A Compact PV Panel Model for Cyber-Physical Systems in Smart Cities

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Abstract---**One of the ambitious goals of the ''Smart city'' paradigm is to design zero-energy buildings. Buildings can be considered as connected cyber-physical systems that require the construction of sound methodologies inherited from the EDA research. In particular, aiming at autonomous buildings, the effective design of renewable energy sources is a key aspect for which such methodologies have to be developed.**

In this work, we propose a modeling strategy for the early estimation of the performance of PV arrays. Although a plethora of PV panel models there exists, most of these models suffer from accuracy/complexity tradeoffs. On one hand, building fast models forces to ignore either the correlation between temperature and irradiance, or the topology of panels, thus yielding inaccurate estimations. On the other hand, more accurate models are time consuming and require costly measurements or circuit analysis, that cannot be extracted from the sole datasheet.

This paper proposes a compact semi-empirical model, suitable for real time simulation and built solely from information derived from the PV panel datasheet. The model is built by empirically fitting an expression of the panel operating point as a function of both irradiance and temperature, and of the adopted PV system topology. The accuracy and effectiveness of the proposed model have been validated w.r.t. the production traces of the PV systems of a real world industrial building.

I. Introduction

The possibility of running real-time simulations of a PV system through emulation is fundamental to avoid costly experimental setups [1]. Making this scenario possible requires models of PV modules or panels that have two essential features: they need to be accurate and to have low computational cost.

The landscape of simulation models for PV modules/panel is enormously vast, and the literature provides basically PV models with a large spectrum of accuracy/complexity tradeoffs. Two features, however, are not always available in these models. Firstly, many of these models *do not consider the correlation between irradiance and temperature*; while most models contain thermal correction factors modeling the temperature effect on the key cell parameters, they do not consider that higher solar irradiance generally implies higher temperatures, partially offsetting the efficiency of the cell.

Secondly, an often underrated issue is that *the process of identifying the model parameters is generally difficult*, and requires either measurements, or rather complicated circuit analysis if they are to be derived from a datasheet. As a matter of fact, most models rely indeed on the conventional single- or double-diode electrical circuit equivalent of a PV element, and the identification of the model parameters requires data that cannot be immediately extracted from a datasheet.

In this work, we propose a simple, semi-empirical model that addresses the above two issues and is suitable for real-time simulation. Our model requires data available on most datasheets (I-V curve, and temperature derating factors) to derive an expression of the module output voltage and current as a function of irradiance G and temperature T through empirical fitting. The model is semi-empirical, however, since it includes an analytical relation for the effect of G on T [2]. Depending on the PV panel topology (series/parallel arrangement) and control (module-level MPPT or string-level MPPT), the voltage and current values yielded by the model have different interpretations.

Results obtained by comparing the output of the model with the measured power produced by an existing installation show that the model provides sufficient accuracy (within 1%) for early assessment of various design choices of a PV installation.

II. Background

Most models of PV cells rely on their intrinsic nature (i.e., a semiconductor diode whose p-n junction is exposed to light), and use an equivalent circuit. The latter usually includes photo current, a diode, a shunt resistor expressing leakage current, and a series resistor describing the internal resistance [3]. The parameters of these circuit models are identified either by measurements of key quantities or through datasheet information [4], [5], [6]. Most of the models available in the literature are strongly focused on its accuracy at the cell or (when derived from datasheet) module level. However, when modules are combined in series/parallel to form an array, several issues need to be considered that make the accuracy of the model for an individual cell or module less important.

For instance, the series connection of modules cannot be simply obtained by summing voltages and restricting current to the one obtained by the least irradiated module. In fact, *bypass diodes* are usually adopted to avoid thermal issues and to reduce the impact of shading [7]. When bypass diodes are used, I-V curves of individual modules must be properly combined into a ''string'' I-V curve, which implies availability of a *closed formula* for the I-V curve. Similar issues occur when considering the parallel combination of I-V curves of a number of series strings.

In summary, for quick simulation of the output power of a PV array, a model is needed that (i) can be derived solely from the datasheet, (ii) provides a closed-form equation for the I-V curve, and (iii) provides rules for the combination of such curves accordingly to the series/parallel topology. To the best of our knowledge, no such model is available in the literature.

III. Proposed Model

We want to derive a power model *for an individual PV module*, so that total power extracted by a panel can be adapted to different series/parallel topology. Total power is in fact generally different from the simple sum of the power values of the individual modules, since it is rather voltage (in series) and current (in parallel) that need to be summed up. Therefore, rather than a model of the *power* of a module, we need models for the extracted *current and voltage of a panel*.

Moreover, the model should be also sensitive to the granularity of the maximum power point tracking (MPPT). Generally speaking two options are available (Figure 1): *module-level* MPPT (micro-inverters) or *string-level* MPPT (string inverters). The model depends on this feature because in the former case each module extracts at the MPP (a), and therefore only individual maximum power voltages and currents can be tracked. Conversely, when using string inverters (b), the MPP is tracked on the resulting I-V curve of the series of modules, which has to be computed from the individual curves.

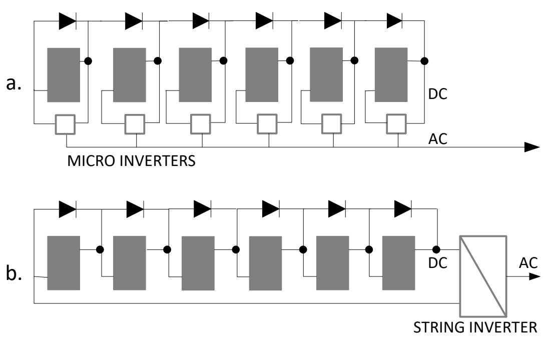

Fig. 1: String-level and module-level MPPT architectures.

In this work we consider the configuration using a string inverter, since the case of module-level MPPT is in fact as a special case of the string-level one; moreover, for cost reasons it is still the most popular implementation in typical PV installations.

One last architectural parameter that needs to be considered is the distribution of the bypass diodes in the installation. This is essential because it determines how to compute the aggregate I-V curves of the series string. We assume the most intuitive strategy in which bypass diodes are used around each module [7], as shown in Figure 1.

A. Panel Model Using a String-Level Inverter

For the description of our methodology, we use a PV-MF165EB3 module by Mitsubishi as a working example, as this is also the module used for our validation in Section IV. The methodology has however general validity, since it relies on basic information available in any datasheet.

For our example PV-MF165EB3 module, the datasheet provides the three curves shown in Figure 2: from left to right, (1) the I-V curve for different irradiances G, (2) the temperature sensitivity coefficients ($\partial V_{oc}/\partial T$ and $\partial I_{sc}/\partial T$), and (3) the

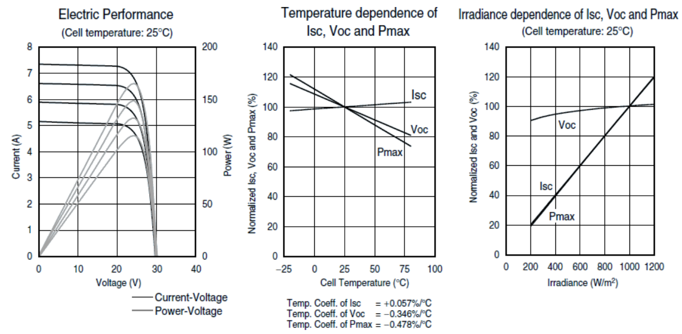

Fig. 2: Datasheet information for Mitsubishi's PV-MF165EB3.

dependence of V_{oc} and I_{sc} of irradiance G. These are very basic information available for almost any PV module.

The derivation of the model proceeds in two phases, as described hereafter.

1) Model for an Individual PV Module: We derive a model for the output voltage V_{module} and current I_{module} of a single module, as a function of irradiance G and temperature T. This phase consists of three main steps:

1. Derivation of the dependence of V_{oc}, I_{sc} on G and T.
We first derive the dependence of V_{oc} and I_{sc} on T and G, by using the center and right plot of Figure 2. This simply achieved by digitizing the curves and empirically fitting them using minimization of least-square errors. For our specific case:

$$I_{SC}(G,T) = \alpha \cdot I_{SC,nom}(-0.00055T + 0.9885) \cdot (0.000992G - 0.000344) \quad (1)$$

$$V_{OC}(G,T) = V_{OC,nom}(-0.00338T + 1.088) \cdot (-3.069G^{-0.02289} + 3.62) \quad (2)$$

In Equation 1, the nominal value of I_{sc}, derived from the datasheet, is weighted by an aging factor α. PV panels are indeed subject to an average 0.4%/year degradation rate, that mainly affects current production, while voltage distribution does not change substantially over panel lifetime [8].

It is worth emphasizing that Equations 1 and 2 do an approximation in considering the effects of G and T as two independent factors.

2. Derivation of the dependence of T on G.
An important aspect to be considered is that T and G are obviously correlated: when irradiance is high, temperature will also be high. We therefore correct ambient temperature T_{amb} (available from weather stations) with a term depending on G, according to the model of [2].

The module temperature $T(G)$ is modeled as:

$$T_{amb} + k \cdot G \quad (3)$$

where $k = \frac{\alpha}{h_c} = 0.05 \frac{W}{K \cdot m^2}$ is the ratio of the absorptance of the roof divided by the radiative loss factor of the roof [2]. In Equations 1 and 2, T will thus be replaced by $T(G)$ (as in Equation 3). Notice that relating T and G allows smoothing the approximation contained in Equations 1 and 2.

3. Derivation of the module I-V curves.

The last step is to derive a function describing the I-V curve for different G's. We use an equation template that matches the underlying diode equation regulating a PV cell behavior:

$$I = I_{SC} - a \cdot (e^{b \cdot V} - 1)$$

The approximation consists in assuming a zero series resistance in the dependence. By imposing then that $I(V_{oc}) = 0$, parameter b can be expressed in terms of a as:

$$b = \frac{1}{V_{OC}} \cdot ln(1 + \frac{I_{SC}}{a})$$

leaving therefore a as the only parameter. We then empirically fit the curves in Matlab and obtain a value of $a = +4.428 \cdot 10^{-5}$. The overall model for the I-V curve is therefore given by the equation:

$$\begin{cases} I(G,T) = I_{SC}(G,T) + 4.428 \cdot 10^{-5} \cdot (e^{b \cdot V} - 1) \\ b = \frac{1}{V_{OC}(G,T)} \cdot ln(|1 + 22,583.56 \cdot I_{SC}(G,T)|) \end{cases} \quad (4)$$

Figure 3 shows the comparison w.r.t. the datasheet curves using the model of Equation 4. The curves are relative to 25^{o}C. The average error of the interpolation is 2.79%.

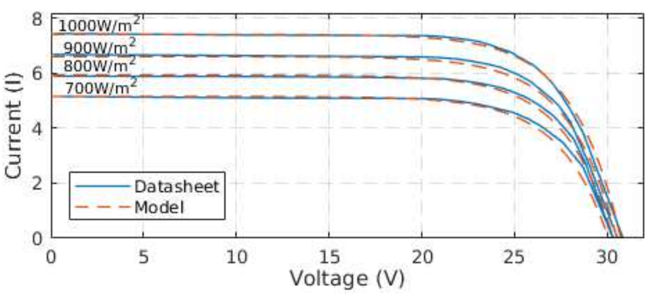

Fig. 3: Comparison of the proposed equation-based model (dashed lines) w.r.t. datasheet specifications (solid lines).

B. Building the Panel Model

An expression of the extracted power of a generic series-parallel interconnection of modules must consider (1) the overall series-parallel topology, and (2) the operations of the bypass diodes.

1) Combining the Models for Series String: For the sake of simplicity, we will describe the procedure by considering a string of two modules. The generalization to the general case of n series modules is straightforward.

Due to the presence of bypass diodes, the weakest of the two modules (i.e., the one with lowest irradiance) does not constrain the current of the strongest one; rather, when the current gets larger than the value that can be produced by the weakest module, the latter gets bypassed and only the strongest module produces power [7]. The total curve is therefore obtained by summing the I-V curves as follows: for each current value in the range $[0, I_{SC,H}]$ the resulting voltage is:

$$\begin{cases} V_{string} = V_L + V_H & \text{if } I < I_{SC,L} \\ V_{string} = V_H - V_d & \text{if } I_{SC,L} < I < I_{SC,H} \end{cases} \quad (5)$$

where subscript L and H apply to the low and high irradiance modules, respectively, and $V_d = 0.6V$ is the voltage drop across a forward-biased diode. This yields to the classical I-V curve with multiple ‘‘steps’’, as shown in Figure 4.a.

Once this curve has been built, the MPP is extracted as the maximum of the corresponding P-V curve, thus emulating the operation of a string inverter implementing the MPPT.

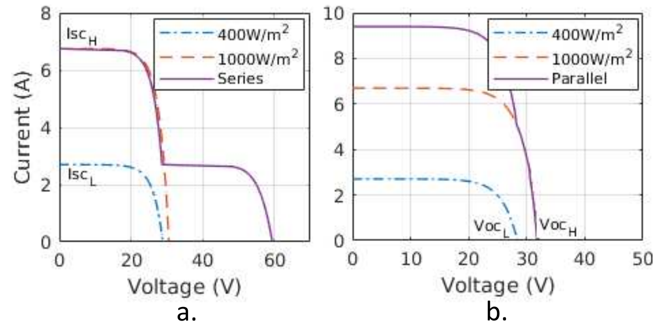

Fig. 4: I-V curves of the series (a.) and parallel (.b) connection of two modules with different irradiance with bypass diodes.

2) Combining the String Models in Parallel: Given the I-V curves (and the corresponding MPPs) for the various series strings, we combine them by summing the currents. The process in this case is simpler that the series case because there is no diode involved.

Again, we consider the simple case of two strings in parallel for the sake of illustration (Figure 4.b). The resulting parallel curve is obtained, by summing the current of the two modules for each voltage value in the range $[0, V_{OC,H}]$ as follows:

$$\begin{cases} I_{panel} = I_L + I_H & \text{if } V < V_{OC,L} \\ I_{panel} = I_H & \text{if } V_{OC,L} < V < V_{OC,H} \end{cases} \quad (6)$$

IV. Experimental Results

We tested our model against real data obtained from an installed PV array on the roof of an industrial building. The array consists of the parallel connection of 4 strings in parallel, each consisting of 10 modules in series, with bypass diodes around each module. The MPPT with the inverter is placed after the parallel connection of the 4 strings, and therefore the MPP is extracted on the global curve of the entire array. The modules are the Mitsubishi panel described in Section III. The analysis covers one year, from March 2010 to February 2011, for which both environmental data and power production traces were available.

A. Irradiance and temperature data generation

Solar and temperature data are obtained using the GIS-based infrastructure of [9]. Input GIS data are expressed through a *Digital Surface Model* (DSM), which is a high-resolution raster image representing terrain elevation of the building of interest. The DSM allows to recognize obstacles over the surface (e.g. chimneys) and to estimate the evolution of shadows with 15 minutes intervals. The evolution of temperature and irradiance over time is obtained by combining weather data, retrieved from weather stations, along with the shadow model.

B. Model implementation and usage

The proposed model has been implemented in a Matlab R2017a script, that incorporates all the steps in Section III. At any time point, the overall flow is as follows:

1) Temperature T and irradiance G of each module are derived from GIS data based on their position [9];
2) These values are used to derive $T(G)$ (Equation 3);
3) Using Equations 1 and 2, we calculate I_{SC} and V_{OC} of each module for the corresponding G and $T(G)$;
4) Using Equation 4, we compute the I-V curve for each module for those G and T conditions;
5) We then combine the I-V curves of each series string using Equation 5;
6) The I-V curve of the overall PV system is obtained by combining the I-V curves of each string series, by using Equation 6;
7) Finally, we extract the MPP from the overall I-V curve.

These operations are repeated for each time point so to derive a trace of I, V, and P over time.

C. Experimental validation

The resulting traces have been compared to the actual power extracted *before the inverter*, as returned by the measurements on the actual PV installation. Figure 5 provides a graphical comparison of the traces (from top to bottom, total power, voltage and current of the panel). For space constraints, we restricted our analysis to 12 days (from August 8th to August 21st). The plot highlights that the proposed model (solid lines) follows quite well the experimental measurements (dashed lines). Our model slightly overestimates the current and the total power; this is likely due to a conservative assumption on the aging of the modules, which we derived from the literature [8] as we did not have this information for our PV installation. In order to assess accuracy, we compared the proposed model to two state-of-the-art works that provide accuracy figures for the same panel considered in our work. [9] models power as a function of the PV panel efficiency and occupied area, while [10] models energy as a function of the panel rated power, manufacturing losses and shading effects. Table I reports four indicators for each model: (i) the Root Mean Square Difference (*RMSD*), (ii) the coefficient of determination R^2 (i.e., the proportion between the variance and the predicted variable), (iii) the Willmott's index of agreement (*WIA*, measure of prediction errors), and (iv) the Legate's coefficient of efficiency (*LCE*, ratio between the mean square error and the variance of observed data) [11]. The former two are percentages that measure dispersion, and thus the lowest the better. The latter two are indicators of performance, for which a higher value indicates a better model. Table I highlights that the proposed model outperforms both [9] and [10] on all indicators.

The high level of accuracy is additionally confirmed by the analysis of the yearly power production. The estimated power production is 6.695MWh, very close to the *measured* production of the actual PV system (6.708MWh). The very low error rate (<0.2%) highlights that, despite of local fluctuations, the proposed model adheres to the actual PV system behavior. This is even more meaningful when considering that the proposed model requires as inputs only the datasheet of the adopted PV panels and the system topology. This high level of accuracy, together with the computation speed (26.6s for model construction and 259.7s for one year long simulation) prove the effectiveness of the proposed model in the context of autonomous building design.

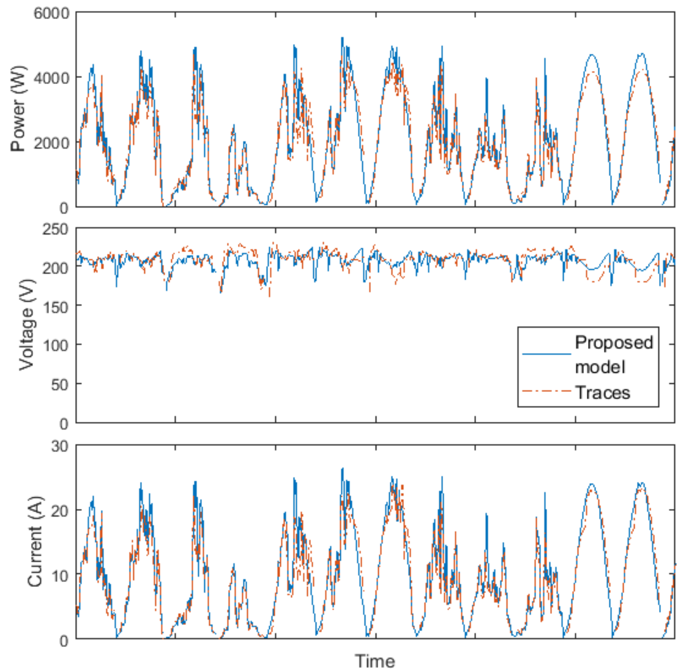

Fig. 5: Comparison of the proposed model (solid lines) w.r.t. the experimental traces (dashed lines).

TABLE I: Statistical performance indicators of the proposed model w.r.t. [9] and [10].

MODEL	RMSD	R^2	WIA	LCE
Proposed	22.20%	0.006	0.975	0.751
[9]	28.29%	0.870	0.970	0.700
[10]	45.60%	0.386	0.880	0.183

V. Conclusions

We have proposed a semi-empirical model for the voltage and current of a PV array whose distinctive features are (i) it is obtained solely from basic data provided in a datasheet, (ii) it account for the dependence of temperature on irradiance, and (iii) it is built by taking into account the series-parallel topology and the position of bypass diodes in the array.

By using accurate temperature and irradiance data obtained with a novel GIS-based infrastructure, we have shown that it is possible to track the actual power produced by a PV array with reasonable accuracy. The model can be therefore used for the preliminary design of the array (e.g., its placement) or for a quick assessment of the quality of the array (e.g., module mismatches, faults, etc).

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