Optimal PV Panel Reconfiguration Using Wireless Irradiance Distributed Sensing

Antonino Laudani, Gabriele Maria Lozito, Martina Radicioni, Francesco Riganti Fulginei, and Alessandro Salvini

Abstract The aim of this paper is to provide a dynamic reconfiguration method for partially shaded photovoltaic arrays. The implemented strategy is able to increase power production of the array with respect to the initial topology in real time and with any shading pattern. The array is supposed to be made of strings of modules interconnected in parallel and each module is constituted by series-connected photovoltaic cells. Irradiance values are calculated through a closed-form relation given the operating point of the modules, their temperatures, and their equivalent circuit model. This procedure frees the system from the necessity of costly pyranometers. The implemented method has been validated in Matlab environment simulating random shading conditions and implemented on a low-cost 32-bit microcontroller with wireless connectivity capabilities. The results prove the efficiency of the proposed solution.

1 Introduction

Mismatching conditions are due to different properties of interconnected cells and heavily influence photovoltaic (PV) power generation, leading to great efficiency reductions; the main mismatch affecting PV systems is non-uniform irradiation of the PV plant, corresponding to a partial or full shading condition [1, 2]. Shadows often occur in PV arrays, in particular when embedding PV modules in buildings. As a matter of fact, shadows coming from other buildings, dirt, dust, approaching clouds, falling leaves and atmospheric fluctuations are just some of the factors that can determine a shading condition. The most serious problem arising is determined by power losses that can be significant. Considering the structure of a PV panel, it can be seen that it is made of groups of series-connected cells, representable as

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W. Zamboni, G. Petrone (eds.), *ELECTRIMACS 2019*, Lecture Notes
in Electrical Engineering 615, https://doi.org/10.1007/978-3-030-37161-6_40

power sources. When a cell, or a group of cells, is affected by shading, its current is reduced since the cell(s) starts acting as a load, absorbing power: this determines a reduction in the power delivered by the whole module [3]. The standard practice adopted to mitigate the effects of shading is the use of bypass diodes connected in parallel to PV cells or groups of cells; in this way the shaded portion never operates with negative voltages; however, this solution does not allow to retrieve the lost power, but just cuts-off the ill cell(s). Moreover, the insertion of diodes modifies the $P - V$ characteristic of PV arrays [4, 5], introducing further maximum power points (MPPs) and so, making the assessment of the unique global MPP (GMPP) hard. To face this problem, several maximum power point tracking (MPPT) algorithms have been developed able to detect the MPP in fast and accurate ways and not to remain trapped in the local solutions (LMPP) [6]. Some of the main problems of these methods are their complexity and costs; moreover, they often need embedded sensors. Another key issue is hot spotting; hot spots are areas of the array characterized by higher temperatures with respect to the rest of the system and this is caused by differences in the level of irradiance, [7, 8]. The resulting overheating may bring the cell(s) temperature well above the limit to which they can operate, with possible irreversible damages of the case of the cell and of the PV device itself. Hence, the need of accurate measurements of the level of irradiance on the whole array. In this work, an analytical model is used to calculate the exact value of irradiance of a cell given the operating point and the temperature [9]. As a matter of fact, measuring temperature is quite trivial, while irradiance is a quantity whose determination is often hard: irradiance sensors need a control system and are quite costly, the price of a good quality pyranometer ranges from 200 to 500 dollars; moreover, their placement is quite tricky and requires the exact knowledge of the inclination of sun rays on the surface of the system. The method here adopted provides an accurate and low-cost solar irradiance sensing for PV systems: the cost of the whole system is around 20 dollars. Other methods can be found in literature for sensing accurately and monitoring solar irradiance, such as in [10–13].

In the development of a technique aimed at mitigating shading effects the observation of the particular shading pattern is generally a key point [14]; as a matter of fact, reconfiguration methods are based on this concept. The modules that make up the array are rearranged in ways aimed at retrieving power with respect to the initial configuration, according to the shading pattern. As a consequence, each configuration is suitable for a certain shading scenario and several topologies have been proposed and studied in literature [15–17]. In this paper, a real-time reconfiguration based method is proposed able to provide an optimal configuration for each shading scenario. After having identified the optimal configuration, a network of switches is supposed to be driven by an MCU based master device to rearrange the PV modules accordingly. The switching topology of this work which allows complete reconfiguration of the devices must be considered ideal. Switch boxes seldom offer the possibility to rearrange freely the PV devices in a network. In general, PV devices can be either excluded from the series by means of a smart bypass or at most switched with devices belonging to adjacent strings.

The paper will be structured as following: in Sect. 2 the method for calculating irradiance analytically is shown; in Sect. 3 two shading compensation strategies are presented: the traditional insertion of bypass diodes and the reconfiguration technique; Sect. 4 presents the proposed dynamic reconfiguration and the algorithm developed; in Sect. 5 the implementation of the method on a 32-bit microcontroller unit is shown; Sect. 6 presents the conclusions.

2 Analytical Irradiance Extraction

2.1 One Diode Circuital Model for PV Cells and Arrays

The most common model used to characterize the I–V curve of a PV device is the one diode mode, illustrated in Fig. 1. This tool can be used to characterize either a single PV cell or an array made of series or parallel connected cells. In this way, the current generated by the cell or module can be expressed through a relation taking into account the values of five parameters: the shunt resistance R_p, the series resistance, R_s, the photocurrent, I_{irr}, the diode inverse saturation current, I_o, and the ideality factor, n. Moreover, the number of cells connected in series N_s and in parallel N_p have to be considered:

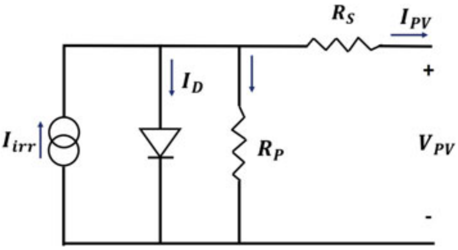
$$i_{pv} = N_p I_{irr} - N_p I_o \left[e^{\frac{q\left(v_{pv} + \frac{i_{pv} N_S R_S}{N_p}\right)}{N_S n k T}} - 1 \right] - \frac{v_{pv} + \frac{i_{pv} N_s R_s}{N_p}}{N_s R_p / N_p} \tag{1}$$

In Eq. (1) $q = 1.602 \times 10^{-19}$ C is the electronic charge, $k = 1.3806503 \times 10^{-23}$ J/K represents the Boltzmann constant, and T is temperature.

Each of the five parameters appearing in Eq. (1) is a function of environmental conditions, i.e., solar irradiance, G, and temperature, T, according to the following relations:

$$I_{irr} = \frac{G}{G_{ref}} \left(I_{irr,ref} + \alpha_T (T - T_{ref}) \right) \tag{2}$$

Fig. 1 One diode model



$$I_0 = I_{0,ref}\left(\frac{T}{T_{ref}}\right)^3 e^{\left[\frac{E_{g,ref}}{kT_{ref}}-\frac{E_g}{kT}\right]} \tag{3}$$

$$R_p = R_{p,ref}\frac{G_{ref}}{G} \tag{4}$$

$$R_s = R_{s,ref} \tag{5}$$

$$n = n_{ref} \tag{6}$$

In equations from (2) to (6) the subscript ref refers to quantities at standard reference conditions (SRC), i.e., $T = T_{ref} = 25\,°\mathrm{C}$, $G = G_{ref} = 100\,\mathrm{W/m^2}$. The five parameters can be extracted both from datasheet information or from experimental I–V curves: several procedures are available for this purpose [18–20]; in this work the method proposed in [19] is implemented to provide an accurate identification of the PV device through the one diode circuital model. If more accurate identifications are needed, it is worth considering the uncertainty introduced by the error declared in the devices datasheet. A strategy to reduce as much as possible this uncertainty is described in [21].

2.2 Closed-Form Irradiance Formulation

As mentioned above, the I–V characteristic of the cell or module is strongly dependent on atmospheric conditions; as a consequence of this, the operating point, as well as the power produced, deeply changes according to the values of T and G; hence, the need of assessing these quantities accurately. The followed approach makes use of a closed-form expression of solar irradiance, knowing the operating point of the device, i.e., v_{pv} and i_{pv}, and its temperature. The following equation, derived from algebraic manipulations of (1), allows to derive the expression of irradiance as a function of temperature:

$$\begin{aligned}\frac{G}{G_{ref}}\left(N_p I_{irr,ref} + N_p \alpha_T\left(T - T_{ref}\right) - \frac{v_{pv} + i_{pv}N_s R_{s,ref}/N_p}{N_s R_{p,ref}/N_p}\right)\\ = i_{pv} + N_p I_0\left[e^{\left(\frac{v_{pv}+i_{pv}N_s R_{s,ref}/N_p}{N_S nkT}\right)} - 1\right]\end{aligned} \tag{7}$$

3 Shading Compensation Techniques

3.1 *Bypass Diodes*

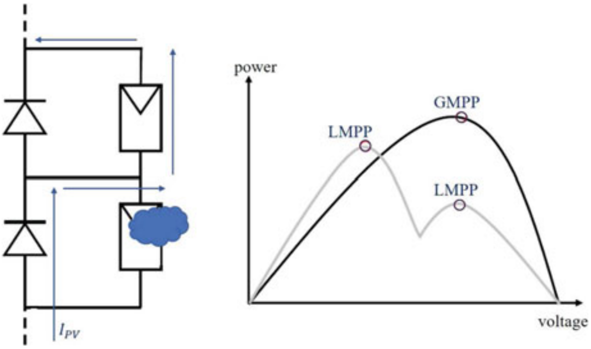
Nowadays, PV modules are generally equipped with several bypass diodes connected in parallel to each cell or group of cells. When a cell of a string gets shaded its photocurrent decreases and becomes smaller than that of the other cells. The failing cell becomes reverse biased and starts operating like an external load, consuming power; the function of bypass diodes is to provide an alternative path to the string current in order to bypass the shaded cell. This strategy allows the power production to be unaffected by shading. However, some drawbacks still persist. The presence of bypass diodes severely alters the $P-V$ characteristic of the PV device; as a matter of fact, instead of a unique GMPP, multiple peaks, LMPP, appear.

The risk of MPPT traditional algorithms of falling in local maxima causes their failure in finding the exact solution of the problem, Fig. 2. Computational intelligence strategies based on artificial neural networks (ANNs) [22], fuzzy logic [23], and meta-heuristic methods [24], such as particle swarm optimizers or genetic algorithms, have been successfully applied to improve the searching capability. These algorithms are able to escape local minima, but they are more computationally demanding and the continuous operating-point commutation can damage the DC-DC stage. Moreover, further power losses are involved because of voltage drops of the conducting bypass diodes.

3.2 *Reconfiguration Techniques*

The process of changing the physical position of the PV modules that constitute an array in order to provide a new arrangement often allows to enhance power extraction. Besides the particular configuration of the system, the shading scenario is a factor of main relevance. As a matter of fact, several studies can be found in

Fig. 2 Bypass diodes operation and $P-V$ characteristic



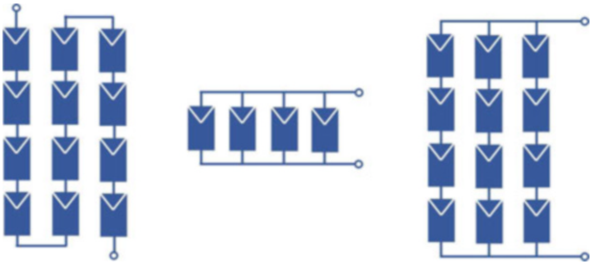


Fig. 3 Regular configurations. From left to right: S, P, and SP

literature providing rearrangement based solutions, but most of them are not able to give an absolutely optimal strategy that can be applied to any shading pattern. Among regular configurations total cross tied (TCT) one is worthy of note, since has been demonstrated to be the best solution in most cases [25]. The basic series (S) and parallel (P) configurations both present severe shortcomings: S scheme is affected by current reduction when a cell gets shaded since the overall current of the string is forced to that of the ill cell; P scheme, instead, even if guarantees a higher power production with respect to S, suffers from drawbacks concerning voltage. Hence, a series parallel (SP) solution, taking the benefits of both schemes, should be preferred, Fig. 3.

The class of the regular configurations includes, also, Bridge Linked (BL) and Honey Comb (HC) schemes that allow to diminish the number of interconnections with respect to TCT one and, thus, reducing the power losses due to cabling. However, the best performances are achieved through irregular reconfigurations, among which the Sudoku and the Zig Zag are the best known [26].

Moreover, reconfiguration methods can be classified into two main groups: dynamic and static techniques, to which the aforementioned schemes belong. Rearranging dynamically an array means varying the physical location of its panels by mean of switches, sensors, and controllers. The approach that is going to be shown is based on this latest concept; as a matter of fact, such a strategy allows not to take into account the particular shading scenario since the system will be able to reconfigure itself in real time, providing, to each situation, a suitable arrangement of the panels.

4 Smart Switching Reconfiguration: Method and Results

The proposed algorithm, implemented in MATLAB environment, takes under exam an $S - P$ scheme, in which a number of N PV modules are connected in series to provide a string, and M strings are connected in parallel to form an array. The aim of the work is that of developing a simple rearranging scheme able to suit any atmospheric condition, also in rapidly changing scenarios, and to retrieve the power that, otherwise, would be lost. At this purpose, a random irradiance pattern has been generated providing unevenly shading of the array. The $I–V$ characteristic of each

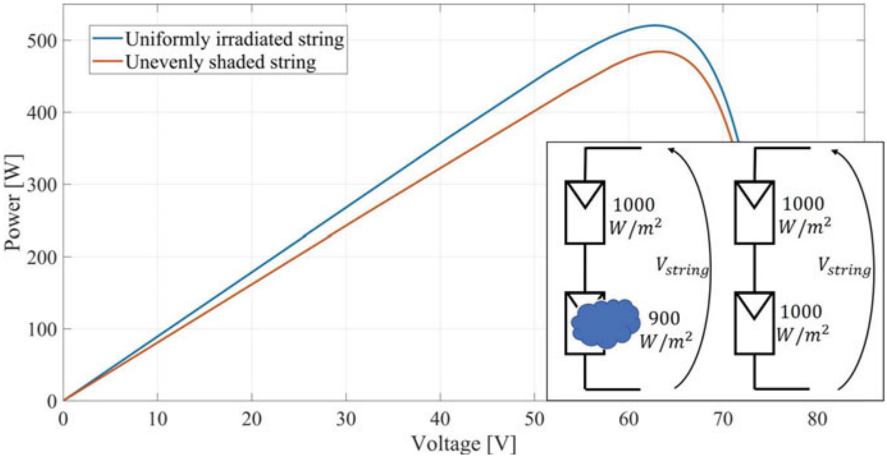


Fig. 4 Comparison between power generated by differently shaded strings

of the modules used to test the algorithm has been extracted by means of the one diode model from datasheets information by using the procedure presented in [18]. Results are reported for Mitsubishi Electric Photovoltaic Module PV-MLE260HD. Each module is constituted by 120 monocrystalline silicon cells of 78 × 156 mm.

Once the benchmark is generated, the P–V curve of each of the string is extracted. The power of a single string is computed by knowing the open-circuit voltage of the string, that is, $v_{oc} = \sum_{k=1}^{N} v_{oc,k}$, where $v_{oc,k}$ is the open-circuit voltage of the k-th module of the string and imposing $i_{sc} = min_k(i_{sc,k})$, i.e., the short-circuit current of the string is limited by the cell with the lowest irradiance. Thus, from the knowledge of the voltage of each, V_{pv}, it is possible to calculate its current, I_{pv}, by means of an explicit formulation based on the use of the *Lambert-W* function, such as in [19]. So, the power of the string is the product $P_{pv} = V_{pv} I_{pv}$. As can be seen from Fig. 4, a unique shaded module is enough to limit the power generation of the whole array. Once the power generated by a string is known, its modules are rearranged to provide higher power. As far as the power of the whole array is concerned, it is calculated as the product of the summation of the previously calculated current of the strings, $I_{array} = \sum_{i=1}^{M} I_{pv,i}$, and the voltage range of the string associated to the lowest open-circuit voltage.

The algorithm presented rearranges the modules in ascending order with respect to their irradiance level; in this way, modules with similar values of irradiance G are positioned close to each other. Figure 5 shows the reconfigured array. In this way, the shortcomings about power reduction can be limited. In Table 1 the results concerning three different simulated shading patterns are reported. In the table, $\Delta G(\%)$ refers to the maximum difference of irradiance between modules of the same string while the second column represents the percentage portion of the array that is shaded. The results are analyzed in terms of P_{MPP}: it can be noticed that, at the same level of $\Delta G(\%)$, the more the shaded portion, the less is the percentage

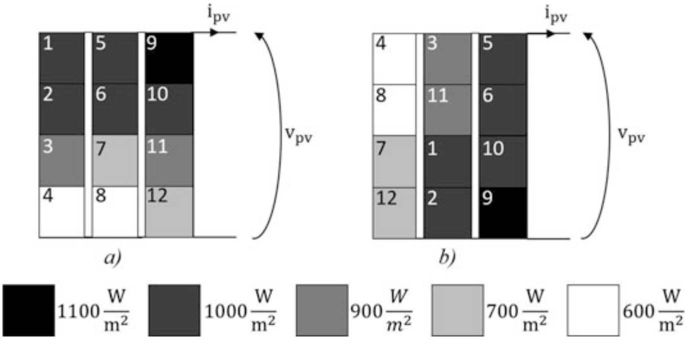


Fig. 5 Comparison between the initial configuration of the array (**a**), and the reconfigurated array (**b**)

Table 1 Percentage power gain at MPP with respect to the maximum power of the initial configuration

ΔG (%)	Shaded portion (%)	ΔP_{MPP} (%)
40	25	20.14
40	50	11.30
30	25	15.18
30	50	6.08
20	25	10.38
20	50	2.26

in power gain achieved through reconfiguration; on the other side, fixing the shaded portion, it is evident that the method is more efficient when dealing with higher values of $\Delta G(\%)$. Hence, the benefits of this approach can be highly appreciated especially when dealing with strings with large irradiance differences and lower shaded portions of the array. Lastly, it has to be highlighted that the scheme allows to avoid the use of bypass diodes, since all modules are exploited and there is no need to cut-off any of them.

5 Implementation on a Low-Cost 32-Bit MCU

5.1 Irradiance Estimation Equipment

The algorithm for the irradiance estimation must be implemented on a microcontroller (MCU) unit with two important characteristics. First, the MCU must be able to provide analog and digital interfaces for the measurement of the panel voltage, panel current, and panel temperature. Second, since the optimal reconfiguration strategy is based on the knowledge of the irradiance on every panel in the system, the MCU must be able to implement wireless communications.

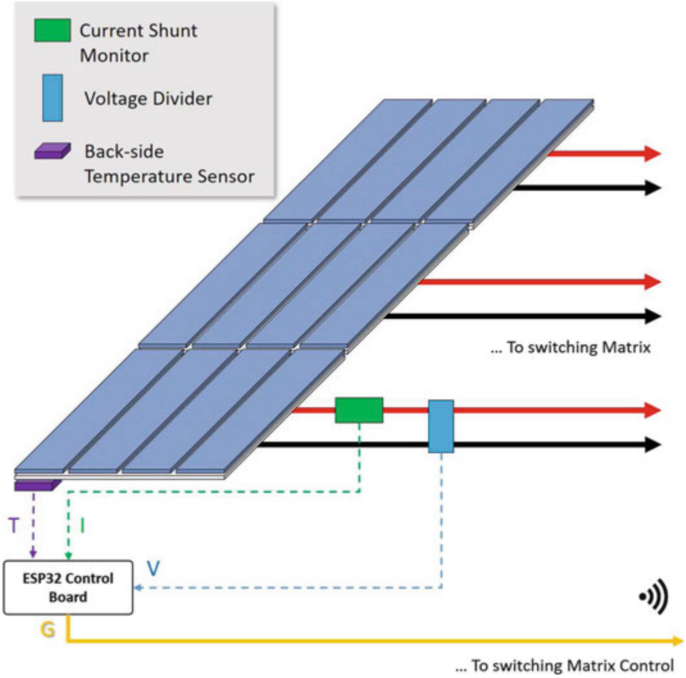


Fig. 6 MCU scheme for irradiance assessing

The MCU chosen for this application is the low-cost 32-bit device ESP32 microcontroller. This microcontroller features two accurate 12-Bit ADCs, a wide set of digital interfaces (SPI, UART, I2S, and I2C), 52 kB of SRAM, and a full stack for both Wi-Fi 802.11 b/g/n and Bluetooth 4.2. The microcontroller is usually sold on a micro-board where additional components such as FLASH memory and the RF antenna are added. The ESP32-WROOM-32D, shown in Fig. 6, features 4 MiB of external flash to be used as program memory and a printed RF antenna. The whole system can be easily programmed from the Arduino IDE after the installation of the board package for the ESP32 microcontrollers.

The proposed MCU features all the three characteristics specified for the project, assuming some servicing circuitry is provided. The measurement of the PV panel voltage can be done directly from the MCU ADC, providing a resistive divider for the voltage, which can be implemented with simple resistors (the use of a buffering circuit should not be needed considering the large input resistance of the ADC). Current measurement is more delicate and must be implemented sensing the voltage on small series resistance, properly amplified. Alternatively, integrated circuits, such as the Texas Instruments INA260, provide voltage, current, and power measurements that can be accessed via I2C interface. This solution is more costly, but reduces the burden in terms of analog circuit design.

Temperature measurement can be performed by using a digital thermometer such as the DS18B20. This thermometer is very well suited for PV application due to the temperature range, the programmable resolution, and the 1-Wire interface that allows easy communications with the MCU device.

The second characteristic is featured since the ESP32-WROOM-32D is equipped with all the hardware required to implement wireless communications. In particular, considering the application can have large spatial extension, a mesh topology (supported by the chosen device) can be appealing thanks to its robustness and redundancy.

5.2 Switching Matrix Control

The information on irradiance for single panels must be collected by a master device where the algorithm described in Sect. 4 determines the optimal reconfiguration and then arranges the switching matrix accordingly (Fig. 7). The device characteristics in this case are less stringent than the ones for the slave devices (i.e., the ones on the panels measuring the irradiance) because there is no need to perform actual measurements. On the other hand, the device must be able to support wireless communication with the slaves, and most importantly, feature enough computational capabilities to run the reconfiguration algorithm. The ESP32-WROOM-32D features a 240 MHz 32-bit microcontroller with a large FLASH memory bank that allows implementing the algorithm proposed in Sect. 4 and most of the algorithms present in literature. However, if more complex algorithm should be implemented, such as ones involving evolutionary computation, or neural networks, a more advanced platform featuring at least a floating-point unit co-processor should be considered for the master.

6 Conclusions

This work has analyzed the issue of partial shading as well as its effects on PV array. An analytical method has been used to assess the irradiance pattern on the array, avoiding the use of standard solar sensors, whose installation is often tricky. Moreover, this application is useful in the evaluation of the degradation and aging of PV devices, for which real-time irradiance sensing can be a valuable asset [27]. An algorithm has been implemented in MATLAB providing a solution for the rearrangement of the modules constituting the array in order to achieve higher power levels with respect to the initial configuration. The solution suits any shading scenario since it is based on the knowledge of the actual values of irradiance that are calculated in real time. This computation step is performed by a system of MCU slave units. Moreover, the reconfiguration algorithm is implemented on a MCU master unit that collects irradiance data from the slave network via Wi-Fi and

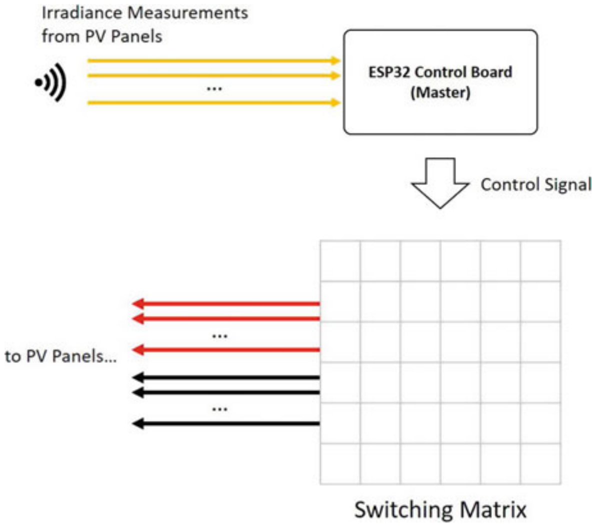


Fig. 7 Control block for the switching

drives the switches. The proposed method allows to improve the performances of a unevenly shaded array and, moreover, allows not to resort to traditional solar sensors since the pyranometer is directly implemented on MCU units. Since the proposed approach considers an $S - P$ reconfiguration strategy, sorting modules according to irradiance takes into account the main factor for current mismatch. A further step could include a comparison between the proposed method and a reconfiguration strategy based on rearrangement according to MPP values: the two approaches are computationally similar; a good discrimination between the two should come from a sensitivity analysis with respect to the $\{v, i, T\}$ triplet. Even without considering an electrical simulation of the switch box, associating a cost-function to the switching activity, thus creating a hysteretic behavior could greatly benefit the approach in terms of stability. Indeed, if such cost-function were to be implemented, the problem should be formulated as a multiobjective one. In this case, suitable optimization algorithms should be used. Once this framework is in place, computing the cost-function through the switch-box simulation should be an easy task. Moreover, to account for the actual spatial distribution of the modules, such cost-function should penalize the switching according to the distance.

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