A memristor-based sensing and repair system for photovoltaic modules

A Memristor-based Sensing and Repair System for Photovoltaic Modules

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Abstract

Among renewable energy sources the sun is certainly one of the easiest to exploit. Solar panels allows to generate electrical energy but they generally have low efficiency. It is therefore important to optimize a solar module to maximize its energy production. Faults can have for example a big impact on the amount of energy production, and should be avoided if possible. This goal can be achieved by designing fault tolerant photovoltaic modules.

In this paper, we propose a sensing and repair system for photovoltaic modules. The system is based on two key elements: sensing of the photovoltaic cell status through memristors and dynamic reconfiguration of the connections among cells. Using a memristor for sensing allows to create a simple yet effective measuring systems that is able to detect the state of each cell of the modules. These information can be read externally or can be used internally by the reconfiguration system. The second key element of our system is indeed a new reconfiguration scheme that allows to dynamically change the connections among cells. This system can be used to reconfigure the connections among cells to maximize energy production, depending on the health state of each solar cell. The same system can be used to substitute redundant cells in the array to compensate faults and to improve energy production. We present a detailed characterization and power analysis of the system, highlighting the improvements in energy production and demonstrating its ability to compensate faults. The solution that we propose is modular and can be extended to arrays of any size. It can also be potentially embedded inside a solar panel, leading to a self-healing device that can improve the energy that is generating.

Keywords: Photovoltaic Array, Memristor, Reconfigurable Architecture

1. Introduction

Solar energy harvesting is gaining every year increasing interest in the energy production field. The great benefit given by this technology is a reduced carbon emission footprint for energy production. Photovoltaic systems are used for energy production in many different environments. Photovoltaic modules are easy to install and to manage, so they can be used not only in big plants but also for small domestic installations. Since sunlight is available everywhere and the solar panels are low cost, this technology can be used also as an auxiliary source of energy for embedded applications, where a connection to the electric grid is not often available.

The capability to provide energy in presence of faults or non-optimal environmental conditions has become very important for a photovoltaic system. Even a single fault in complex photovoltaic systems can lead to a non-negligible loss in the whole system produced power.(Bai et al., 2015) Normally, in photovoltaic systems, cells are grouped inside modules that are connected together exploiting serial and parallel configurations to obtain the required current and voltage. A common configuration for a photovoltaic module is a series connection. The output voltage of a single cell is normally quite low, by using a series connection the output voltage of the module is the sum of the voltages of each cell. The energy production depends on the "health" of each individual cell. When all cells are in their best condition, the system will output the maximum current and voltage. However, the presence of even a single faulty cell, or the shading of even a small part of the panel, can lead to high degradation of the whole module performance. For this reason, usually one or more bypass diodes are connected in parallel to the cells to mitigate the negative effect in case specific cells operate in sub-optimal conditions (Vieira et al., 2020). This is the simplest solution, but other possibilities have been proposed in literature to solve this problem: in (Yanli Liu et al., 2010) and (Nguyen and Lehman, 2008) the authors propose a reconfiguration scheme based on a total cross tide (TCT) scheme. This configuration implies the connection of groups of cells in parallel to obtain the required current and then in series to obtain the required voltage. In the proposed design a set of reconfigurable cells are connected to the fixed photovoltaic array. Thanks to a switching matrix every reconfigurable cell can be attached to any row to compensate shaded cells in the fixed array. In (Lin et al., 2012), the cells starting from a TCT configuration are regrouped in an unbalanced connection topology where parallel connections within the same module can have different number of cells. In the presented articles, the proposed reconfiguration algorithms use voltage, temperature or lighting measurements to compute the required parameters to obtain an efficient reconfiguration. In (Mahto et al., 2020; Cadena et al., 2016) the authors propose a reconfiguration approach starting from a different type of photovoltaic cells with embedded CMOS switches. The algorithms proposed perform complete reconfigurations of the arrays reshaping the array configuration almost completely. These approaches, having a great flexibility, are able to reach very good results even if this optimization can significantly modify the output voltage characteristic at the output, differently from the approaches presented so far. In (Mahto et al., 2020) the quantity sensed is the power produced by the array and based on its measure a search for the optimal configuration is performed. In (Cadena et al., 2016) the authors need a voltage measurement of the disconnected cell to perform the reconfiguration. Finally, in (Udenze et al., 2018) the authors present a method to obtain an optimal configuration within a set of photovoltaic cells connected in series parallel configuration. In the paper, the array can be totally reconfigured to obtain series connection of cells with similar level of aging. In this article a measure of short circuit current is required for every cell to obtain an estimation of the aging of the circuit. In (Gnoli et al., 2019), we proposed a different reconfiguration approach based on a highly distributed sensing procedure. The sensing circuit, based on a memristor state change, is used to measure the status of the module, cell by cell. With this information the reconfiguration is performed modifying the series connections between the cells maintaining the same output voltage but increasing as much as possible the current produced by the module. This paper extends (Gnoli et al., 2019) leveraging its two core ideas: i) a sensing mechanism based on memristors that allows in a simple way to detect the state of each individual cells, ii) a reconfiguration system that allows to dynamically change the connections among cells. The use of memristors make it possible to create a simple and effective measuring system that can be easily embedded inside each cell, making the proposed approach suitable also for small-dimension systems. The reconfiguration system is based on switches to change the connections among cells. Thanks to this solution it is possible to create paths of cells with the same level of performance connected serially. Furthermore, it is possible to substitute back-up cells to faulty ones, improving overall the energy generated by the panel.

The novel contributions of this paper are summarized as follows:

- We propose a revised reconfiguration and redundancy system with a more efficient use of the spare cells that are in this configuration always available for power delivery. In the previous solution, proposed in (Gnoli et al., 2019), the redundancy was added in series to the last cells of every branch, giving only a limited help to the recovery from a fault. Moreover, these cells were part of the computation during the reconfiguration. These cells in the proposed configuration are connected dynamically to a faulty cell to improve its performance in case cell with lower performance are present. This enables the continuous operation of the panel even if some distributed damages are present on the panel. In particular, even in presence of damaged cells in the redundancy part, the connection to the redundancy branch can help maintaining a higher level of power.
- We have improved the sensing mechanism by adding an interface system that allows to read the state of the cell by external means. The status in the previous implementation was only available for internal use to perform the optimization algorithm. The control is now capable to interact with external systems sharing the cell-wise status of the module and coordinating its operation by means of external signals, allowing further optimization of the energy production and an element-wise diagnostic on the state of the panel.
- The proposed solution is validated by means of simulations in different scenarios where the module is not in optimal conditions.
- We performed an accurate power and energy analysis by a combination of SPICE simulations and characterization of the control system.

While this solution is intended to be applied to photovoltaic modules inside a single module, it can also be extended to photovoltaic arrays made by many modules. Overall the idea that we propose in this paper can be used to create ”smart” solar modules and arrays that can greatly improve the energy produced by solar farms and have a better knowledge of the status of the system.

2. Reconfigurable Photovoltaic Module

2.1. System description

The proposed design is based on a standard series-parallel (SP) configuration of the photovoltaic cells composing the module, as depicted in figure 1. In this configuration the current of a branch is given by the worst performing cell. The total current produced by the module is instead the sum of the output currents of every single branch. The output voltage depends on the number of cells connected in series in a branch. The

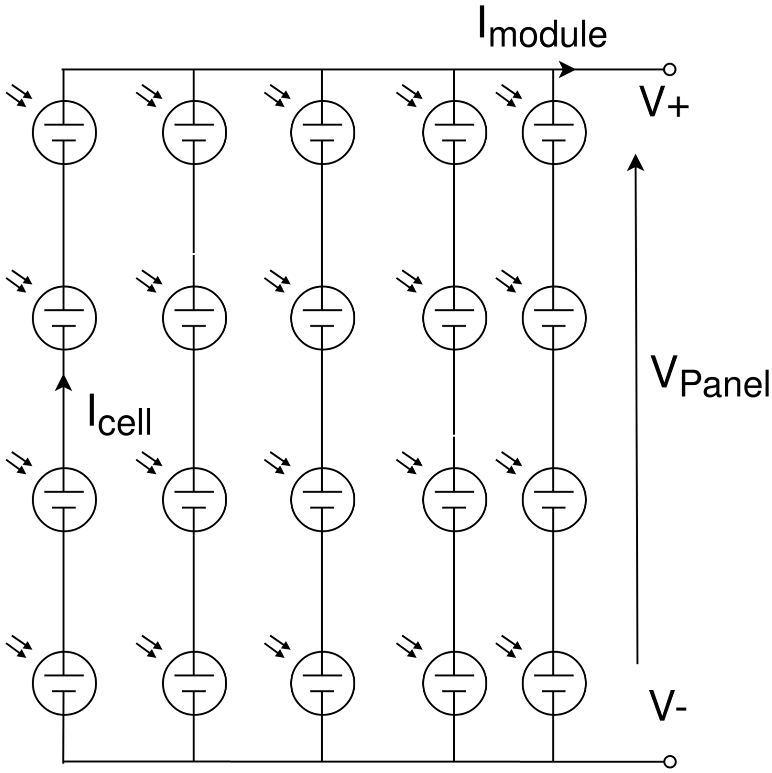


Figure 1: Photovoltaic module with fixed SP configuration

reconfiguration proposed is based on the idea that, to optimize the energy produced, every cell should be placed inside a series connection with cells performing at the same level. If a cell working in the best condition is connected serially with a faulty cell, its current will be much lower than its nominal one. Furthermore, the reconfiguration mechanism must be able to equalize the performance inside every series connection to mitigate as much as possible the lowering of the output power. The connections among cells are modified connecting neighboring rows by means of switch matrices. These devices make it possible to connect every cell within a row to any of the cells of the next row, as represented in figure 2d. The switches are activated by a control unit which rearranges the series connections to obtain the least possible mismatch, creating "virtual" columns of cells with the same level of performance.

Every photovoltaic cell is equipped with two additional switches to enable the disconnection from the array during the reading operation as shown in figure 2a. A bypass diode is connected in parallel with every element. It protects the element from dangerous reverse voltages and in the proposed solution allows the continuous operation of a series when reading is performed. In addition, to the main array, spare cells can be added to

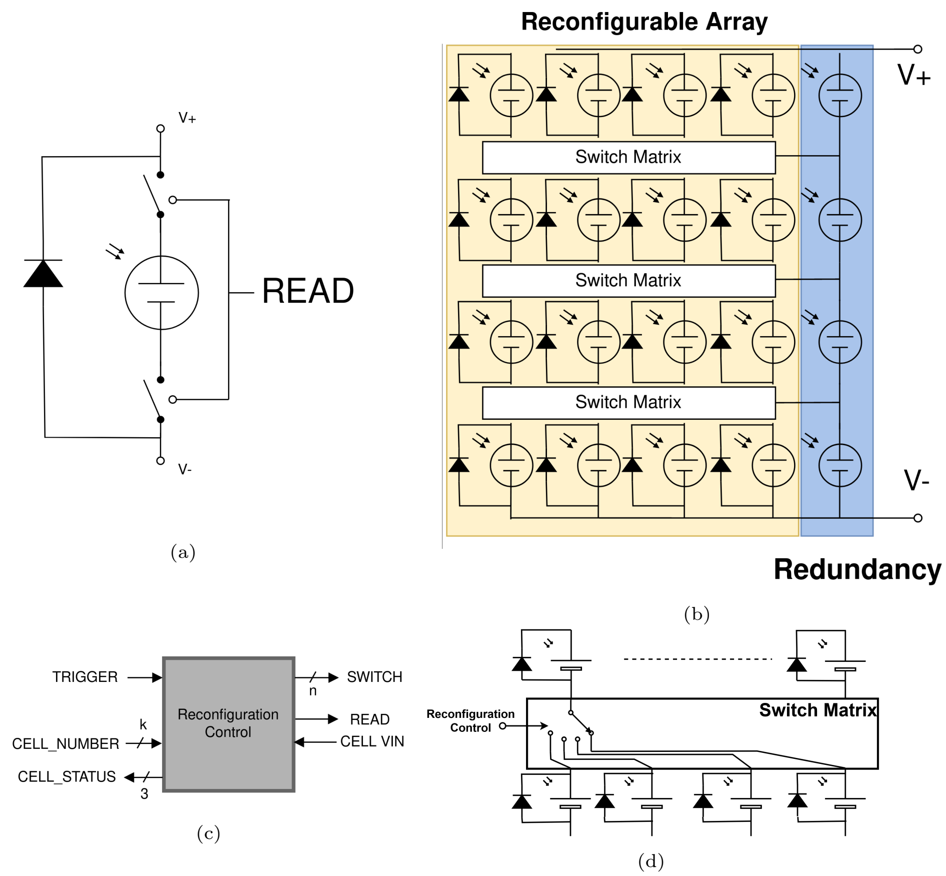


Figure 2: Reconfigurable module architecture in a) the basic cell of the reconfigurable array, b) the complete structure, c) the control unit interface, d) the switching matrix connecting subsequent rows

the panel as shown in figure 2b. The spare cells are connected in series, always contributing to the power produced by the module. Moreover, every element has also the chance to be connected in parallel to the elements of the main array as shown in figure 3. Even if many connections would be possible, the control unit is designed to activate the redundancy only for cells belonging to the same branch as shown in figure 3. The cells of the redundancy branch and the ones of the selected branch will be connected in parallel increasing for both the chance to conduct even in presence of faulty cells. To acquire the health status of every single cell, a reading circuit is connected to the cell 4a. The circuit is dedicated to the conversion of the state of the connected element in a voltage transition, that will be sampled and encoded by the control unit. The circuit presented in literature (Mathew et al., 2014, 2015) takes advantage of a memristor to generate a voltage transition on the output. The reading circuit is shared by all the elements of the array. To get the status of all the cells, the reading operation, presented in detail in section 2.2 is repeated for all the elements sequentially. Finally, the control logic coordinates the reading operations, stores the status of the array, performs the reconfiguration

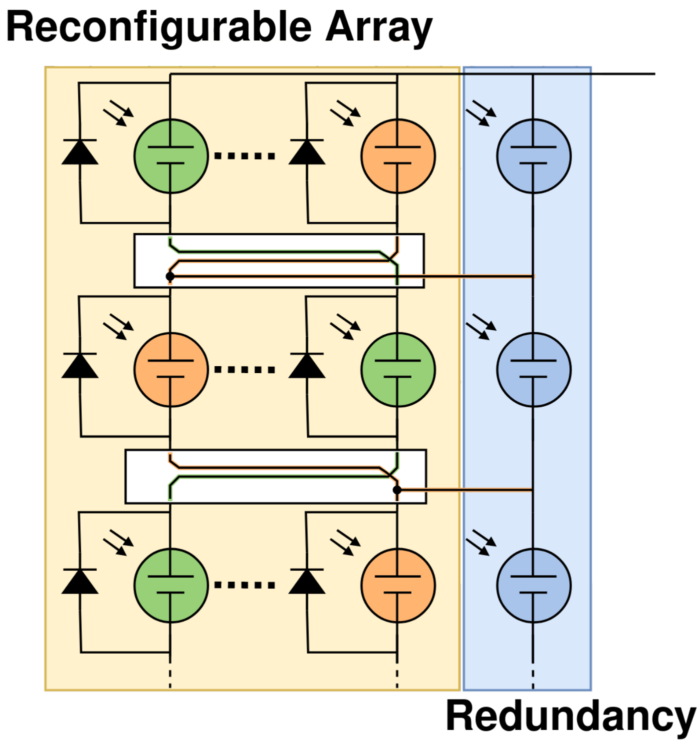
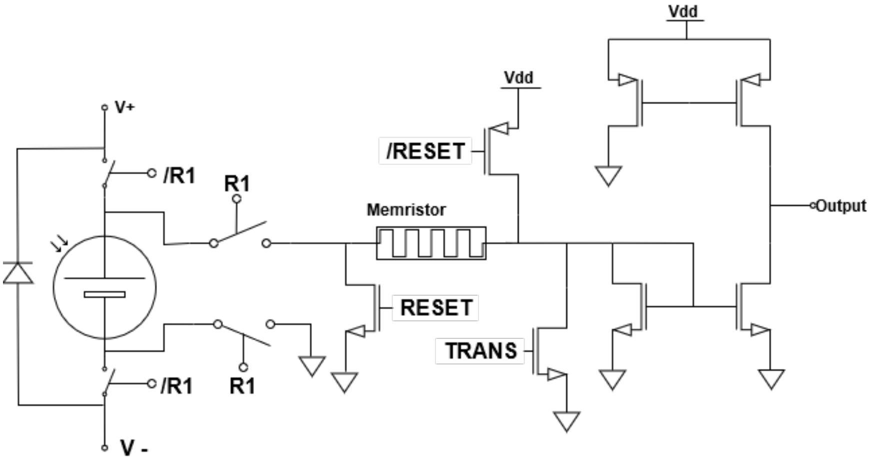


Figure 3: Redundancy cell connection. The cells are connected to a reconfigured series connection selected by the control unit

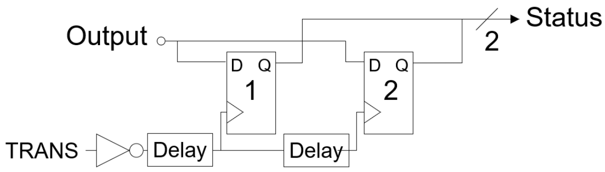
and enables the redundancy. Its operation relies on three different controls: Reading, Sorting and Redundancy. The three control units, use different finite state machines and works synchronized. The control unit is designed also to communicate with external systems, giving to other devices the chance to read the acquired status as shown in figure 2c. The circuit can also interact with external control systems allowing them to start its operation, read the acquired data and know the status of redundancy calculation. This allows to further optimize the energy production.

2.2. Cell health status acquisition

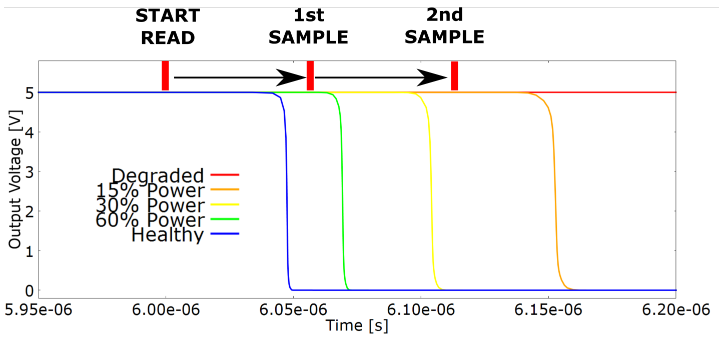
The first phase of the system operation is the acquisition of the status of the cells. The circuit used to accomplish this task is showed in figure 4a. It is composed by a memristor connected on one side to a current sensing circuit and on the other to the target cell. The reading circuit is additionally equipped with three transistors to reset the memristor state and to force a transition on the output node of the sensing circuit. Before every reading operation, the memristor is reset to the OFF state. To perform the reading operation the cell is then disconnected from the module and connected to the reading circuit. By means of the TRANS signal, the correspondent transistor is activated and a transition to Vdd



(a) Reading circuit based on the circuit presented in (Mathew et al., 2014)



(b) Sampling circuit



(c) Reading circuit output voltage transition with cells with different output power

Figure 4: Reading circuit and sampling circuit.

is forced at the output node. When the TRANS signal is released, the sensing circuit is able to produce a negative transition used for the cell evaluation. In this configuration, depending on the voltage and current produced by the photovoltaic cell, the memristor state changes. In particular, the change in the state of the memristor produces different delays in the transition of the output pin of the sensing circuit. The delay of the transition is used to determine the health status of the cell. In figure 4c the transitions triggered by cells with different output power are shown. The reading circuit has been tuned to obtain such transitions. It is worth noticing that the system can be made resilient to variations in the manufacturing parameters and operational parameters of the memristor by applying a calibration both at manufacturing and periodically during circuit life, To make the delay information available to the control circuit a sampling circuit is connected to the output of the reading circuit. The schematic is shown in figure 4b. To sample the transition two flip flops are used. The first flip flop samples the signal after a predefined delay from the moment TRANS signal is removed, the second flip flop samples the signal after an additional delay from the previous one. In the simulated circuit both the delays were set to 60ns setting a threshold at about 60% of the nominal power between healthy and partially degraded cells and of 20% between partially degraded and degraded cells. The difference of the sampling times of the two elements with respect to the TRANS signal transition defines two timing windows. If the cell is able to produce a transition on the output node in the first window the status of the cell is evaluated as healthy, if the transition occurs in the second window the status is evaluated as partially degraded, in any other case the cell is considered completely degraded. Finally, after the sampling, the status of the cell is available for the control unit. In the presented implementation only three possible states have been considered, if a higher precision is required more states are possible adding sampling elements to the circuit and by calibrating them accordingly to the delay of the sampling signal. To acquire the health state of the complete module, the reading operation is performed serially on every element of the array. Due to the long time constants of state change in photovoltaic systems, the reading is performed serially connecting every element to the same reading circuit until the complete module state is available.

2.3. Reconfiguration and Redundancy operation

. The second phase of the system operation is the sorting algorithm. Knowing the health status of the single elements, the circuit can compute the optimal configuration to minimize the mismatch. This goal is accomplished sorting the array row by row on the basis of the health status. The sorting operation follows a bubble-sort scheme. The computed configuration is then stored and will be used for the next redundancy phase. The configuration is not applied yet to the switching matrix.

Finally, the last phase controls the redundancy elements of the array. The redundancy control has the goal to connect the cells of the redundancy branch to one of the reconfigured branches. The topology obtained is a TCT between the redundancy branch and the selected reconfigured branch. This configuration permits to mitigate the faults effects exploiting the parallel connection of two mismatched cells. The limiting faulty cells are, in every parallel configuration, avoided thanks to the healthy cell. To obtain the described goal two requirements should be met: 1. The redundancy branch have at least one healthy cell 2. There is a reconfigured branch compatible with the redundancy branch. To meet the first condition the redundancy unit triggers the reading unit to read the redundancy cells status. A degraded redundancy branch would not give any advantage. Then for the second condition the compatibility is checked. If a branch can provide healthy cells in positions where another branch has faults and vice versa the branches are compatible. If a matching branch is found the redundancy switches are configured to be connect the redundancy branch with the matching one. If no branch is compatible the branch is connected to the one with best performance.

2.4. External Interface

During the reading phase the health status of all cells is acquired and memorized by the control unit. This information can be very useful also for an optional external control system. Knowing the status of the single cell an external system can track the evolution of the status of the panel and understand if everything is working as expected, or the module presents some problem. By using an external control system more advanced and refined algorithms can be used to control the connections among cells and to further improve energy generation. Furthermore, information on the status of the cells inside the panel can be used by tracking systems to control the orientation of the panel. Different positions of the panel will produce different transition times on the memristor and different health status sensed. Such information can therefore be used to control the orientation of the panel, optimizing the energy generated.

The information given by the panel can help also in diagnosis. Knowing the evolution of the status of a single cell can help to recognize defects and faults with a granularity smaller than the module. To provide this service to the external systems there are dedicated pins on the control unit as show in figure 2c. The output reading interface requires to the external system to provide the number of the cell that the system want to know one at a time. On CELL_STATUS pins the control unit provides the status of the cell selected through the CELL_NUMBER port. The possibility to read from outside the cell status opens many different scenarios. The health status of the cell is monitored by reading the current generated by a cell, that is also a measure of the amount of light received by the solar cell. Using this information, it is possible to use a solar panel as an external sensor.

3. Results and Discussion

3.1. Methodology

To verify the validity of the proposed design, the whole system was simulated in different conditions: in partial shading and permanent fault conditions. The simulation is divided in two parts: a SPICE simulation and a VHDL simulation. The former was set up to study the effect of the reconfiguration on the performance of the array, by simulating each solar cell using SPICE, and to study the behavior of the reading circuit in different cell conditions. The latter was set up to model the control circuit, with the goal of testing the reconfiguration algorithm and its impact on the performance of the solar panel. In SPICE the photovoltaic cell was simulated using a 5 parameters model (Wang and Hsu, 2009; Ali Naci Celik, 2007; Duffie et al., 2020) depicted in figure 5.

To simulate the memristive device the Yakopcic model proposed in (Yakopcic et al., 2011) was adopted and in particular, the parameters used were the ones proposed in the article by the authors to fit experimental data for high speed TaOx memristors. This choice was made in order to test the reading circuit with data as close as possible to real devices. CMOS switches are included in the simulation to simulate the cell reconfiguration. To simulate the whole system the solar module is reset into a basic configuration with all redundancy cells turned off. Then the faulty condition is applied to the cells. The cells are then connected to the reading circuit and the transition time is collected. Then the simulation moves to the VHDL environment. The transition times are used as inputs by the control unit modeled with VHDL. After the VHDL simulation is concluded

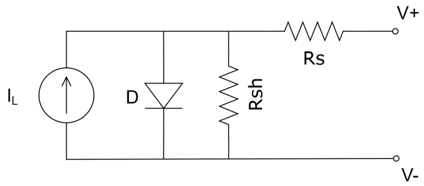


Figure 5: 5 parameters model of a photovoltaic cell

the switch controls are sent back into the initial SPICE simulation environment. The reconfiguration and redundancy control signals produced by the digital circuit are applied to the circuit and the power profile is computed. This iterative simulation process gives us the possibility to evaluate the effect of any kind of fault on the array, understanding if and how the control circuit behaves. It is also possible to evaluate the net energy produced by the solar panel, considering both the energy saved by the control circuit and its power consumption.

3.2. Simulation

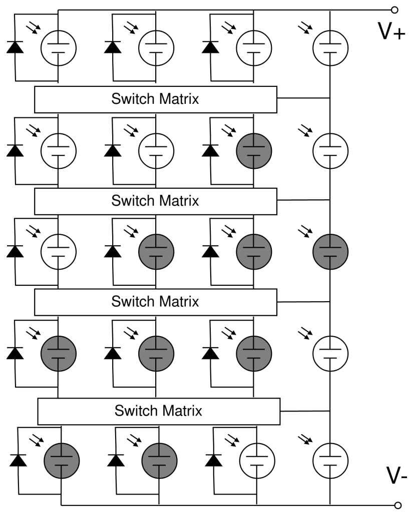
The system used as case of study is a photovoltaic module following the electrical specifications highlighted in Table 1. The system is simulated in two specific conditions: In shadowing (the array is partially covered by a shadow) and in permanent fault conditions.

Electrical PV module parameters	
Open Circuit Voltage	3V
Short Circuit Current	13.4A
Current MPP	12.5A
Voltage MPP	2.6V
Power MPP	32.5 W

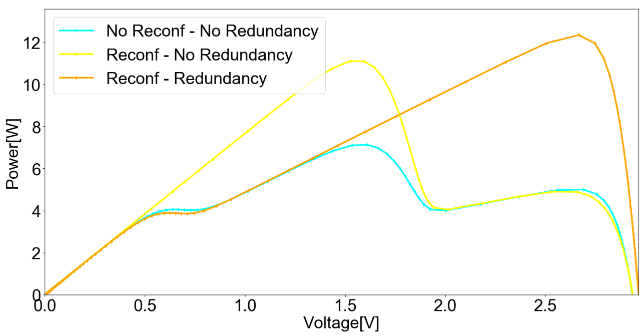
Table 1: PV module specification used in simulation. MPP(Maximum Power Point) referes to the panel characteristic under adapted load.

3.2.1. Partial Shading

To verify the effect of reconfiguration under different shadowing conditions two particular pattern were used to test the proposed system. These patterns are depicted in figures 6a and 7a. The shadowing of the panel was simulated lowering to 20% the current produced by the shadowed cells. In the first case the shadow covers completely two rows of the panel. In the second case the shadow covers only partially the rows. Comparing the first and the second simulation figure 6b and figure 7b, the reconfiguration gives an advantage when the pattern is not blocking an entire row. This because the reconfiguration cannot move an element from the row it belongs and a covered row will limit the whole array performance. In the second case the reconfiguration of serial connections and the redundancy allows the panel to increase the output power as shown in figure 6b. The registered increase after the reconfiguration is 57% with respect to the starting configuration. After the redundancy branch connection the output power reach the 71% of increase at the maximum power point. We can conclude that the system proposed can successfully mitigate the effect of a partial shadowing. If the complexity of the system is increased, by introducing additional switch matrices among columns, the system may be able to compensate the effect of shadowing even if a shadow is blocking an entire row.



(a) Not uniform partial shading

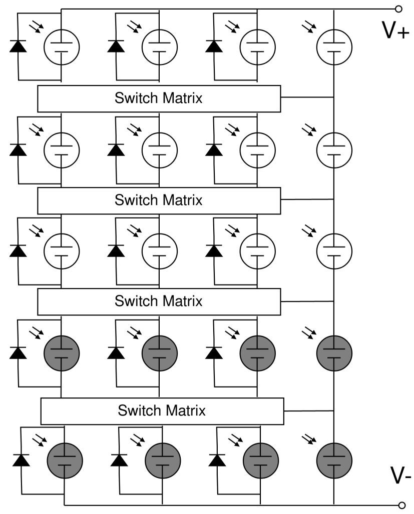


(b) P-V characteristic of the partial shaded panel before and after reconfiguration.

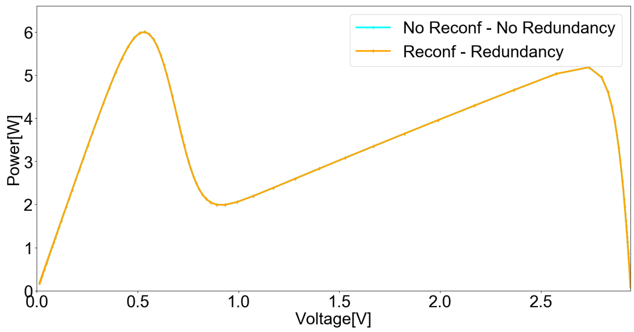
Figure 6: Partial shading. a) Simulated shade distribution. b) P-V characteristic of the module in a normal SP configuration, with reconfiguration only and with redundancy applied.

3.2.2. Distributed Faults

Differently from shadowing, other faulty conditions can arise in different areas along the surface of the panel for many possible reasons (like a hailstorm for example). The difference with the previous case is that faults can happen at the same time in different



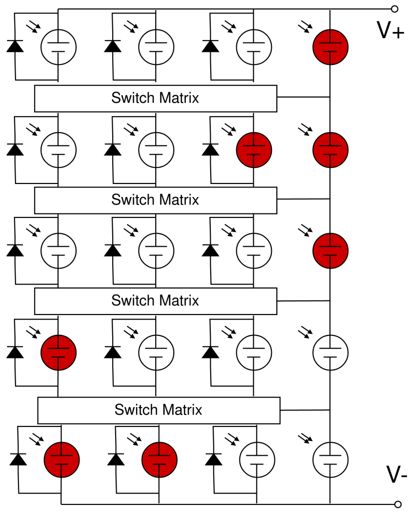
(a)



(b)

Figure 7: Partial shading covering entire rows. a) Simulated shade distribution b) P-V characteristic of the module in a normal SP configuration, with reconfiguration only and with redundancy applied. The uniform shading of the lower rows does not allow any reconfiguration for the module.

zones on the panel, in a non-uniform distribution. The test pattern used in this case is depicted in figure 8a. In a standard solar panel, where the connections among cells cannot be changed, the panel performance would be heavily affected, due to the fact that every series has at least one faulty cells and the mismatch between cells in the branches is high. The system that we propose, by rearranging the connections among cells, can greatly improve the performance. All branches are able to work, so the panel works almost as if it has not been affected by faults. In the simulation the faulty cell was simulated reducing the current produced by the normal cells to 50 uA. The new configuration obtained with the connection rearrangement and the redundancy application gave an improvement in performance of 70% with respect to the reference SP configuration.



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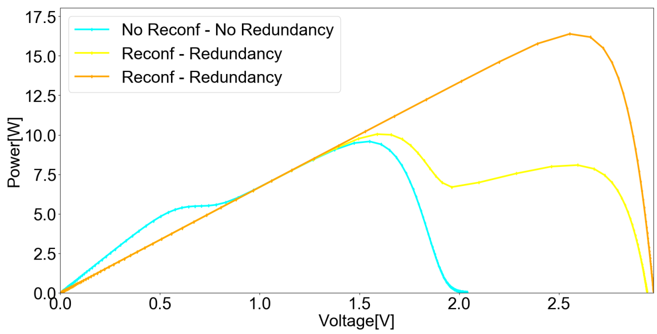

(b)

Figure 8: Multiple faulty cells in a module. a) Simulated distribution. b) P-V characteristic

3.3. Discussion

Few considerations about the implementation will follow in this section. The solution that we propose offers advantages especially in situations where a direct intervention on the panel is not possible and the module should continue to provide energy with high efficiency. In case the proposed solution would not be equipped with bypass diodes, the reconfiguration directly impact the working life of the panel. Single faults located on different columns can impact strongly on the whole panel performance eventually inhibiting completely the energy production. The reconfiguration and redundancy can then re-enable the panel function as long as a single cell is available for every row. Differently, considering the bypass diodes, also in the not reconfigured fixed series-parallel configuration, the operation of the panel is allowed in presence of faults. In this scenario, the proposed approach allows a grateful degradation of the panel attenuating the mismatch between cells. Nevertheless, some fault configurations are still critical as shown in section 3.2.1, due to the degrees of freedom of the proposed reconfiguration, limited only to rows. Regarding the sensing circuit, in other solutions proposed in literature (Nguyen and Lehman, 2008; Yanli Liu et al., 2010; Cadena et al., 2016; Udenze et al., 2018), the evaluation of the state requires a dedicated acquisition circuitry. The proposed sensing circuitry directly translate the sensed quantity in a digital value for further elaboration. The health status of the cells is available to the control circuit without the need of a dedicated acquisition circuitry to acquire sensors and output quantities of the cells composing the array. This reading method lowers the hardware overhead of the control circuit and allows in case a higher reliability for the system is needed, to duplicate such structure without great impact on the costs. Finally the compatibility of particular classes of perovskites both for solar energy harvesting and for memristor production (Zhao et al., 2019; Xiao et al., 2020), opens a very interesting scenario in which the reading circuit or part of it can be brought very close or even integrated in the solar harvesting element. Regarding the control unit, the chance of collecting from outside the state of the single elements can also improve the diagnosis process. Faults or loss of performance happening in different locations can be effectively recognized and tracked. This can give to an external system important information about possible faults affecting the systems that needs a manual intervention like obstacles, dust, misplacement of the panel, unrecoverable faulty conditions and similar. The hardware and the energy overhead introduced by the proposed reconfiguration scheme should not impact heavily on performance to avoid overcoming its benefits. A first contribution to the hardware overhead is the area introduced by the control circuit. As shown in table 3 the area occupied by the chip is minimal and can fit also in small configurations even considering an overhead for the auxiliary circuitry to guarantee its functioning. As shown in table 2 the highest impact on the additional hardware required by the proposed implementation with respect to the static configuration is represented by the switches needed to perform the repair procedure, as shown in table 3. The number of switches needed for the whole reconfiguration and redundancy is equal to the number of cells in the reconfigurable part of the panel excluding a row from the computation. In (Nguyen and Lehman, 2008; Yanli Liu et al., 2010) the number of switches is equal to 2 times the number of rows. In (Mahto et al., 2020; Cadena et al., 2016) the proposed approach requires 4 switches for every cell.

	Number of switches	Outputs per switch
(Cadena et al., 2016; Mahto et al., 2020)	4*N*M	Single-Output
(Nguyen and Lehman, 2008; Yanli Liu et al., 2010)	2*M	N-outputs
This work	(N-1)*(M+1)	M-outputs

Table 2: Switches required for reconfiguration for a system with N rows and M columns

The proposed system could have a strong cost efficiency impact in particular for smaller photovoltaic systems. The integration of the sensing circuit within the photovoltaic array would have a twofold benefit: first the area overhead would be much smaller compared to a dedicated external circuit and second, the cost of this devices would be negligible with respect to the cost of the photovoltaic array. Another cost efficiency aspect that should be carefully evaluated during the implementation is the type of switch to be used for the implementation and the bypass diodes placement in the panel. Regarding the switches, different cells arrangements will require different kind of switches, in particular arrangements with a higher number of columns will require more complex switches with a higher number of possible outputs. Finally the number of bypass diodes has also to be taken into account, as reducing the the number of bypass diodes would improve the cost efficiency reducing only partially the performance the panel.

To obtain the first two parameters a synthesis of the digital circuit has been performed with $90nm$ technological library. The power consumed by the circuit was obtained with back-annotation executing a common circuit operation in which the circuit went through a complete reconfiguration and all the redundancy cells are activated. The data is presented in table 3. Compared to the power produced in a module, like the one mentioned

Reconfiguration Overhead	
Estimated Power	$5uW$
Estimated Area	$4000um^2$
Estimated Energy for complete operation	$0,27 * 10^{-12}Wh$
Switches required	(M-1)*(N+1) N-throw switches *

*referred to a panel with N columns and M rows in the reconfiguration zone

Table 3: Power and Area data extracted from the synthesis of the control unit

in simulations, the power required for the circuit operation is several orders of magnitude lower. Moreover, as stated above, the circuit is not always active but its operation is triggered by external events or periodically by external monitoring systems. This reduces even further the impact of the circuit operation on the energy obtained by the array.

4. Conclusions

In this work, we presented a reconfiguration system for solar modules. The reconfiguration scheme is based on a low-overhead measuring system that uses a memristor as sensing element. Switch matrices among rows of solar cells and redundant cells are used to compensate for fault and anomalous working conditions, improving the energy generated by the panel. The goal of the system is to create a "smart" solar panel with embedded control electronics, capable of self-repair. The results presented in this paper highlight that this system not only works well, but it also has low power overhead and an acceptable hardware overhead, mainly due to the electrical switches required for the reconfiguration. To reduce the overhead we chose a non exhaustive reconfiguration control algorithm, therefore the energy production cannot be optimized in every faulty condition, however the proposed scheme is effective to correct random failures and provides positive improvements to several shading conditions. Furthermore, the system is designed to provide an external interface that can be used to control the switches from remote, thus improving and optimizing the behavior of the solar panel. The proposed approach will enable the design of highly controllable energy production facilities with optimized power production and prolonged useful life thus effectively boosting the overall sustainability of future solar power systems.

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Answer to reviewers

We would like to kindly thank the reviewers for their analysis and suggestions regarding the article we presented. We think that the paper had a good benefit from the modifications that came out thanks to the review. We have revised the paper according to the Reviewers comments; the revised contents are colored in red within the paper and referenced below (language corrections are not highlighted in red). The answers to the comments are listed in the following and are marked in bold.

Reviewer 1

1) In this manuscript a sensing memristor based and repair system for solar modules is proposed. The proposed system, taking the lead in from authors' previous works in the field (references [6] and [7] of the manuscript) concerning memristor sensing and expanded from latest authors' work [5], is briefly presented and, moreover, simulation results in cases of shadowing and in permanent fault conditions are also provided in a meaningful way. The manuscript is well organized and easy to follow; however, its presentation leaves a few more to be desired. Although the manuscript is indeed an extended version of the earlier conference paper (reference [5]) it is not always straightforward how the introduced novelty in the proposed systems outperforms the previous conference paper. In particular, the revised and more effective reconfiguration system is not compared by any figure of merit with the earlier system and the same applies for the improved redundancy scheme, and, generally speaking, more similar comparisons would be helpful for the potential reader to further appreciate the proposed overall system implementation in correspondence to its ancestral main parts.

We thank the reviewer for pointing out to this issue. As suggested, to give a better understanding to the reader of the differences and the improvements of the current extension paper with respect to the conference one, we modified the final paragraphs of the introduction section 1 to better highlight the improvement in the connection system and to the control system. In particular, we underlined that in this extension the redundancy connection and computation is different from the previous proposed: the redundancy previously was connected serially to every column of the array while in the proposed implementation it is connected in parallel. Finally, the contribution to the power produced from the redundancy cells is always available even if the remaining part of the panel is perfectly healthy and functioning.

2) Furthermore, it would be also helpful, if the state of the art referring to the repairing and mainly reconfigurable would be presented more thoroughly. For example, which are the main differences between the proposed system and others cited in literature like the paper entitled "Improving performance of photovoltaic panel by reconfigurability in partial shading condition" earlier published in Journal of Photonics for Energy, 10(4), 042004 (2020) or any other similar work found in literature? To be more specific, how the memristor based proposed sensing mechanism and the repair system can outperform a typical digital based system in terms of performance, cost, endurance or any other

appropriate term that could be useful for the potential to identify the possible advantages of the presented approach? As such, the authors are kindly requested to proceed with a more detailed presentation of the advantages of their system when compared with other similar systems.

We improved the introduction adding other papers on the argument to give to the reader a better view on the proposed solutions so far. We then joined the comments on the hardware overhead with a longer discussion addressing the advantages and disadvantages of our approach with respect to the state of the art. In particular, we compared our sensing mechanism with those reported in literature papers where those mechanisms were explicitly described. Furthermore in section 3.3, we analyzed and discussed in more details the hardware overhead of our proposed solution focusing on the control and the switches required to perform the reconfiguration.

3) Considering the sensing mechanism based on memristor, although it has been thoroughly described in the conference papers of references [6, 7], this reviewer feels that a short presentation now missing would be also necessary for reason of completeness and self-establishment of the presented work. This is more critical when considering the title of the manuscript with main focus on the memristor based implementation while any reference to the specific nano-device characteristics and attributes is mainly limited to Yakopcic model without further justifications. Why this model has been selected and how is this important in the context of the presented analysis?

We would like to thank the reviewer for this comment in the revised paper we added an additional section (Section 2.2) introducing and describing more in detail the reading circuit and its working principle. This section comes with two additional figures showing also in detail the transition time of the reading circuit in response to different power level of the connected cell. Regarding the chosen memristor model a more in depth presentation about the model used in simulations has been added in section 3.1, in this section we also argue that the chosen Yacopcic model used for our simulations closely describes the experimental behavior of the reference memristive device used in our work.

4) Furthermore, memristor devices to the best of the reviewer's knowledge are affected and usually suffer by intrinsic variability. Does this affect the proposed sensing mechanism and in which way? Moreover, which are the referred different transition times on the memristor dictated by different positions of the panel?

We agree with the Reviewer that variability is a main issue in memristive devices: the variability of the memristor will impact the predefined threshold delaying or anticipating transitions, shifting substantially the transition between the different states. However we believe that our proposed scheme would be resilient to this issue for two reasons: first we actually use just one memristors for the monitoring scheme therefore we would not need to take into account differing behaviors from different devices. Second, in order to address a possible variation of the memristor parameters after a certain num-

ber of cycles, as stated in 2.2, every reading circuit might be calibrated not only after manufacturing, but also periodically during operation to correctly tune all the parameters of the reading circuit.

5)It is mentioned, if well perceived by this reviewer, that the selected control algorithm arrives with specific characteristics of compactness and efficiency which can be further improved if more advanced control algorithm/system is used. Is there any estimation for this kind of improvement? Furthermore, is there any estimation, if quantitative even better, on the prolonged useful life of the photovoltaic modules due to the introduced system?

We thank the reviewer for the question. Regarding the improved efficiency, we do not have a precise estimation, the external system can be different depending on the application and the environment in which the panel operates. As an example a photovoltaic system can be set in advance by a different control system to counteract the negative effects of known shadowing or covering patterns that can affect it. In other possible scenarios, a more advanced control systems can take advantage of the switch matrices to realize other configurations different from the default series-parallel configuration to balance some faults conditions. All these system would require a different effort to compute the optimal configuration and will give different results in terms of efficiency. Regarding the estimation of the improved life, we added some consideration about the reviewer question in section 3.3. The effect on the working life and on the improved efficiency given by the proposed approach has been discussed taking as reference a configuration with fixed series-parallel connections.

6) It is clear that the system presents small hardware overhead as mentioned by the authors. This reviewer wonders if there were will be different measurement in a real photovoltaic panel and if the authors have proceeded with the implementation of such system. This should be made also apparent in the manuscript. Furthermore, in conjunction with the aforementioned comments, are there any fair estimations of the implementation cost in a financial basis? Would this system for the reconfiguration and repairing of the photovoltaic modules be appropriate for implementation in terms of financial cost? This issue deserves a more thorough analysis and I would suggest the authors to discuss a little bit further on this in their revision.

We would to thank the reviewer for the intriguing question. At the current level of implementation we don't have specific implementation data that would allow us to provide cost figures. However we provided in section 3.3 a discussion about the possible cost efficiency features of our proposed solution. In section 3.3 we argue that the novel idea of embedding memristors within the photovoltaic array would certainly provide a strong cost efficiency. More detailed evaluation of the cost of the implementation would be quite difficult not knowing exactly the specification of the implemented panel and having few open issues like the wiring on the panel and the fact that we're basing our study on a non-standard device

For readability reasons, I would suggest in Figures 6-8, the P-V characteristics for the different presented configurations shall be provided in a colorful mode to be more easily distinguishable. Finally, there are a few typos and grammatical issues apparent across the manuscript and the authors are welcomed to take good care of them. For example, the left quotation marks are always indicated as right; an extra space exists in page 3 of the manuscript in the sentence: "as represented in figure 2d ." and should be deleted; in page 10, at the last paragraph, the sentence "In a panel with n rows and m columns in the reconfigurable part." looks incomplete; in page 11, last paragraph before Section 4, the word "buts" should better be replaced by "but" in the expression: "... the circuit is not always active buts its operation is..."; the term TCT should be provided also in full form instead of its only abbreviated form, etc.

We thank the reviewer for pointing out these errors, we corrected them in the text. We also updated the figures as suggested, now the readability should be improved.

Reviewer 2

1) The key contribution of this paper is to propose a sensing and repairing system for photovoltaic modules with the memristors. The proposed design can monitor the photovoltaic cell status through memristors, then activate the dynamic reconfiguration function to re-route the connections among cells. The sensing information can be read externally or used internally in order to compensate faults and maximize the produced energy production. The detailed characterization and power analysis of the system are also presented. The key idea is properly presented in general. The simulation results support the contributions. However, the benefits from the usage of the memristor is not clear. The memristor is used as a measurement and categorization function in the proposed systems connected to each cell at a time. Then, what would be the benefit of memristor instead of measurement tools such as multimeter? I think that the memristor has much smaller form factor, and therefore, it can be deployed into the cells. I also hope that I can see the result even with miniaturized implementation. To my understanding, it requires a dedicated controller with very high frequency to capture the transition time at the output of reading circuit in real system. So it is better to analyze the implementation overhead.

We thank the reviewer for the comment. We answered to the reviewer question in two different sections. In Section 2.2 we explained the way in which the reading circuit works and how the transition is produced by the reading circuit and then sampled by the sampling circuit to make the information available to the control. We also commented about the advantage of applying such a hardware solution in section 3.3. To recall the concept expressed in the text the output value is directly translated by the combination of the reading circuit and the sample circuit in an encoded state that represents the status of the target cell. This circuit is cheap compared to a complete acquisition system and due to the simple schematic is also easily reproducible in a cell to improve also the reliability of the sensing mechanism

2) Minors:

- Page 3, row 28: “the cells of therow that follows” ← Is that row of backup cells?
- Page 4, row 2: “ . . . is connected to the cell 4” ← Is that fig. 4?
- Page 5, fig.2 : The description for fig. c) and d) are missing.
- Page 5, row 2-5 should be paraphrased. It is difficult to differentiate cell and element.
- Page 6: “TCT” should be explained.
- Page 9, table 1: What is MPP ?
- Page 10, row 6: “in a panel . . . reconfiguration part” ← grammar error, verb missing
- Page 10, fig. 6: Please explain why (no reconfiguration-no redundancy) and (reconfiguration-no redundancy) settings produce different P-V characteristic.

We thank the reviewer for signaling us these problems. We corrected the signaled errors in the text and in the captions as suggested. Regarding the last point, we checked our simulations carefully to fulfill the request and noticed an error in the simulation, so we corrected it and updated the results in the paper. The figures shows that the performance of the panel benefits from the reconfiguration due to the reduction of the mismatch between the column even in presence of faulty cells.