel-level hot spots, thus improving the system reliability, and the resulting architecture simplifies both the installation and the planning of future expansions [1]. The MIC topology, however, suffers from two main drawbacks. The first is related with the lower efficiency of MICs with respect to larger converters. However, in most of the cases, the increase of conversion losses is way lower than the power saving achieved because of the reduction of mismatch losses. The second is its higher cost because of the larger number of power converters. Because the price of power electronics is, however, decreasing continuously, this architecture is expected to be competitive in the near future [2]. Several MPPT algorithms can be implemented in MICs. In general, they perform very similar in quasi-stationary environmental conditions. The most significant differences among them, however, lie in their dynamic behavior, which becomes evident in rapidly changing conditions. Model-Based (MB) MPPT techniques seemed to be very attractive for MIC applications. It is easy to accurately model the behavior of a single panel with respect to an array of modules. They offer an interesting dynamic performance, but the conventional implementations need an expensive high-precision pyranometer. To overcome this problem, the authors have proposed a novel MB MPPT algorithm, which requires a pyranometer just during the identification of the relevant parameters in the panel but not during its operation [3]. Starting from the assumption that a MB MPPT for MIC applications requires an efficient yet accurate model of PV panel, Cristaldi *et al.* [4], have also presented a new single diode model whose parameters can be more easily estimated with respect to conventional ones.

In this paper, the authors employ this result to implement a MB MPPT. The advantages will be pointed out and an evaluation of the performance will be also reported. Section II contains a comparison between the conventional MPPT techniques, while Section III is a brief recall about the model in [4]. In MB MPPT algorithms, it is a key to accurately estimate the relevant parameters. Section IV explains a possible technique allowing the identification of parameters in a closed form. Section V describes different implementations of MB MPPT while Section VI shows how the employment of a dedicated pyranometer can be avoided. The last part of this paper is dedicated to the experimental activity. Section VII reports the experimental setup, and in Section VIII, the performance of the proposed MPPT technique has been evaluated.

II. Comparison Between MPPT Techniques

As mentioned in Section I, the efficiency of the PV system is strictly related to that of the switch-mode converter, which controls the output voltage or current, and to the performance of the MPPT algorithm, which provides the voltage or current reference. Many MPP algorithms can be found in the literature, and several authors have performed a comparison between these techniques pointing out their benefits, drawbacks, and performances [5], [6].

Because of the ease of implementation, Perturb and Observe (P&O) method is still the most widely employed technique [6]–[8]. It requires evaluating the sign for the derivative of the power with respect to the voltage through the superimposition of a voltage perturbation ΔV

$$\frac{dP}{dV} \cong \frac{\Delta P}{\Delta V}. \tag{1}$$

The voltage perturbation (also when the MPP has been reached) affects the global efficiency of the system. Several papers have explained why its amplitude cannot be reduced below a threshold to achieve a stable tracking [5], [7]–[9]. In addition, an acceptable accuracy and stability can be guaranteed only if the tracking speed is quite low. This further decreases the efficiency of the algorithm in case of rapidly changing atmospheric conditions [5]–[11].

Another widely used MPPT technique is the Incremental Conductance (IC) method. It is based on the comparison between the incremental conductance (dI/dV) and the instantaneous conductance (I/V) [5]–[8], [10]. Once MPP has been reached, the following condition is met:

$$\frac{dP}{dV} = 0 \quad \rightarrow \quad \frac{I}{V} = -\frac{dI}{dV}. \tag{2}$$

The IC tracking technique does not introduce any voltage perturbation once the MPP has been reached. In general, it is more accurate and stable [6] with respect to the P&O. Unfortunately, despite IC is typically faster than P&O, it is still too slow and inaccurate in case of quick variations of the solar radiation [7], [9] and [10].

A very simple MPPT algorithm is the constant voltage (CV) method. It is based on the assumption that the ratio between the MPP voltage and the open-circuit voltage is weakly affected by the solar radiation and the panel temperature

$$V_{mp} \cong k V_{oc}. \tag{3}$$

The main difficulties to be faced during the implementation of this algorithm are the choice of the constant k [6] and the estimation of V_{oc}. This voltage can be measured by disconnecting the power converter [5], [6], [8] and [9], but it results in production losses. Alternatively, it can be evaluated by measuring the open-circuit voltage on an independent PV cell (defined as pilot cell) [5]. Another method is based on the equations that provide the value of V_{oc} starting from the measurement of the PV cell temperature T_c [5], assuming that the effect of the solar radiation G is negligible. Unfortunately, whichever estimation method is employed, (3) is a rather rough approximation and the global efficiency guaranteed by this technique is poor with respect to the others [5], [6].

When the focus is moved toward MICs, a method that overcomes most of the previously explained problems is the MB MPPT. If an accurate model of the PV panel is available as well as a precise estimation of the environmental parameters, it will be possible to locate the MPP for each module. The main advantage lies in its extremely quick response to sudden variations of the solar radiation with respect to the conventional hill climbing MPPT techniques, which do not allow fast jumps of the module voltage. This permits better conversion efficiency during rapidly changing conditions. This approach has been already investigated in [6], [12], and [13], but until now it has been considered hardly feasible because it requires a fine tuning of the model and an accurate (and very expensive) pyranometer [6]. In [3], the authors have proposed a MB MPPT technique, which does not need a pyranometer, except for a preliminary tuning of the parameters. The method can be further enhanced if the innovative model presented in [4] is employed instead of the conventional single diode model with an infinite shunt resistance.

III. Simplified Model of the PV Panel

Many different models of the PV cell can be found in the literature. One of the most widely used is the single diode model, which, in many applications, represents a good compromise between accuracy and simplicity [14]–[18]

$$I = I_{ph} - I_s\left(e^{\frac{V+R_s I}{V_T}} - 1\right) - G_{sh}\left(V + R_s I\right) \tag{4}$$

where V and I are the panel voltage and current, I_{ph} is the photocurrent, I_s is the reverse saturation current, and V_T is the thermal voltage. Finally, R_s and G_{sh} are the series resistance and the shunt conductance, respectively. Often G_{sh} is supposed to be zero, because it does not produce relevant effects around MPP, where the PV module is supposed to operate [16], [17].

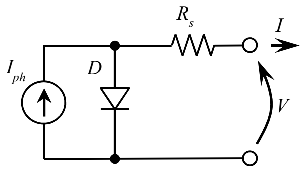

Fig. 1. Single diode equivalent circuit.

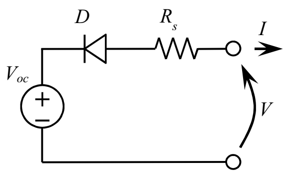

Fig. 2. Equivalent electric circuit of the proposed model.

A good match with the actual V–I characteristic can be anyway reached by opportunely tuning the thermal voltage and series resistance [16], [18]. On the contrary, R_s cannot be usually neglected because small variations may significantly affect the V–I curve around the MPP [16], [18]. The equation of the single diode model with zero-shunt conductance (Fig. 1) can be written as follows:

$$V = V_T \ln\left(1 + \frac{I_{ph} - I}{I_s}\right) - R_s I. \quad (5)$$

The open-circuit voltage V_{oc} is considerably higher than the thermal voltage, so it is possible to assume that $e^{V_{oc}/V_T} \gg 1$ [4]. These assumptions lead to the following approximate expression of the panel voltage:

$$V = V_{oc} + V_T \ln\left(1 - \frac{I}{I_{ph}}\right) - R_s I. \quad (6)$$

Equation (6) is a simple model for PV modules, which practically has the same behavior of the conventional single exponential formulation. It can be represented with the equivalent circuit shown in Fig. 2. The diode is characterized by the thermal voltage V_T and the reverse saturation current equal to the photocurrent I_{ph}.

Equation (6) provides an approximate expression of the whole V–I curve for given environmental conditions. It is very important to point out that the parameters are affected by the solar radiation intensity G and by the cell temperature T_c, which are supposed to be uniform on the module. Literature [18] reports an approximate expression of these dependencies

$$I_{ph}(G, T_c) = I_{ph0} \frac{G}{G_0} \left[1 + \alpha (T_c - T_{c0})\right] \quad (7)$$

$$V_{oc}(G, T_c) = V_{oc0} \left[1 + \beta (T_c - T_{c0})\right] + V_T \ln\left(\frac{G}{G_0}\right) \quad (8)$$

$$V_T(T_c) = V_{T0} \frac{T_c}{T_{c0}} \quad (9)$$

where I_{ph}, V_{oc}, and V_T are the values of the parameters when the solar radiation and the cell temperature are equal to G and T_c, respectively. α and β are the thermal coefficients. I_{ph0}, V_{oc0}, and V_{T0} are the photocurrent, the open-circuit voltage, and the thermal voltage when the solar radiation intensity is equal to G_0 and the temperature is T_{c0}. Finally, it is important to note that the series resistance R_s is weakly dependent on the environmental conditions, therefore it can be considered as a constant (as shown in [14] and [19]).

IV. Estimation of the Parameters

The main advantage of this model becomes evident when its four parameters (V_{oc}, I_{ph}, V_T, and R_s) have to be evaluated. V_{oc} can be directly measured, whereas in most of the cases, I_{ph} can be assumed to be equal to the short-circuit current I_{sc}. The identification of the other parameters requires two equations. Because the PV panel is supposed to operate around its MPP, the model shall be particularly accurate near it. Therefore, a first equation can be found by imposing that the V–I characteristic of the model includes the MPP of the panel, defined by the voltage V_{mp} and by the current I_{mp}. The second equation shall guarantee that this point is a maximum, which is equating to zero the derivative of the electrical power. The following system of equations can be written down:

$$\begin{cases} V_{mp} = V_{oc} + V_T \ln\left(1 - \frac{I_{mp}}{I_{sc}}\right) - R_s I_{mp} \\ \left.\frac{d(VI)}{dI}\right|_{I=I_{mp}} = V_{mp} + \frac{V_T I_{mp}}{I_{mp} - I_{sc}} - R_s I_{mp} = 0. \end{cases} \quad (10)$$

It can be easily solved for V_T and R_s

$$\begin{cases} V_T = \frac{(2V_{mp} - V_{oc})(I_{sc} - I_{mp})}{I_{mp} + (I_{sc} - I_{mp}) \ln\left(1 - \frac{I_{mp}}{I_{sc}}\right)} \\ R_s = \frac{V_{mp}}{I_{mp}} - \frac{2V_{mp} - V_{oc}}{I_{mp} + (I_{sc} - I_{mp}) \ln\left(1 - \frac{I_{mp}}{I_{sc}}\right)}. \end{cases} \quad (11)$$

The knowledge of the open-circuit voltage, short-circuit current, and MPP for a known value of temperature and radiation allows directly calculating all the parameters of the proposed PV model. In contrast, the traditional formulation requires a numerical procedure [15], [16], [20]–[22]. Usually, the manufacturers declares the open-circuit voltage, the short-circuit current, and the MPP voltage and current in Standard Test Conditions (STC: light radiation intensity 1000 W/m^2, cell temperature 298.15 K, and air mass coefficient 1.5) [23]. Therefore, the parameters of the model in STC can be directly obtained from the rated values. Furthermore, in many cases, the thermal coefficients α and β are also reported, so that the model is completely defined by the data provided by the manufacturer.

In spite of this, it has been shown [4] that because of the dispersion of the production process and the uncertainty of the rated values, the model obtained from the datasheet may be quite inaccurate. When a high precision is needed, it is mandatory to measure V_{oc}, I_{sc}, V_{mp}, and I_{mp} for the known values of solar radiation and cell temperature, which therefore have to be monitored as well. The radiation intensity can be measured using a pyranometer, while the estimation of the cell temperature is trickier. Because the cells are enclosed in the module, a direct measurement is not feasible.

It is well known that PV panels have a relatively low efficiency. The main reason is because the cells operate effectively just in a relatively narrow band of the sunlight spectrum. Most part of the solar radiation is not converted into electricity, and heats the module. Following the typical approach reported in the literature, the temperature difference between the cells and the surrounding environment can be considered proportional to that unconverted power P_{loss} and to a thermal resistance R_{th}, which models the heat exchange. It has been assumed that the thermal inertia can be neglected. P_{loss} is clearly proportional to the solar radiation and to the surface of the cells S

$$P_{loss} = [1 - \eta(G, T_c)]\, SG \tag{12}$$

where η is the efficiency of the panel, which is in general a function of the solar radiation and of the cell temperature. A simplified expression of these dependencies is reported in [24]

$$\eta(G, T_c) = \eta_0 \left[1 - \mu(T_c - T_{c0}) - \sigma \ln\left(\frac{G}{G_0}\right)\right] \tag{13}$$

where η_0 is the efficiency of the module in STC. In most of the cases, σ is quite small, so that the efficiency can be supposed to be unaffected by G [24]. Therefore

$$P_{loss} \cong [1 - \eta_0 + \eta_0 \mu (T_c - T_{c0})]\, SG. \tag{14}$$

Neglecting the dynamics, the temperature difference ΔT_e between the PV panel and the environment can be approximated with the product between a thermal resistance R_{th} and the power losses. Therefore

$$\Delta T_e = R_{th} P_{loss}. \tag{15}$$

Substituting (14) in (15), reminding how ΔT_e has been defined and solving for T_c

$$T_c = \frac{(1 - \eta_0 - \eta_0 \mu T_{c0}) R_{th} SG + T_e}{1 - R_{th} SG \eta_0 \mu}. \tag{16}$$

Because $R_{th} SG \eta_0 \mu$ is much smaller than one, it can be written as follows:

$$\Delta T_e \cong (1 - \eta_0 - \eta_0 \mu T_{c0}) R_{th} SG = k_{\Delta T env} G. \tag{17}$$

Equation (17) shows that the temperature difference ΔT_e is directly proportional to the solar radiation. The goodness of the approximation is also evident in the experimental results reported in [24]–[26].

In the literature, it is possible to find several methods to estimate R_{th}. Most of them rely on the complex thermal models [24], [27], and therefore require knowing a lot of parameters, which are not easily available. In many cases, the thermal resistance can be considered constant, thus the manufacturers usually provide the value of $T_{c,\mathrm{NOC}}$ (normal operating conditions temperature) [28]. It is the cell temperature measured for a given environment temperature $T_{e,\mathrm{NOC}}$ and solar radiation G_{NOC}. Starting from this information, it is quite easy to obtain $k_{\Delta T env}$

$$k_{\Delta T env} = \frac{T_{c,\mathrm{NOC}} - T_{e,\mathrm{NOC}}}{G_{\mathrm{NOC}}}. \tag{18}$$

Recent works have demonstrated that R_{th} is heavily affected by the wind speed [24] and that in some conditions, the thermal transients cannot be neglected. For this reason, this approach is valid for a given wind speed and for a slowly variable solar radiation. Therefore, it is very difficult to obtain an accurate evaluation of the cell temperature starting from the measurement of T_e.

To overcome the limits of the described method, it is possible to obtain more precise results if this estimation is performed by measuring the temperature T_p of a point, which has to be as close as possible to the cells. It is clear that the amplitude of the temperature correction to be predicted decreases noticeably, thus the accuracy of the estimated cell temperature is greatly enhanced. In particular, it is much less affected by the wind speed and the thermal transients. The coefficient $k_{\Delta T}$ can be introduced to write down the following equation:

$$T_c = T_p + k_{\Delta T} G \tag{19}$$

where T_p can be chosen as the temperature of the rear surface. The cells are usually attached to a thin frame, which is designed to act as heat sink, therefore $k_{\Delta T}$ is very small. When the radiation level is, however, high, it cannot be neglected [29].

It has been shown that the measurement of four electrical quantities allows estimating the parameters of the proposed model for a given value of G and T_c, which therefore have to be monitored. Equation (19) sets a relationship among T_c, the solar radiation and the temperature of the rear surface in the panel. This means that the parameters of the model can be considered as functions of the solar radiation G and of T_p, which can be easily measured. Substituting (19) in (7)–(9), then substituting (9) in (8) while reminding $I_{sc} \cong I_{ph}$ leads to

$$I_{sc}(G, T_p) = I_{sc0} \frac{G}{G_0} \left[1 + \alpha (T_p + k_{\Delta T} G - T_{c0})\right] \tag{20}$$

$$\begin{aligned} V_{oc}(G, T_p) &= V_{oc0} \left[1 + \beta (T_p + k_{\Delta T} G - T_{c0})\right] + \\ &\quad + \frac{V_{T0}}{T_{c0}} (T_p + k_{\Delta T} G) \ln\left(\frac{G}{G_0}\right) = \\ &\cong V_{oc0} \left[1 + \beta (T_p + k_{\Delta T} G - T_{c0})\right] + \\ &\quad + \frac{V_{T0}}{T_{c0}} T_p \ln\left(\frac{G}{G_0}\right) \end{aligned} \tag{21}$$

$$V_T(G, T_p) = V_{T0} \frac{T_p + k_{\Delta T} G}{T_{c0}}. \tag{22}$$

Because of the typical values of the parameters, the term $k_{\Delta T} G$ can often be neglected in the expression of the short-circuit current. The previous equations can also be rewritten as linear combinations of unknown parameters

$$I_{sc}(G, T_p) = G (K_{sc1} + K_{sc2} T_p). \tag{23}$$

$$\begin{aligned} V_{oc}(G, T_p) &= K_{oc1} + K_{oc2} T_p + K_{oc3} G + \\ &\quad + K_{oc4} T_p \ln(G). \end{aligned} \tag{24}$$

$$V_T(G, T_p) = K_{T1} T_p + K_{T2} G\ . \tag{25}$$

An experimental activity allows evaluating I_{sc}, V_{oc}, V_T, and R_s for different values of solar radiation G and temperature T_p.

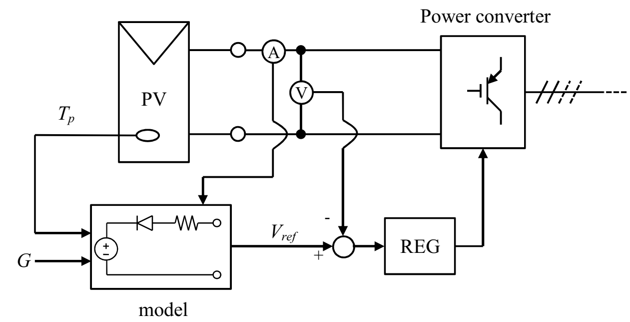

Fig. 3. MB MPPT: asymptotic solution of the power derivative.

The unknown parameters appearing in (23)–(25) can be computed starting from this data using an Ordinary Least Squares (OLS) estimation. The series resistance R_s has been assumed to be unaffected by the environmental quantities. Therefore, it can be estimated as the mean of the values obtained from the experimental results in the different operating conditions.

V. Conventional MB MPPT Technique

The model described in the previous sections can be used to predict the MPP [3], [12], [13]. With previously estimated relevant parameters and having measured the environmental quantities G and T_p, (23)–(25) together with (6) allow to estimate the V–I characteristics of the panel. The MPP can then be obtained by equating to zero, the derivative of the electrical power with respect to the current

$$\left.\frac{dP\left(I,G,T_p\right)}{dI}\right|_{I=I_{mp}} = V\left(I_{mp},G,T_p\right) + I_{mp}\left.\frac{dV\left(I,G,T_p\right)}{dI}\right|_{I=I_{mp}} = 0 \quad (26)$$

where the derivative of the voltage with respect to the current results [1]

$$\frac{dV\left(I,G,T_p\right)}{dI} = \frac{V_T\left(G,T_p\right)}{I - I_{sc}\left(G,T_p\right)} - R_s. \quad (27)$$

Unfortunately, (26) cannot be solved in a closed form. However, the MPP can be reached without explicitly solving (26), but using a proper closed-loop controller. The derivative of the power with respect to the current can be computed in closed form, as reported before by solving (27). According to (26), it is possible to reach the MPP by introducing a voltage controller (REG) having the following reference (Fig. 3):

$$V_{ref}\left(I,G,T_p\right) = -\frac{dV}{dI}I = V_T\left(G,T_p\right)\frac{I}{I_{sc}\left(G,T_p\right)-I} + R_sI. \quad (28)$$

The previous equation has a unique solution (the MPP) in the operating voltage and current range of the panel. Therefore, there is a single equilibrium point. Let us introduce the voltage error ε, namely the difference between the voltage reference and the panel voltage. It can be easily shown that the derivative of the voltage error with respect to the panel voltage is always negative. It is therefore relatively easy to design a proper controller REG, which allows the panel to reach the MPP. Unfortunately, this approach suffers from a strong drawback: it is highly sensitive to the deviation between the actual V–I characteristic and that predicted by the model. MPP is reached with high accuracy only when the match between the panel and its model is very good.

The MPP can also be found using a numerical method (e.g., Newton–Raphson) to solve (26). Either the MPP voltage or current can be provided as the reference of a regulator, which controls the power converter. It is clear that the accuracy in finding the MPP depends on the accuracy of the model. However, it can be shown that computing V_{mp} and controlling the panel voltage (instead of the current) ensures a better robustness with respect to the errors and to the uncertainty of the parameters.

VI. Estimation of the Solar Radiation Intensity

The MB MPPT technique reported in Section V requires the installation of temperature and light radiation sensors. Because of the procedure discussed in Section IV, it is possible to avoid the direct measurement of the cell temperature.

The measurement of the solar radiation remains the most critical task. It is considered as the main drawback of the MB MPPT technique [6] because the cost of an accurate pyranometer could be nonnegligible with respect to that of the PV plant. Furthermore, multiple sensors are required if the panels are not oriented in the same direction [14].

However, it is possible to solve this limitation through a procedure, which provides an estimation of the solar radiation G_{est} based on the measurement of the panel voltage, current, and temperature. This means that the PV module, in normal operating conditions, can be used like a light radiation sensor by inverting the model discussed in Section III

$$V(I,G,T_p) \xrightarrow{\text{inversion}} G_{est}(V,I,T_p). \quad (29)$$

The inverse model cannot be obtained in closed form; therefore, the light radiation intensity has to be estimated using a numerical procedure. Nevertheless, few simplifications can be introduced to analytically compute G. In fact, by substituting (7) and (8) in (6) and supposing that $k_{\Delta T}$ is very small, it is possible to write

$$G_{est}\left(V,I,T_p\right) \cong \frac{G_0 I}{I_{sc0}\left[1+\alpha\left(T_p-T_{c0}\right)\right]} + G_0 e^{\frac{T_{c0}}{T_p}\frac{V+R_sI-V_{oc0}\left[1+\beta\left(T_p-T_{c0}\right)\right]}{V_{T0}}}. \quad (30)$$

Neglecting the temperature difference between the frame and cells leads to inaccurate results in the prediction of the V–I characteristics especially near open circuit. In fact, the sensitivity to the cell temperature is the highest in this working point. However, because V_{mp} weakly depends on G, a relatively coarse estimation of the solar radiation does not produce a relevant error in predicting the MPP [4]. It has been previously explained how to identify the model through least square fitting. Equation (30) can be rewritten to make use of these results. Reminding (21) and (22), K_{oc4} should be equal

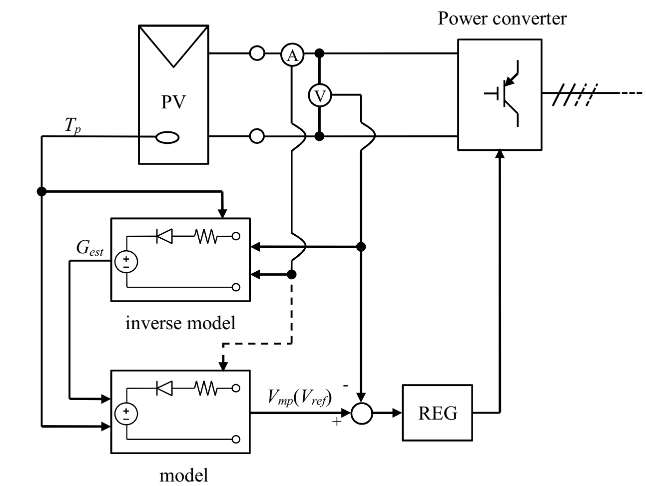

Fig. 4. Block diagram of the proposed MPPT system.

to K_{T1}. Least square fitting does not impose this relationship; therefore, they may be not exactly equal because the model is not able to perfectly represent the behavior of the panel. However, assuming that they are very close, it can be written as follows:

$$G_{est}\left(V, I, T_p\right) \cong \frac{I}{K_{sc1} + K_{sc2}T_p} + e^{\frac{V+R_s I - K_{oc1} - K_{oc2}T_p}{K_{oc4}T_p}}. \quad (31)$$

The functional diagram of the proposed MPPT algorithm is shown in Fig. 4.

Being a MB algorithm, its performance strictly depends on the accuracy of the model itself in predicting the MPP voltage. The model parameters have to be tuned during a preliminary training, but they may change during the operating life of the module. However, it can be shown [14] that during sunny days, it is possible to accurately estimate the solar radiation from the data provided by the nearby weather stations. This allows a periodical retuning of the model parameters without a dedicated pyranometer. Furthermore, dirt and dust may significantly affect the operation of the module. Having assumed that their effect is similar to a reduction of the (effective) solar radiation [30], the operation of the proposed MPPT algorithm is not jeopardized. Because the cells are employed as solar radiation sensors, just the effective solar radiation that contributes to the energy conversion is measured. Therefore, the module operates so as it were clean, but with a lower irradiance level.

VII. Measurement Setup

The MPPT technique described in Section VI requires estimating the parameters of the PV panels. For this reason, a measurement setup, which allows acquiring the V–I characteristic of PV panels, has been developed. Its architecture is shown in Fig. 5. A NI 9215 board has been employed to acquire the voltage and current signal. It features four analog inputs with a range of ±10 V, a maximum sampling frequency of 100 kSamples/s and a 16-bit resolution. A resistive divider and a shunt with very low parasitic inductance have been employed as voltage and current transducers. The formulation of the model also requires monitoring two environmental quantities.

1) The temperature T_p: it has been measured using a PT100 placed on the rear surface of the panel.
2) The solar radiation G: it has been measured with a class 1 CMP 21 global pyranometer, placed with the same orientation of the PV module under test.

A proper 16-bit serial interface connected to a PC has been employed to acquire the output of the two sensors.

In the previous paragraph, it has been explained how the proposed MB MPPT does not need a pyranometer. In fact, the setup of Fig. 5 is required just during the estimation of the parameters. The advantage is clear, because the characterization process is relatively fast and can be carried out by a third part during the preliminary test and the periodical maintenance. Therefore, the owner of the PV plant does not need to buy an expensive instrumentation.

The acquisition of the electrical and the environmental quantities have been managed by a virtual instrument, developed in NI LabVIEW, which also controls the electronic load allowing to change the working point of the PV module. In this way, it is possible to acquire the whole V–I characteristic, from short circuit to open circuit. The measurement takes less than 100 ms. The PV module under test is a FVG Energy model 72-125-180M-MC [31] made of 72 125 mm × 125 mm mono crystalline silicon cells.

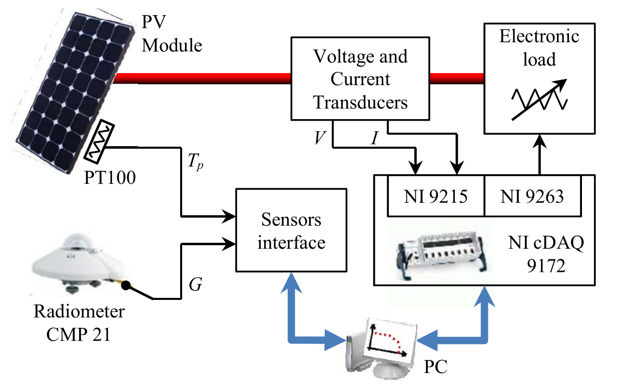

Fig. 5. Measurement system.

TABLE I

Values of the Parameters Computed from the Experimental Data

	PV OLS parameters
K_{sc1}	2.263 mAm^2/W
K_{sc2}	9.603 µAKm^2/W
K_{oc1}	80.65 V
K_{oc2}	-169.9 mV/K
K_{oc3}	-869.5 µVm^2/W
K_{oc4}	6.597 mV/K
K_{T1}	7.032 mV/K
K_{T2}	216.6 µVm^2/W

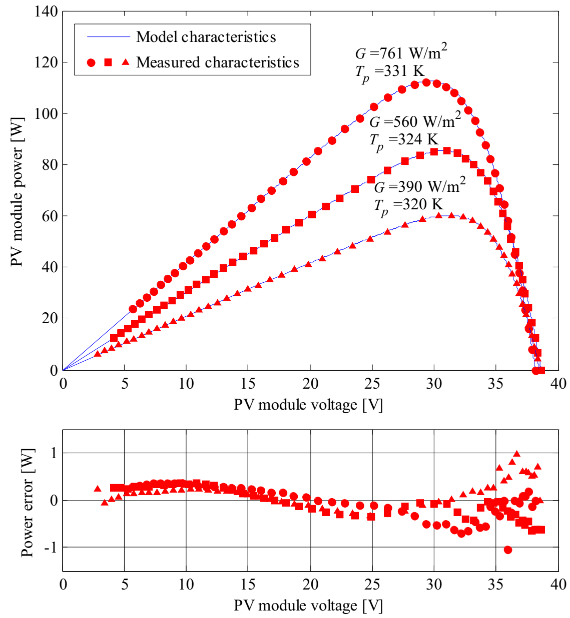

Fig. 6. Comparison between measured and simulated V-P characteristic of a PV panel.

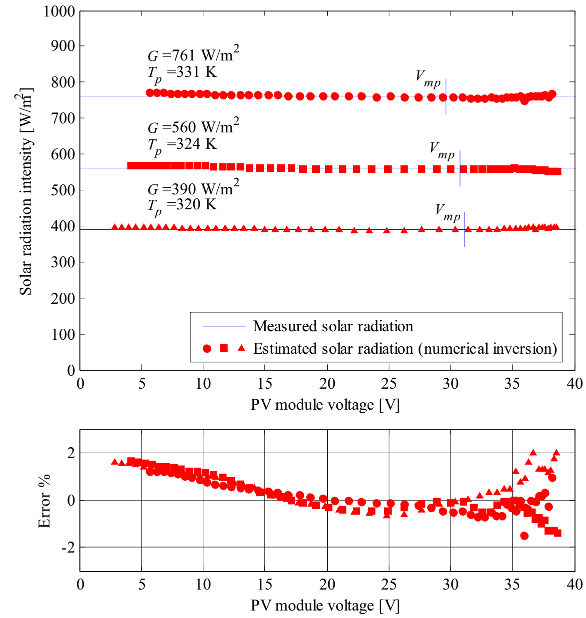

Fig. 7. Comparison between measured and estimated solar radiation (numerical inversion).

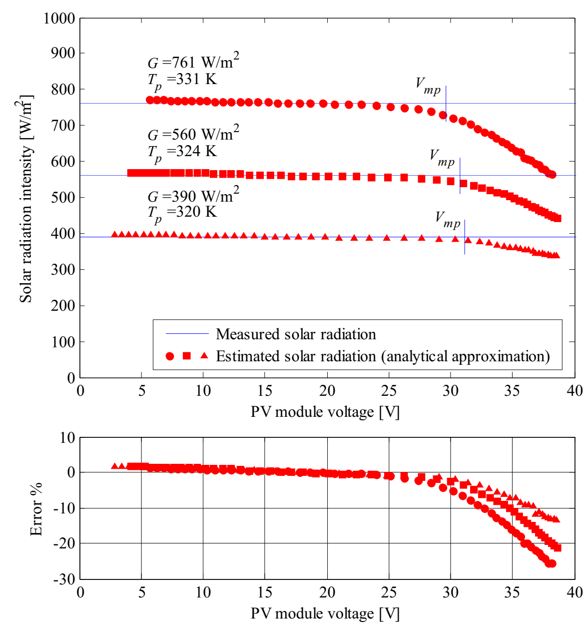

Fig. 8. Comparison between measured and estimated solar radiation (analytical approximation).

VIII. Validation of the Proposed MPPT Algorithm

To validate the proposed algorithm, an experimental activity has been carried out. The first step has been devoted to the modeling of the PV module under test; 300 V–I curves in different environmental conditions have been measured. The parameters appearing in (23)–(25) ensuring the best match between the model and the experimental results have been computed using the OLS method as explained in Section IV. The results are shown in Table I.

Then, the capability of the model to estimate the power at MPP has been tested. More than 1000 V-I curves curves have been measured in different environmental conditions, and compared with those predicted using the proposed model. Some results are shown in Fig. 6, which shows a good agreement between the measured and the predicted curve, especially near the MPP.

Then, the technique allowing the estimation of the solar radiation without a pyranometer has been tested. The model has been inverted using both a numerical method and the analytical approximated expression (30) for the values of temperature and radiation shown in Fig. 6. The measured (G) and the estimated solar radiation (G_{est}) starting from different working points of the electric characteristic have been shown in Figs. 7 and 8, respectively. As expected, it can be noticed that the numerical inversion of the model provides more accurate results, especially above the MPP.

In fact, as mentioned in Section VI, (30) does not provide a good estimation of the solar radiation for voltages close to V_{oc}. In this case, the obtained solar radiation corresponds to a MPP voltage slightly different from the actual one. Another computation of (30), however, provides a more accurate G_{est}. Performing a few iterations, both of the model inversion techniques converge to the same estimation of V_{mp}. Furthermore, the experimental activity shows that the deviation between the estimated and the measured MPP voltage is not greater than 2.5%. Some relevant results are shown in Fig. 9.

It is clear that the error in estimating V_{mp} results in an operating point different than the actual MPP. It is important to evaluate the efficiency loss because of the proposed MPPT technique, namely the difference between the power generated at the actual MPP (which can be found by tracing the V–I characteristic) and at the predicted MPP. Fig. 10 shows its value over a whole day. It can be noticed that the error is always lower than 0.5%.

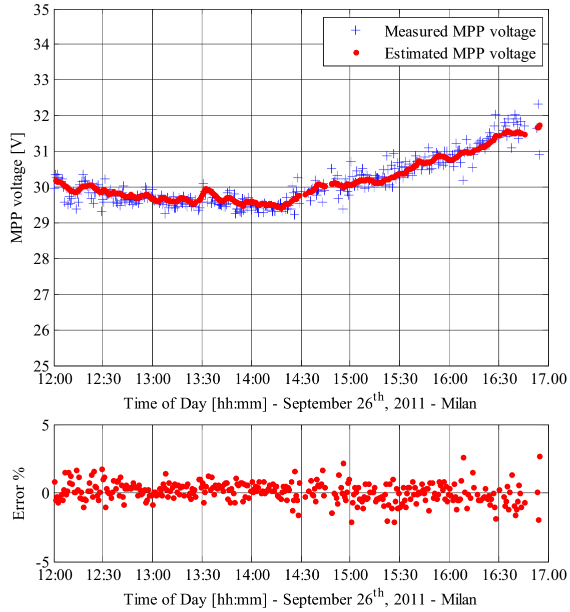

Fig. 9. Comparison between measured and estimated MPP voltage.

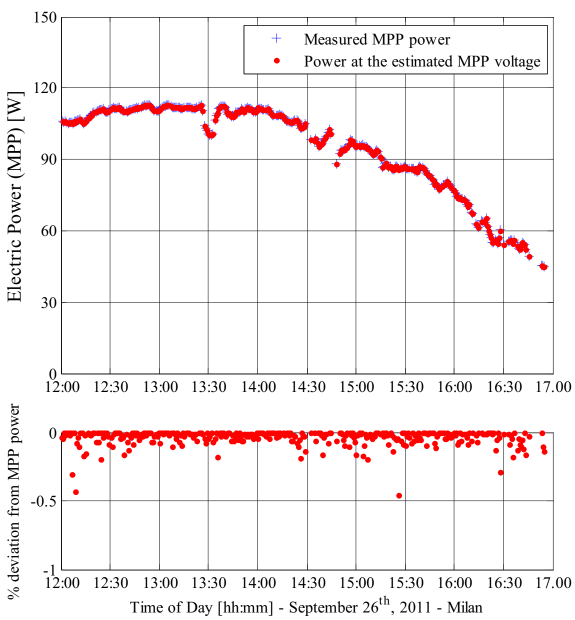

Fig. 10. Comparison between the measured maximum power and the power generated using the proposed algorithm.

IX. Conclusion

MB MPPT algorithms appear to be very attractive for MICs. Unlike a string of modules, in a single panel, it can be assumed that all the cells have the same temperature and are exposed to the same solar radiation. In this case, the PV panel can be easily modeled and its MPP voltage can be predicted from the measurement of solar radiation and cell temperature. The advantage of MB MPPTs in terms of dynamic response in rapidly changing conditions is well known, but until now they have been rarely employed because of the high cost. The research activity we developed and summarized in this paper has shown that, introducing some original expedients, the cost can be reduced and it may become an alternative to the conventional MPPT methods in MICs topologies. The MPPT technique is based on a single-series-diode model of PV module that the authors have introduced in a recent paper. Its simple formulation permits to obtain the parameters in closed form, while maintaining a good accuracy. After a training process aimed at estimating the dependence of the parameters on the solar radiation and the temperature, the model can be employed to predict the MPP for known environmental conditions. We have shown how to avoid a direct measurement of the cell temperature, which is usually difficult to achieve. Furthermore, the model can also be used to estimate the solar radiation with an adequate accuracy, thus eliminating the need for a radiometer or a dedicated cell, which is required by the conventional MB MPPT techniques. This feature dramatically reduces the cost and increases its robustness, thus making the method competitive with respect to the others techniques. The experimental tests have shown the performance of the proposed MPPT method, which provides a fast and accurate tracking of the MPP.

References

[1] Z. Liang, R. Guo, J. Li, and A. Q. Huang, "A high-efficiency PV module-integrated DC/DC converter for PV energy harvest in FREEDM systems," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 897–909, Mar. 2011.

[2] Q. Li and P. Wolfs, "A review of the single phase photovoltaic module integrated converter topologies with three different DC link configurations," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1320–1333, May 2008.

[3] L. Cristaldi, M. Faifer, M. Rossi, and S. Toscani, "MPPT definition and evaluation: A new model-based approach," in *Proc. Int. Instrum. Meas. Technol. Conf.*, 2012, pp. 594–599.

[4] L. Cristaldi, M. Faifer, M. Rossi, and S. Toscani, "A simplified model of a photovoltaic panel," in *Proc. Int. Instrum. Meas. Technol. Conf.*, May 2012, pp. 431–436.

[5] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Trans. Energy Convers.*, vol. 22, no. 2, pp. 439–449, Jun. 2007.

[6] D. P. Hohm and M. E. Ropp, "Comparative study of maximum power point tracking algorithms," *Progr. Photovolt., Res. Appl.*, vol. 11, no. 1, pp. 47–62, Jan. 2003.

[7] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, "Optimization of perturb and observe maximum power point tracking method," *IEEE Trans. Power Electron.*, vol. 20, no. 4, pp. 963–973, Jul. 2005.

[8] V. Salas, E. Olìas, A. Barrado, and A. Làzaro, "Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems," *Solar Energy Mater. Solar Cells*, vol. 90, no. 11, pp. 1555–1578, Jan. 2006.

[9] A. Zbeeb, V. Devabhaktuni, and A. Sebak, "Improved photovoltaic MPPT algorithm adapted for unstable atmospheric conditions and partial shading," in *Proc. Int. Conf. Clean Electr. Power*, Jun. 2009, pp. 320–323.

[10] J. H. Lee, H. Bae, and B. H. Cho, "Advanced incremental conductance MPPT algorithm with a variable step size," in *Proc. 12th Int. Power Electron. Motion Control Conf.*, Sep. 2006, pp. 603–607.

[11] P. Sanchis, J. Lòpez, A. Ursùa, E. Gubìa, and L. Marroyo, "On the testing, characterization and evaluation of PV inverters and dynamic MPPT performance under real varying operating conditions," *Progr. Photovolt., Res. Appl.*, vol. 15, no. 6, pp. 541–556, Sep. 2007.

[12] T. Ikegami, T. Maezono, F. Nakanishi, Y. Yamagata, and K. Ebihara, "Estimation of equivalent circuit parameters of PV module and its application to optimal operation of PV system," *Solar Energy Mater. Solar Cells*, vol. 67, nos. 1–4, pp. 389–395, Mar. 2001.

[13] W. Xiaolei, J. Huai-Zhen, Y. Liang, and Y. Pan, "A new method of MPPT control based on the model of photovoltaic array," in *Proc. Power Energy Eng. Conf.*, Mar. 2011, pp. 1–3.

[14] L. Cristaldi, M. Faifer, F. Ponci, and M. Rossi, "A simple photovoltaic panel model: Characterization procedure and evaluation of the role of environmental measurements," *IEEE Trans. Instrum. Meas.*, vol. 61, no. 10, pp. 2632–2641, Oct. 2012.

[15] G. Walker, "Evaluating MPPT converter topologies using a MATLAB PV model," *J. Electr. Electron. Eng.*, vol. 21, no. 1, pp. 49–56, 2001

[16] M. G. Wanzeller, R. N. C. Alves, J. V. da Fonseca Neto, and W. S. dos Santos Fonseca, "Current control loop for tracking of maximum power point supplied for photovoltaic array," *IEEE Trans. Instrum. Meas.*, vol. 53, no. 4, pp. 1304–1310, Aug. 2004.

[17] J. C. Wang, Y. L. Su, J. C. Shieh, and J. A. Jiang, "High-accuracy maximum power point estimation for photovoltaic arrays," *Solar Energy Mater. Solar Cells*, vol. 95, no. 3, pp. 843–851, Mar. 2011.

[18] A. Luque and S. Hegedus, *Handbook of Photovoltaic Science and Engineering*, 2nd ed. New York, NY, USA: Wiley, 2010.

[19] G. Farivar and B. Asaei, "A new approach for solar module temperature estimation using the simple diode model," *IEEE Trans. Energy Convers.*, vol. 26, no. 4, pp. 1118–1124, Dec. 2011.

[20] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Comprehensive approach to modeling and simulation of photovoltaic arrays," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1198–1208, May 2009.

[21] E. Matagne, R. Chenni, and R. E. Bachtiri, "A photovoltaic cell model based on nominal data only," in *Proc. Int. Conf. Power Eng. Energy Electr. Drives*, Apr. 2007, pp. 562–565.

[22] W. Xiao, W. G. Dunford, and A. Capel, "A novel modeling method for photovoltaic cells," in *Proc. IEEE 35th Annu. PESC*, Jun. 2004, pp. 1950–1956.

[23] *Measurement of Photovoltaic Current-Voltage Characteristic*, Standard IEC 60904-1:2006, Apr. 2005.

[24] E. Skoplaki, A. G. Boudouvis, and J. A. Palyvos, "A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting," *Solar Energy Mater. Solar Cells*, vol. 92, no. 11, pp. 1393–1402, Nov. 2008.

[25] M. Koehl, M. Heck, S. Wiesmeier, and J. Wirth, "Modeling of the nominal operating cell temperature based on outdoor weathering," *Solar Energy Mater. Solar Cells*, vol. 95, no. 7, pp. 1638–1646, Feb. 2011.

[26] J. Kurnik, M. Jankovec, K. Brecl, and M. Topic, "Outdoor testing of PV module temperature and performance under different mounting and operational conditions," *Solar Energy Mater. Solar Cells*, vol. 95, no. 1, pp. 373–376, Jan. 2011.

[27] G. M. Tina and S. Scrofani, "Electrical and thermal model for PV module temperature evaluation," in *Proc. 14th IEEE Mediterranean Electrotechnical Conf.*, May 2008, pp. 585–590.

[28] M. C. Alonso García and J. L. Balenzategui, "Estimation of photovoltaic module yearly temperature and performance based on nominal operation cell temperature calculations," *Renew. Energy*, vol. 29, no. 12, pp. 1997–2010, Oct. 2004.

[29] D. A. Adkins, "Novel method and system for monitoring CPV cell and module temperature," in *Proc. 35th IEEE PVSC*, Jun. 2010, pp. 1660–1665.

[30] M. Catelani, L. Ciani, L. Cristaldi, M. Faifer, M. Lazzaroni, and P. Rinaldi, "FMECA technique on photovoltaic module," in *Proc. IEEE Instrum. Meas. Technol. Conf.*, May 2011, pp. 1717–1722.

[31] FVG Energy LTD. London, U.K. (2010). *Photovoltaic Module FVG 72-125–180M690 MC*, [Online]. Available: http://www.fvgenergy.com