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A Simulation Study of Reconfigurable Modules for Higher Yields in Partially Shaded PV Systems

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***Abstract*—Photovoltaic systems in urban environments are usually partially shaded, thus the need for shade tolerant solar panels in the urban environment. We present the design of a series-parallel reconfigurable photovoltaic module. Given a specific irradiance distribution on its surface, it can change the interconnections between its solar cells to maximize the output power. First, we analyze the main trade-offs involved in the design of such module; then we propose an algorithm to choose the optimal module configuration; finally, we simulate the performance of different solar module architectures inferring the potential gain in annual energy yield.**

***Index Terms*—Reconfigurable PV module, Shade tolerant PV, Urban Integrated PV**

I. INTRODUCTION

Urban environment has a high photovoltaic (PV) potential, but conventional modules underperform therein, as available solar irradiance is uneven and constantly changing due to the complex geometry of the landscape. The power output of conventional PV modules, which have all the solar cells connected in series and 3 bypass diodes (BPDs), can drop by one third if only a single cell is 50% shaded. Therefore, shade tolerant PV modules are essential to exploit the solar resources available in urban landscapes.

Adding more BPDs [1] and/or increasing the parallel interconnections between solar cells [2], [3] are effective approaches to increase the shading tolerability of PV modules. However, when a BPD is activated all the power that could be potentially generated by the solar cells connected to it is lost. Further, the power-voltage (P-V) curve of a partially shaded PV module can present as many local maximums as BPDs in the module, hindering the maximum power tracking. Alternatively, series-parallel (SP) or total-cross-tied (TCT) PV modules exploit the logarithmic voltage drop of the cells with the impinging irradiance. In fact, the mismatch in parallel connections is lower than in series connection, and all the cells can operate closer to their respective maximum power points. In theory, under partial shading, SP and TCT modules can generate higher power than modules with BPDs. However, the main drawback of the latter approach is the high output current, which implies a significant increase in conversion and conduction losses, increasing quadratically with the module output current.

While under uniform illumination conditions (either totally shaded or unshaded), a module with all its cells connected in series minimizes the losses, under partial shading a module with parallel connections allows to harvest more solar irradiance from each solar cell. Based on this observation, reconfigurable PV modules use a switching matrix to change the interconnections between solar cells depending on the illumination conditions and maximize the power output [4] at every instant. It has been reported that gains in the annual energy yield up to 15% can be achieved with reconfigurable modules compared to conventional modules (with 3 BPDs) when partial shading is present during the entire year [5].

In this work, we analyze different trade-offs involved in the design of reconfigurable modules and we present an implementation of a reconfigurable matrix alongside a reconfiguration algorithm to maximize the energy yield of partially shaded PV systems.

II. THE SERIES-PARALLEL RECONFIGURABLE MODULE

The concept of a series-parallel reconfigurable module with a switching matrix is depicted in Fig. 1. The reconfigurable units, each consisting of several series-connected solar cells, are connected to a switching matrix inside the module's junction box. The switches in the matrix are controlled by an algorithm that allows the module to adopt different configurations depending on the illumination conditions.

It is clear that a trade-off between the reconfigurability level of a PV module and the complexity of the switching matrix has to be addressed. Indeed it can be shown that a module with N solar cells, where cells are divided in r groups, each with s cells connected in series, can adopt $c = N!/(r!\,(s!)^r)$ electrically different series-parallel configurations [6]. The number of switches n_{SW} required to design a switching matrix for such a module increases quadratically with the number of reconfigurable units.

As the number of switches increases, two main problems arise. First, the switches add to the series resistance of the solar cells, effectively decreasing the module's efficiency. Second, when the upper most switches in the schematic in Fig. 1b are open, they must withstand high voltages between the source and the drain terminals. FET transistors with higher drain to source voltage ratings exhibit high channel resistance; hence,

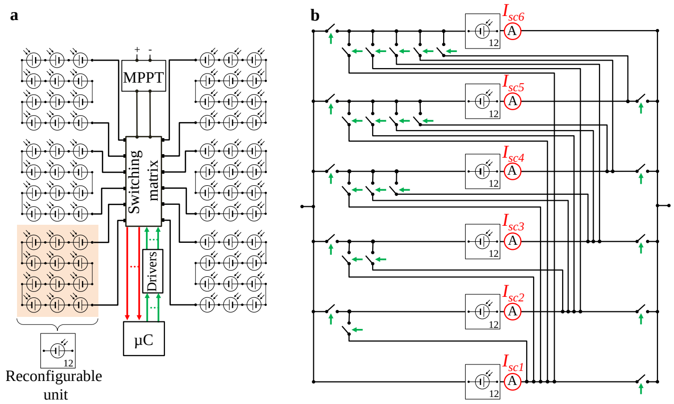

Fig. 1. (a) Schematic of the proposed PV module with 6 reconfigurable groups of cells with 12 series-connected cells each. The output signal of the current sensors is indicated in red and the signals that control the switches are depicted with green arrows. (b) Switching matrix for a PV module with 6 reconfigurable groups of cells. The current sensors can measure the short-circuit currents of each reconfigurable unit which are necessary for the reconfiguration algorithm.

there are also practical limitations on the maximum number of reconfigurable units and cells per unit in a PV module.

To find a balance between shading tolerability and design complexity, we performed cell-level ray-tracing simulations [7] to calculate the irradiance in different urban scenarios (see one of them in Fig. 2). We simulated the annual electrical yield of 24 module layouts shown in (Fig. 3a) in 3 different shading scenarios, using 10 different climates data files [8]. A comparison of the yields obtained with different layouts at the position of the most shaded module in Fig. 2 is presented in Fig. 3b.

From the results of these simulations and the above-mentioned practical aspects, it was decided to further investigate configuration C4 highlighted in yellow in Fig. 3a, which consists of 6 reconfigurable units, each with 12 cells connected in series as shown (see Fig. 1a). The switching matrix has 25 switches and allows the module to adopt 27 different configurations: 1 with all units connected in series (6x1 SP); 10 with 2 parallel-connected groups of 3 series-connected reconfigurable units (3x2 SP); 15 with 3 parallel-connected groups of 2 series-connected reconfigurable units (2x3 SP); and 1 with all units connected in parallel (1x6 SP).

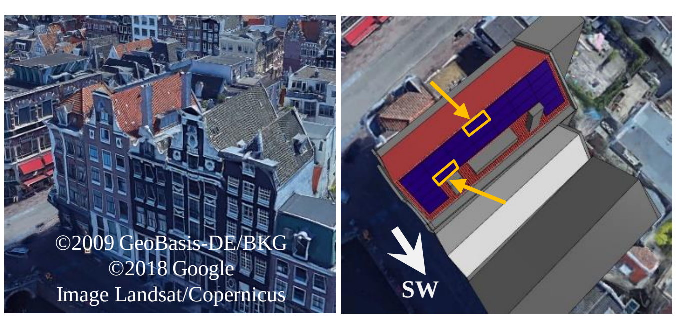

Fig. 2. Irradiance simulation in urban scenarios. One of the three modeled scenarios to evaluate the performance of different PV module layouts. In the 3D model, 25 modules (in blue) were placed on a Southwest-facing rooftop. The arrows point at the most and least shaded modules in the array.

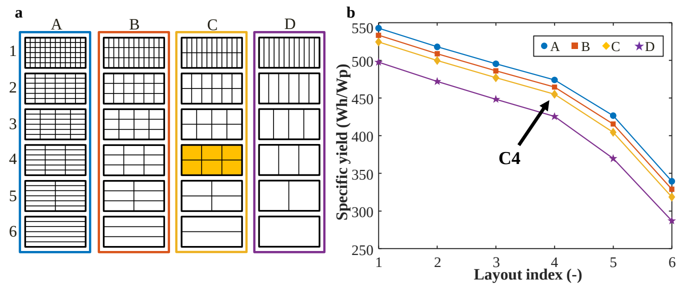

Fig. 3. (a) Module layouts analyzed. All layouts consist of 72 cells (6 by 12 matrix).The thin solid lines indicate how reconfigurable units were divided. (b) Comparison of the simulated annual yield obtained with the different layouts for the most shaded module. Simulations were performed using annual climate data for the city of Rotterdam, the Netherlands, and assuming 20% efficient solar cells with 100% fill factor. Even though the assumption of an ideal fill factor results in an overestimation of specific yield, it allows to perform accurate comparisons between the different module layouts in relative terms.

III. Simulation results

The electrical yield of layout C4 was simulated for 3 different modules configurations[1]: (1) a static module with all units connected in series and 6 BPDs, (2) a static module with all units connected in parallel and (3) the reconfigurable module shown in Fig 1 . Selected the module layout, the energy yields were simulated using the 2-diode electrical equivalent circuit of 6-inch solar cell with $\eta = 19.5\%$ and $FF = 0.78$ [9], and taking into account electrical losses in smart BPDs ($V_{on} = 10$ mV), tabbing wires ($\rho = 17$ pΩ m) and switches ($R_{sw} = 3$ mΩ).

The simulation results presented in Table I indicate that when a module is slightly shaded all configurations generate approximately the same amount of DC energy. Instead, when the module is significantly shaded, the parallel and reconfigurable modules can produce about 14% more energy than the module with bypass diodes.

[1]For all the results presented in this section, we have used 10-min resolution Meteonorm climate data for the city of Rotterdam, and it was assumed that the reconfigurable module always adopts the configuration that delivers the highest power. The problem is further discussed in section IV.

TABLE I
Simulated annual DC energy yields in Rotterdam for the most and least shaded modules considering 3 different types of modules: a static module with 6 units connected in series and 6 bypass diodes (6 BPD), a static module with 6 units connected in parallel (6 SP) and a reconfigurable module with 6 units (6 REC). The relative performance with respect to the 6 BPD module is shown next to the energy yields of the 6 SP and 6 REC modules.

Annual yields	Least shaded (kWh)	(%)	Most shaded (kWh)	(%)
6 BPD	280.7	-	142.0	-
6 SP	283.5	+1.0	162.6	+14.5
6 REC	283.0	+0.8	161.5	+13.7

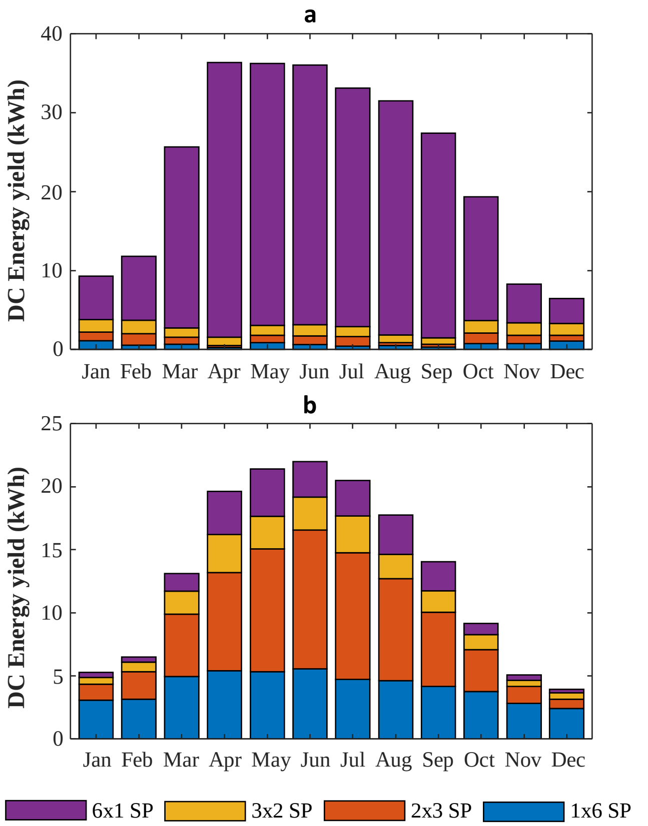

Fig. 4. Contribution of each of the module configurations to the monthly energy yield of the (a) least and (b) most shaded modules in the PV array. The contributions of the different 2x3 SP and 3x2 SP configurations is shown altogether.

In Table I, we can see that, both in the case of the least and the most shaded modules, the energy generated by the reconfigurable PV module is similar to the static series-parallel module 6 SP. In the position of the least shaded module, the reconfigurable module delivers power at a much lower current level than the 6 SP module because it mostly operates in the all-series (6x1 SP) configuration as shown in Fig. 4a. This implies that a power converter for the reconfigurable PV module could have much lower conversion losses than a converter for the 6 SP PV module. In the position of the most shaded module, both 6 SP and 6 REC perform significantly better than the module with 6 bypass diodes. Despite the fact that the 6 REC module spends 47% of the year in the all-parallel configuration (1x6 SP), this configuration is mostly chosen when shading is significant, hence it only contributes to 31% of the total annual energy yield. In Fig. 4b it can be noticed that during summer months, when irradiance is the highest, the reconfigurable module tends to operate in the all-series configuration (6x1 SP) delivering power at a low current level. As a result, 6 REC not only performs better than 6 BPD but it can also allow considerably lower power conversion losses than 6 SP.

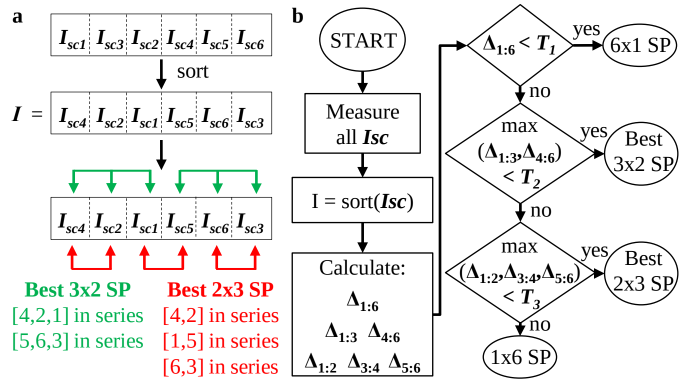

Fig. 5. (a) An example of how the best 3x2 SP and 2x3 SP configurations are preselected based on the measured short-circuit currents. (b) Reconfiguration algorithm to control the switching matrix. Notation: $\Delta_{i,j}$ is defined as $(I_i - Ij)/I_i$, where I_i and I_j is the ith and jth values of sorted current vector I, respectively.

IV. Reconfiguration algorithm

A reconfigurable module must be able to dynamically identify at every time instant which of all the possible configurations can deliver the highest power [10]. For our module and switching matrix designs, we propose an algorithm which only requires current measurements for each of the reconfigurable subgroups and 3 threshold values (T_1,T_2 and T_3) which are chosen based on the characteristics of the solar cells.

The algorithm begins by measuring and sorting the short-circuit currents of each of the six reconfigurable units. Based on the order of the sorted currents, the best 3x2 SP and 2x3 SP configurations are preselected. One example of this preselection is shown in Fig. 5a, where we arbitrarily assume that the order of the sorted currents is (4,2,1,5,6,3). In this case, from the 10 possible 3x2 SP configurations, the algorithm chooses the one with units 4,2 and 1 forming one series-connected group and units 5,6 and 3 forming another series connected group. Likewise, from the 15 possible 2x3 SP configurations, the algorithm chooses the one with unit 4 in series with 2, unit 1 in series with 5 and unit 6 in series with 3. The overall best module configuration is obtained after comparing the relative differences between the measured current and the thresholds as described in Fig. 5b.

It must be noted that, since this algorithm is based only on one current measurement per reconfigurable unit, it does not ensure that the actual best configuration will always be chosen. To evaluate the efficiency of the algorithm, we performed annual electrical yield simulations for the most shaded PV module in Fig. 2 considering $T_1 = 5\%$, $T_2 = 8\%$ and $T_3 = 12\%$[2]. For this analysis, the I-V curves of all possible module configurations were simulated every 10 minutes during an entire year. Results indicated that, in average, the algorithm only guesses the actual best configuration 50% of the time.

[2]These threshold values were obtained from a preliminary optimization study aiming to minimize DC yield losses. The values depend on the type of solar cells used, the characteristics of the switching matrix and, eventually, the characteristics of the power converter.

However, when we calculate the resulting annual DC yield obtained when using the algorithm, in the case of the most and least shaded modules, the energy loss is 0.3% and 0.03%, respectively, when compared to the DC yield obtained when manually picking the actual best configuration at every time instant.

V. Conclusion

We have presented a series-parallel reconfigurable module with 6 reconfigurable units capable of boosting the energy yield of a static module with the same layout and smart BPDs by more than 10%. We have explained that a reconfigurable module can deliver almost the same DC energy yield as a static series-parallel module but at much lower current level, which will result in much lower conversion losses at the AC side. Finally, we have presented a simple and effective algorithm that allows to reconfigure the module depending on the irradiance distribution on its surface. These promising simulation results have encouraged us to manufacture prototypes of a reconfigurable module and its switching matrix.

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