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Photovoltaic Arrays Dynamical Reconfiguration for Fighting Mismatched Conditions and for Meeting Load Requests.

A review of the architectures and of the methods

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Abstract

In the last five years, the desire to improve the control of photovoltaic arrays working in mismatched conditions has stimulated substantial research and development. Recent research has revived the previously discounted idea of changing the electrical connection between the photovoltaic modules according to their operating conditions and load requests. The switching matrix is reliable and allows to avoid the additional cost of module-level switching converters as well maintaining high efficiency under infrequent mismatched conditions. The photovoltaic array electrical reconfiguration also enables the best load matching between the photovoltaic source and its varying load. Such issues are discussed in this paper, with an overview of the main aspects introduced in the technical literature.

List of Acronyms

CIA – Computational intelligence algorithm
COA – Classical optimization algorithm
DCL – Direct-coupled load
DRA – Distributed reconfiguration algorithm
DPPS – Distributed power processing systems
ERA – Exhaustive evaluation reconfiguration algorithm
MPPT – Maximum power point tracking
PRA – Programmed reconfiguration algorithm
PV – Photovoltaic
RA – Reconfiguration algorithm
RSP – Reconfigurable series-parallel arrays
RST – Reconfigurable strings
RTCT – Reconfigurable total cross-tied arrays
SRA – Sorting reconfiguration algorithm

I. Introduction

One of the main issues discussed in the recent literature on photovoltaic (PV) systems concerns the control of the mismatched PV source [1]. It has been the common practice to scale the behavior and the current vs. voltage (*I*-*V*) model of the PV cell up to the string and array level, thus assuming that all the cells are exactly identical to each other and that they work in the same irradiance and temperature conditions. Unfortunately, this is only an ideal situation because temperature inhomogeneity, shadowing and parametric drifts occur in many practical cases. Mismatching can cause a significant power loss due to the non-linear relationship between the amount of mismatch and the power drop. In fact, it is possible that even a single cell producing near-zero power could cause an entire series connected string of PV cells to also produce near-zero power. In order to avoid this dramatic effect, some bypass diodes are usually added to commercial PV panels, placed in anti-parallel with a suitable number of cells. This restricts the detrimental effect of the shadowed cell to a limited number of cells, but the power vs. voltage curve (*P*-*V*) of the PV panel can exhibit more than one Maximum Power Point (MPP). This situation might lead to failures of the Maximum Power Point Tracking (MPPT) system of the inverter, which might be unable to reach the global MPP [2].

PV panel mismatch may also be caused purposely in the system's design. For example, an installer may need to use new PV panels to replace older, damaged panels, either of a different type or from a different manufacturer because the original stock is no longer available. Another example concerns building integrated PV applications, in which the PV cells/modules have to follow the profile of the building structures, so that cells/modules in the same string might have different orientations with respect to the incident sunlight.

Distributed power processing systems (DPPS), consisting of power electronics solutions dedicated to small portions of the PV array, usually to single modules, have often been proposed to reduce the effects of mismatching. Indeed, in the last five years the attention of some companies, both big businesses (e.g. [3]–[5]) and startups (e.g. [6]–[9]), has been focused on DPPS solutions based on DC/DC or DC/AC converters to process and maximize the power at the string level or at the individual panel level. Power optimizers and micro-inverters – inverters on each individual PV panel – have been proposed by a number of companies, with a variety of solutions, efficiencies and add-ons [10]. These products have also been supported by the research effort of many academic groups in the world, which have concentrated their studies on novel architectures (e.g. [11]–[14]), efficient topologies (e.g. [15]) and high performance control strategies (e.g. [16] and [17]). Moreover, some studies have assessed the performances allowed by the distributed power interfaces. For instance, in [18] a 4% minimum annual performance improvement is documented, when a micro-inverter equipped PV array is compared with one using a standard string inverter. In [19] it is shown that distributed MPPT solutions that are based on submodule integrated converters offer 6.9% to 11.1% improvements in annual energy yield with respect to a baseline centralized MPPT scenario.

Power optimizers, especially those whose output terminals have to be connected in series to form a string, ensure a high conversion efficiency, but in some extremely, although realistic, mismatched conditions they do not allow the maximum power extraction from the PV source [2]. Some DC/DC converter solutions featuring the straightforward connection of the switching converter at the input terminals of the inverter have recently appeared [20]. These solutions allow to bypass the constraints arising from the series connection but show limitations in terms of efficiency. The drawback is due to the fact that the DC/DC converter has to step the PV module voltage up to the value accepted by the inverter at its input, requiring a very high voltage conversion ratio. This same drawback affects micro-inverters: they offer the maximum flexibility but require a large voltage gain.

Module-dedicated DC/DC and DC/AC converters allow to inspect the performance of every single PV module in real time. This technology is helpful for detecting power drops due to specific modules or PV array sections. Unfortunately, any solution employing a module-dedicated converter suffers from the non-unitary efficiency of the converter itself. This seems an almost obvious consideration, but it is less evident by accounting for the aspect that the converter is forced to work during the day with a wide range of input power, due to the intrinsic variability of the irradiance. In the literature, some procedures for optimizing the energy efficiency of the converter are proposed (e.g. [21]). Unfortunately, the non-unitary efficiency of the converter is a strong penalization whenever any additional power processing operation is useless, e.g. during the hours of the day when the PV array operates at a uniform irradiance. This condition has been addressed by some manufacturers by providing the bypass mode [22], so that the converter suspends the switching mode and gives a straightforward connection to the PV module when any voltage/current adaptation is requested. Unfortunately, in bypass mode the detection of the conditions requesting the resumption of the switched mode may be complicated and/or can be delayed, reducing the power production.

A second drawback of the solution based on the adoption of a module-dedicated converter is in the possible shorter lifetime. Not enough data are currently available to judge the importance of this problem. On one side, the adoption of electrolytic capacitors and the high thermal stresses due to an installation close to the PV module might shorten the switching converter lifetime [23]; on the other side, accelerated aging studies proposed by manufacturers suggest that the converter will have a lifetime that is at least as long as the PV module [24].

The differential power processing architectures, described in [14], [19], [25], exploit the DC/DC converters for processing only a small part of the power delivered by each PV panel and are connected in a way that they process zero power in absence of mismatch. Thus the non-unitary efficiency of the converters has a minor impact on the total delivered PV power. Moreover, the reduced converter power rating helps to relax the component stress by improving reliability. As shown in [25], the presence of the differential power processing architectures improve also the whole system reliability because some PV damages (e.g. the hotspot phenomena) can be reduced for the presence of the DC/DC converters. The drawback is that additional cabling among the PV panels and DC-bus as well as a more complex MPPT algorithm are required. Moreover, these solutions are not suitable to compensate deep mismatched conditions due to the limitation on the converter power rating.

Hardware and software advances in recent years has led to renewed interest in reconfigurable solar arrays in both research literature and patents. The idea of changing the connections among the modules in the PV array as function of their operating conditions or of the load request is not recent: in fact, it was arguably proposed by patents in 1970s and research papers began to appear in the early 1990s. However, at the time, these techniques were not applicable at a reasonable cost or with a significant reliability because of the lack of suitable hardware for switches implementation. A system overview of the PV reconfiguration with these new hardware and software advances is shown in Fig.1 for demonstration purposes. Because of the scalable PV technology, the size of the PV array varies from many PV modules in a solar farm, to a few solar cells in a portable PV panel. A reconfigurable switch matrix is utilized that consists of a number of switches, such as MOSFETs, relays, or manual switches, to allow a change in the internal connection of a PV array. The switches allowing the reconfiguration operation do not work at a high frequency, but they have to ensure some tens of reconfigurations per day for some tens of years, with a reliable operation. The reconfiguration systems available on the market adopt a solution employing an electromechanical switch in parallel with a semiconductor switch. The latter is turned ON before the former is switched off at a low voltage. In addition, in the ON state, the electromechanical switch allows to minimize the conduction losses. This solution was described in [26].

Recent work demonstrates near unitary conversion efficiency and no additional losses in the absence of any mismatching source. Moreover, thanks to the direct access to the terminals of each PV module, the approach also allows for the implementation of efficient monitoring and fault detection strategies. For instance, the method proposed in [27] is helpful in detecting an unexpected distortion of the PV module *I-V* curve. The drawback of the PV source reconfiguration is in a possible failure of some switches and in the fact that, in some approaches, the *I-V* curve of each PV module must be acquired periodically. This may require that the modules are disconnected from the string one after the other, this resulting in an obvious power loss.

In this paper some aspects related to the technology used for the PV array dynamical reconfiguration are discussed. Architectures, algorithms, and implementations presented in the literature are reviewed. The ideas in some of the patents available on this topic are also described and compared.

II. Architectures and Algorithms

The approaches to PV array reconfiguration reported in technical literature differ in hardware structure and control algorithm, but almost all begin with the assumption that the PV units being reconfigured exhibit a single peak of the power vs. voltage (*P-V*) curve. The only exception is the approach presented in [28], which is based on a prior knowledge of the possible mismatched current vs. voltage (*I-V*) curve of each PV unit. Some solutions in the literature require systems to measure or estimate the irradiance and/or the temperature of each PV element. For instance, in [29] the irradiance is estimated through the short-circuit current and in [30] the shadowing level is inferred from the open-circuit voltage. The irradiance is also estimated by current and voltage measurements and/or datasheet values [31], but it requires a significant computational effort. In [32] the string current and voltage values are used to determine all the modules' parameters.

A. Architectures for Reconfiguration

Studies reported in the literature refer to three fundamental architectures: reconfigurable strings (RST), reconfigurable series-parallel (RSP) arrays, and reconfigurable Total Cross-Tied (RTCT) arrays, which are shown in Fig. 2.

1) Reconfigurable strings: The RST architecture consists of a single string in which any mismatched module could be removed from the series connection. Hence, the string MPP voltage changes significantly depending on the mismatching profile.

This architecture is the simplest structure, because only two options are available for each module, requiring only a small number of switches. In [33] an RST architecture employing a commutation network to interface each cell to any other is presented. The network includes switches, storage capacitors, and voltage/current sensors used to detect the MPP and to measure the string current. A dedicated controller decides the cell connection or disconnection to/from the string.

2) Reconfigurable series-parallel arrays: The RSP architecture consists of multiple strings connected in parallel, in which any module could be moved from one string to another or removed from the array. In addition, the array geometry could be fixed or variable, in terms of the number of strings and modules-per-string constant.

Since this architecture connects each module to any string, it requires a much larger number of switches for its implementation [32]. In [34] a RSP architecture is used to reconfigure an SP array for feeding the motor of a water pump in low solar irradiance conditions. Four PV modules are arranged in series, in two strings of two modules each or in parallel. In [35] the analyses and the control algorithm were extended to an arbitrary number of modules.

The literature focuses on achieving the best tradeoff between the flexibility of the RSP structure and the simplicity of the control actions and their implementations. Fixed geometries require a lower number of switches but, at the same time, they limit the number of possible configurations, hence the optimal one might not be achievable. Instead, variable geometries provide more possibilities at the expense of an increased hardware and control complexity. In such a way, in [29] the geometry of the RSP architecture is fixed and the best achievable configuration allowing to reduce the effect of shadowing and fulfilling the inverter input voltage constraint is searched for. In [32] the connections in a fixed geometry RSP structure are optimized in order to fulfill some constraints in terms of output voltage and current ratings.

Some applications of the RSP architecture can be found in the patent literature. For example, a dynamic array configuration has been used to adapt the voltage and current with a reduced number of PV cells by simple topological reconnections for use in spacecrafts, where the extreme variations in irradiance and temperature lead to an oversizing of a fixed PV array with high cost and weight. In [36] a series-parallel configuration of 4 PV elements is obtained by using only 3 switches. In [37] the reconfiguration is used especially for redundancy purposes. An additional benefit of this reconfiguration system is to modify the current path in the PV array for obtaining a controllable magnetic torque useful to regulate the spacecraft attitude. The architecture described in [38] extends the series-parallel reconfigurations for a PV array, composed of Y number of strings with X number of PV elements (cells, panels,..) for each string. Two configurations are possible: a short string PV array, configured as $Y \times X$ matrix, and a long string PV array obtained with $Y/2$ strings of $2X$ length. This approach provides a good tradeoff between flexibility and the use of additional components.

The RSP architecture is also used in [39], in which any PV panel can be inserted in a different string or remain disconnected from the others. If s is the number of strings and n is the number of PV modules, then $3 \times s \times n$ single-pole/single-throw switches should be used. The strings can be connected in parallel to a single inverter or distributed among more than one inverter by using additional switches. Two criteria for selecting the best PV array configuration, based on the current and voltage measurements of each PV panel, have also been proposed. The same approach is also applied to a product which is available on the market [40].

3) Reconfigurable Total Cross-Tied arrays: The RTCT architecture consists of rows made of parallel-connected modules connected in series. Any module could be moved from one row to another or removed from the array. In addition, the array geometry could be either fixed or undefined in terms of the number of rows and modules-per-row. Similar to the RSP case, fixed geometries require a lower number of switches but at the expense of a reduced number of possible configurations. Instead, undefined geometries provide more possibilities to find an optimal solution, at the price of a more complex implementation and control. A typical approach adopted in RTCT architectures consists in fixing the structure of a number of modules, which are not subjected to any reconfiguration process.

A fully reconfigurable RTCT architecture is used in [41] to reduce the mismatching losses, but at the price of a large number of switches [32], increased control complexity, and additional hardware requirements. Also, in the approach proposed in [31], where single-pole/double-throw and single-pole/triple-throw switches are used to move the modules between the reconfigurable rows, all the possible configurations providing different power levels are evaluated before determining the optimal one. The problem complexity is reduced by fixing the connection of a number of modules into a classical TCT array [30]. This configuration reduces the effects of the shaded modules, but the effectiveness of the approach depends on the relation between the sizes of both the fixed and the reconfigurable sections. In [42] it is shown that a global optimization algorithm is helpful in finding the optimal configuration of any RTCT architecture, whether a fixed subsection is included or not.

The patent application [43] proposes an RTCT structure wherein any PV element can be placed in any row. In order to implement this method for an m number of rows and n number of columns RTCT array, $2 \times m^2 \times n$ single-pole/single-throw switches should be used.

The architectures proposed in [44] and [45] refer to a PV panel that is selectively configurable as series, parallel, or mixed series and parallel electrical connections with other configurable PV panels in the array. In [44] the PV array is obtained with a series connection of PV elements. Each element consists of a parallel connection of PV panels. The number of PV panels in the elements can be different but only the “adjacent” PV panel can be inserted in the same PV element. Otherwise, the panel is shifted in the subsequent element. A bypass configuration is also possible but it is mainly used for maintenance reasons: for example to clean the PV panel or to repair a damaged or malfunctioning PV panel without disconnecting the whole PV array. This solution is appreciated mainly for its simplicity: only two switches are used for each PV panel and only a double connection is required between the adjacent panels. The main drawback of the architectures shown in [44] is in the fact that the current and voltage ratings of the switches depend on the maximum number of PV modules connected in parallel and in series, respectively. This might limit the system flexibility and increase the cost. Nonetheless, it is reasonable to assume that, for a typical PV string, a large part of the highest irradiated PV panels are connected in series, in order to assure a suitable operating voltage for the inverter. The parallel connection is applied only to maximize the delivered power of the shadowed panels. This means that switch current ratings can be defined, in the worst case, equal to the current flowing in panels connected in series. Moreover an external switch, selected to support the maximum PV array voltage, can be used to disconnect the PV array from the load before to change the configuration. As a consequence, the voltage rating of the internal switches can be chosen on the basis of the open circuit voltage of a single PV module only. Fig. 3 shows an example of the electrical connection of such architecture.

4) Hybrid architectures: Hybrid architectures, combining RST, RSP and RTCT structures, result in solutions which differ, depending on the level of granularity, in terms of flexibility and hardware requirements. In [46] a hybrid RST/RSP architecture – wherein the shaded modules of the RSP part are removed to form a uniformly irradiated SP array directly connected to the main inverter – is proposed. If the reconfiguration process results in a short PV string, this is connected at the input of an additional DC/DC converter, thus forming a RST structure. In [47] a hybrid architecture based on multiple RST instances is proposed (see Fig. 2). Each string, which can include any module, is connected at the input terminals of a dedicated DC/DC converter. Such a solution increases the number of possible configurations achievable by the same RST architectures operating independently. The main advantage of this solution consists in reducing the number of modules excluded from the strings, so that the achievable maximum power is increased. The main drawback consists in the increment of the number of switches and control complexity.

The joint use of a switching matrix and DC/DC converters is discussed also in some patents. For instance, in [48] an electronic management system is integrated in a PV module. The system comprises a plurality of static DC/DC converters electrically connected to one or more PV cells and a reconfiguration module connected at the converter outputs used to transmit the energy towards a load. A similar approach is shown in [49], but in this case the DC/DC converters are connected after the reconfiguration switches.

B. Algorithms for Reconfiguration

Medium and large size PV arrays give rise to a very large number of possible configurations, so that the number of combinations to be examined must be reduced by introducing some operating constraints, such as the connection architecture (e.g. the RTCT in [30]). The optimal solution is determined by using heuristic, intuitive, or mathematical approaches. Table I compares the main features of some reconfiguration algorithms (RAs) presented in the literature. The analysis is based on the type of implementation, analog or digital, on the convergence speed, on the algorithm and implementation complexities, and on the performance in calculating the best configuration. The algorithms are classified according to the following categories.

1) Programmed reconfiguration algorithms (PRAs): These types of algorithms require a training phase to create the relationship between different operating conditions to an optimal connection among the PV elements. If the actual operating conditions of the PV array do not fall into the set of cases analyzed during the training stage, the system connects the PV modules in a way that does not ensure the maximum power production.

The algorithms usually determine the connections among the PV elements by using lookup tables: in [35] the approach is used to match the modules' MPP with the load requirements. Under a low irradiance the modules are connected in parallel, while under a high irradiance the modules are connected in series. Instead of employing digital devices, in [34] one over three pre-determined configurations is selected by using analog comparators on the basis of the actual irradiance value.

2) Exhaustive evaluation reconfiguration algorithms (ERAs): In these types of algorithms all the possible combinations are evaluated, but in some applications the calculation time is shortened by reducing the width of the search space by imposing certain operating constraints in the connection of the PV units. In [29] an RSP architecture is reconfigured by testing all the possibilities that fulfill the voltage constraint at the inverter input. In [31] the search space is reduced by fixing the number of modules-per-row in an RTCT architecture. Irradiance equalization and the number of relocations are discussed in that paper. The former is used to improve the array power production and the latter is considered for increasing the switches' lifetime by reducing their connection/disconnection frequency. In contrast, an exhaustive search algorithm is used in [32] to reconfigure PV arrays in RSP architecture: it exclusively measures the strings current and the voltage in order to calculate the modules electrical parameters. Parameterized models are used to evaluate all possible configurations. In [47] a hybrid architecture, based on RST instances, is reconfigured using an ERA algorithm. Such a solution tests all the possible configurations to find the one providing similar MPP currents to the elements of each string. The procedure is performed by multiplying a predefined matrix describing each configuration with a matrix formed by the maximum currents of each string to calculate the configuration power, repeating the process for all the configurations.

3) Sorting reconfiguration algorithms (SRAs): In the SRAs the PV elements are organized on the basis of the irradiance level each one of them is receiving. Then, a sorting criterion is applied to search an acceptable solution; some architectural constraints are introduced in order to limit the width of the search space.

In general, SRAs sort the PV modules to search for the configuration that meets a given condition. The first step of the algorithm proposed in [30] is to organize the PV cells depending on their irradiance level (corresponding to their open-circuit voltage measurement). Afterwards, the algorithm relocates the most illuminated cells in the adaptive part of an RTCT architecture to compensate the most shaded cells of the fixed part of the array. A similar approach for a fully reconfigurable RTCT array is presented in [41]. The algorithm uses a matrix arrangement and a sorting algorithm, based on the best-worst paradigm, to speed up the selection of a configuration that equalizes the rows' irradiance. Instead, the solution presented in [46] disconnects the shaded modules from the array, so that only the fully irradiated modules are connected to an RST-RSP hybrid architecture. This type of solution wastes the power produced by the shaded modules, so that it is not able to perform a real maximization of the power produced by the PV array.

4) Distributed reconfiguration algorithms (DRAs): In DRAs, each PV element is equipped with a controller to autonomously decide the connection/disconnection of the element itself to/from the array. This solution increases the quantity of additional circuitry and its use is limited to RST architectures.

The solution presented in [33] uses a DRA algorithm in an RST architecture: the cell is connected to the string for a time interval depending on its maximum power, while the string current is defined by the highest MPP current. In short, the other cells are connected to the string during the time they can contribute to sustaining the string current, thus equalizing the cells' current during the whole period.

5) Classical optimization algorithms (COAs): Those algorithms are based on the classical optimization theory, where the value of a mathematical cost function is optimized by using classical methods. Moreover, some constraints in the possible connections of the solar elements are introduced to limit the width of the search space. For example, a COA solution is proposed in [42] to reconfigure an RTCT architecture with a fixed subsection. The cost function to be minimized through the branch and bound (BB) algorithm is the irradiance difference among the modules in each row. Unfortunately, the COA solutions require a significant computational effort.

6) Computational intelligence algorithms (CIAs): In this type of solutions the optimal configuration is determined by using heuristic algorithms, based on fuzzy sets, neural networks, evolutionary approaches, etc. In general, designer's knowledge or large amounts of data are required to define or train the algorithm rules.

In [50], a fuzzy algorithm is designed using a small set of rules to search for the best configuration depending on the irradiance level and the torque-velocity requirements of a car. Whereas in [51] a set of fuzzy rules also keeps into account the derivative of the irradiance to increase the dynamic performance. Both solutions reduce the search space by fixing the array geometry.

C. Architectures, algorithms and applications correlation

The reconfiguration solutions proposed in patents and scientific papers are categorized in Tables II and III. The columns detail the algorithms, architectures and the reconfiguration level used in each application. Similarly, the number of sensors, switches complexity are classified as low/medium/high. In particular, if an application requires voltage sensors only, it is classified as low complex level, while requiring an additional current sensor gives a medium complex level. The high complex level is achieved by applications requiring temperature, irradiance or other additional sensors. In the same way, the complexity of the switches is linked to the commutation element used, such as transistors/single relays/multi-pole relays/others. Finally the main advantage and disadvantage of each approach is highlighted in the last two columns.

It is noted that some structures and algorithms are adopted for different applications; for example the Water Pump, Battery Charger and Spacecraft applications use PRA algorithms and RSP architectures, which are less complex to implement, but also less adaptive in front of mismatching conditions. Instead, the applications that could be subjected to several shading sources, like Urban and Building integrated ones, require more elaborate reconfiguring algorithms such as ERA or CIA. The number of switching elements are not necessary linked to the algorithms; for example in [34] a simple PRA algorithm requires 9 single-pole switches to form 3 different configurations, while in [31] it is required 6 multi-pole switches to commute between 15 different configurations using an ERA algorithm. Instead, the quantity of switches is linked to the reconfiguration architecture, its constraints, and the switch complexity, e.g. number of poles of the switch. In general, the applications presented in the literature achieve sub-optimal solutions. This limitation is mainly due to the constraints imposed to the search space, e.g. restriction of using a specific architecture, the evaluation of a limited set of possible solutions, among others. This condition is, for example, observed in [35], where 24 solar modules must be connected in a RSP architecture using a PRA algorithm; hence the search space is constrained to only six configurations of the seventy eight possible ones. Such a constraint makes to guarantee the operation not possible with the optimal configuration for all the conditions.

On the other hand, the level of granularity in the reconfiguration is related to the power. For example, medium-high power applications reconfigure modules or panels, while those for low-medium power interconnect modules or cells. The Smart PV and Portable applications reconfigure at low granularity level (cell) using the RSP or RST architectures and executing DRA algorithms [52], [53], [54]. It is also observed that more complex algorithms like ERA or COA are used in medium-high power rated applications [29], [42].

A high quantity of references propose reconfiguration solutions for not specified (NS) applications; those solutions adopt a large variety of algorithms and structures as shown in the last row of Table II. The main disadvantage of such solutions concerns the requirement of mathematical models [29], [30], [31], [42], [51] which increases the computational burden. In some cases, additional difficulties appear due to the high number of complex sensors required to obtain irradiance and temperature values [29], [35], [55]. Other approaches are based on direct measurements to avoid the use of mathematical models, which in turns reduces the computational burden to overcome the errors introduced by the uncertainty in some model parameters. Examples of such solutions are given in [41] and [47], where a single pair of voltage/current sensors is used to profile the I-V characteristic of each PV device. Such an approach, known as "sense configuration," uses the reconfiguration switches to serially connect each PV device to a profiling circuit, reducing the number of sensors required. The main drawbacks of the techniques are related to the increment in the time required to obtain the I-V curves of all the PV devices, the additional hardware in the form of a profiling circuit and switches, and a more complicated control algorithm.

Concerning patents, the most widely adopted algorithm is the PRA associated with RSP architectures. Moreover, some patent solutions also provide monitoring capacity [52], [53] and fault detection [37], [52].

III. PV Reconfiguration for Matching Load Requests

The PV reconfiguration is useful for adapting the source to the load without the need of any other interface. The simplicity, low cost, and reasonable efficiency achieved without any power conversion stage of the direct-coupled load (DCL) is counterbalanced by the fact that it can only be used efficiently under a fixed predetermined output voltage level. In addition, the system output is limited by the short-circuit current and the open-circuit voltage of the fixed PV array. The PV reconfiguration allows modification of the connection of the PV array, leading to changeable *I-V* curves and wider output characteristics. Thus the PV array becomes more available for the load under various real-working circumstances.

Patent [56] protected one of the first ideas to reconfigure the solar cells for terrestrial applications: some cells are connected in series or in parallel allowing to match the load for delivering the maximum power. The conditions for maximum power operation are based on the assumption that the optimal PV array voltage V_{MPP} is a "constant fraction" of the open circuit voltage V_{OC}.

By measuring V_{OC}, it is possible to estimate the optimal number of series PV cells from the ratio between the load voltage and V_{MPP}. Due to the increased number of switches needed to perform such a reconfiguration, it is applied only to a subset of PV cells.

The schematic diagram in Fig. 4 shows typical DCL applications of the PV reconfiguration system. There are four main components: 1) a PV array, which consists of a number of solar cells or PV modules, called charging units; 2) a reconfigurable switch matrix; 3) DC loads; and 4) a microcontroller (or an equivalent circuit), which controls the PV reconfiguration process.

Three PV configurations are achieved to meet the specific DC loads requirements, by turning ON and OFF of switches of the specific example shown in Fig. 4. It is worth noting that they have similar maximum power but different voltage or current levels: 1) 1×4: four units in parallel give the largest current but lowest voltage; 2) 2×2: two units in series as one string, and two strings in parallel – Both the voltage and current are in the medium range; and 3) 4×1: four units in series yield the maximum possible voltage but lowest current. In the second, it is assumed that the PV units have identical electrical parameters and are uniformly illuminated. Different DCL applications are summarized in Table IV. It is necessary to mention that if only a portion of PV units are used, five more configurations can be found to improve the output flexibility of the PV reconfiguration, such as 1×1, 1×2, 1×3, 2×1 and 3×1 configurations [55].

A. PV-Powered Water Pump

A PV-power water pump system employs a water pump coupled with a DC motor, which can be running on the electricity directly provided by the PV array without power conversion unit or battery storage [57] and [58]. The simple operation and low maintenance make it popular in remote areas where a water supply is needed. However, under low irradiance levels (e.g. early morning, late evening, and cloud covers), it might be difficult for a fixed PV array to provide sufficient starting current for the water pump. To solve this issue, oversizing the PV array will improve the performance in low irradiance conditions. Alternatively, a battery or a pump controller can be added between PV array and water pump. Different from these approaches, a switch matrix (see Fig. 4) is first proposed in [34], which reconfigures the PV array to provide a sufficient motor startup current under low irradiance levels, so that the pump can operate for extended working hours.

Specifically, under low irradiance levels, the 1×4 configuration is utilized to provide the maximum possible starting current for the pump. Under medium irradiance levels, the PV array works at 2×2 configuration. Under high irradiance levels, the PV array will work at 4×1 configuration. The controller monitors the solar irradiance as low, medium, and high by using a reference solar cell. According to the instantaneous irradiance level, the controller turns ON the switches in Table IV accordingly. To further improve the reconfiguration control algorithm, the water pump's characteristic is considered in the load matching analysis with the reconfigurable PV array [59]. In addition, increasing the number of PV units and switches can bring more possible configurations to the PV array [35]. Nevertheless, the concept of DCL applications of the PV reconfiguration remains the same in these papers.

B. PV-Powered Vehicle

The DCL application in [50] requires an appropriate control over the torque and speed of the motor. However, this direct connection raises two challenges for the vehicle driver: 1) the vehicle speed is not controllable and 2) slow acceleration to steady-state speed. This occurs once the PV array (in fixed configuration) is connected to the motor, the steady-state speed is only determined by the motor's speed-torque characteristics and the PV's *I-V* curves [58]. In addition, the inverse proportionality of speed and torque of the DC motor makes it impossible to control properly through a fixed PV array [58]. To address these issues, the PV reconfiguration reported in [50] is to control a vehicle with the aid of the same switch matrix in Fig. 4.

As summarized in Table IV, the 1×4 PV configuration is used to start the vehicle, when the maximum current and torque are needed. After the vehicle starts, the PV array reconfigures as the 2×2 topology to accelerate the vehicle, which requires the medium current and torque. Finally, the 4×1 configuration is used to maintain the full speed of the vehicle at the minimum torque requirement. The proposed PV reconfiguration shortens the vehicle starting time by 37.49%, compared with the conventional fixed PV configuration [50].

C. PV Battery Charger

As in [60] and [61], it is common in PV battery chargers to connect a PV array to a battery directly, if the array has maximum power point voltage (V_{MPP}) close to the battery terminal voltage (V_{LOAD}). However, this implies that only one battery voltage level is suitable for the specific PV charger. In order to charge batteries with different voltage levels, [62] has proposed a battery charger using the following three PV configurations (see Table IV): 1) 1×4 for $2.4V$ battery (two NiMH AA batteries in series); 2) 2×2 for $5V$ USB load; and 3) 4×1 for $12V$ lead-acid battery. The reconfigurable solar array for this particular application was a foldable and flexible amorphous-silicon array used by recreational campers. MOSFETs or relays are used to switch internal sub-array solar PV groups of cells (charging units) that each have V_{MPP} around 2.5V to 2.6V in typical irradiance conditions. Fig. 5 shows that sometimes it is not possible to precisely match V_{MPP} to the desired V_{LOAD}. This power mismatch will cause power loss and it depends on the sharpness of concavity of the *P-V* curve. For example, the 4×1 configuration has lower sensitivity to voltage mismatch compared to 1×4, since its $\partial P/\partial V$ near V_{MPP} is relatively small. For the three battery voltages designed for charging, the solid curve represents the operational curve of the reconfigurable PV array for different load voltage. As illustrated in Fig. 5: Theoretically, the charging efficiency from the MPP could reach, according to the *P-V* curves up to $\sim 92\%$ when charging 2 AA series NiMH batteries ($\sim 2.4V$), $\sim 95\%$ when charging USB ($5V$) and at least $\sim 80\%$ when charging lead-acid $12V$ batteries.

Fig. 6 shows a proof-of-concept prototype of the proposed reconfigurable PV charger [62]. The microprocessor controlled PV charger will detect the battery existence by its terminal voltage (or simply activated by end users), then the PV array will change to the optimal configuration.

- The 1×4 PV configuration yields the maximum charging current for 2 AA NiMH batteries (in series). Usually it is desirable to have V_{MPP} closer to V_{LOAD} between $2.5V$ and $2.8V$. After the battery reaches full state of charge (SOC), the PV can reconfigure from 1×4 (point $A1$ in Fig. 5) to 4×1 (points $A2$ in Fig. 5). As a result, the charging current I_{PV} would decrease 2 to 4 times (approximately) and the trickle charging is achieved.
- The 2×2 configuration is optimal for $5V$ USB load. The full-SOC detection relies on the USB load itself, since it usually has an integrated charging controller. The 2×2 configuration may have V_{MPP} around $5.2V$, but USB chargers require $5.0 \pm 5\%V$. To tightly regulate to $5V$, additional zener diode or linear regulator must be added at the USB terminal in the charger. The prototype uses a low-dropout regulator (LDO) to clamp the voltage to $5V$ for the USB device.
- To charge a $12V$ battery, the PV panel will reconfigure to 4×1 topology, and operate at point $C1$ in Fig. 5. As V_{LOAD} approaches the full-SOC voltage at point $C2$, I_{PV} decreases

gradually. This feature shows the PV charger's potential ability to self-regulate I_{PV}.

Two examples of the patent literature concerning the matching between PV sources and batteries are [63] and [64]. In the former, a set of electric-mechanic switches and diode, suitable to prevent DC arcs during the commutations, regulates the output voltage by means of series-parallel connections of the PV elements. Patent [64] makes the first claim of possibility to use the reconfiguration for mitigating the mismatch effect: The approach is used in a battery charger for cameras.

D. Discussion

Compared to the method of using DC/DC converter(s) between PV and load, the DCL PV reconfigurable approach has comparable system efficiency and may have smaller size. Although the previously discussed DCL applications lack of MPPT functions, which are commonly found in DC/DC converters, the reconfigurable PV array improves the PV-load matching under a few pre-programmed circumstances, demonstrating wide range of operating points at high efficiency (at least 80% in Fig. 5). More importantly, the DCL approach avoids power loss at conversion units, and saves the footprint of passive filtering components (e.g. inductors and capacitors) and batteries. For DCL applications, such as PV-powered vehicle and battery charger, the reconfigurable matrix can be further simplified to become a few manual switches (even properly sized rotary or DIP switches). This may lead to smaller size and may improve the system reliability.

E. Smart PV modules

Patents [52]–[54] integrate a monitoring capability in the reconfiguration system that detects degraded problems and/or the fault conditions. This innovation allows the reconfiguration mechanism to change the interconnection paths by disconnecting the failed PV cells. In [52] the reconfiguration approach is applied at the PV cell level. Each solar cell is part of a reconfigurable matrix to form a PV module. A plurality of modules is assembled to form the PV panel; at least an integrated circuit is devoted to monitoring, controlling, and protecting the solar cells, as well as to reconfigure the cells after the panel is assembled and installed. This type of PV panel is also known as *Solar Module Array Reconfigurable Tile (SMART)* module. The patent application [53] refers to PV reconfiguration at cell level too, but it is mainly devoted to explaining how to integrate the solid state switches and sensors in a back sheet of the reconfigurable PV panel.

The patent [54] proposes the use of "detection cells" inside the PV panels for ascertaining the presence of partial shading, if a predetermined threshold value is violated then a single switch disconnects the whole PV panel from the string.

Patent [65] describes a flexible mechanical support with some conducting strips suitable for connecting the PV cells in a module for obtaining a plurality of outputs. The desired output can be selected by the final user by burning or by activating some electrical contacts in order to obtain the desired series/parallel configuration; it is evident that in this case the reconfiguration can be performed only once. This solution allows manufacturers to produce a single product for multiple customer demands and reduces the complexity of installing the modules in locations where constraints related to the placement of the modules require a non-trivial electrical connection. Moreover, when encountering performance degradation due to shading, aging, or hotspots phenomena, the electrical connection can be manually modified by selecting a configuration that is less sensitive to the mismatch.

IV. Conclusions and emerging technologies

In this paper, the main aspects concerning the reconfiguration techniques for PV arrays have been overviewed. The differences with respect to the distributed MPPT approach in reducing the effects of mismatching have been discussed. This has been the first and main objective of the reconfiguration techniques afforded in the paper and patent literature. Three fundamental architectures for reconfiguration were identified: RST, RSP and RTCT. The former one is useful for improving the performance of single-strings inverters at the cost of wasting the power of some mismatched modules. Both RSP and RTCT arrays are useful to improve any PV array without forcing the disconnection of some modules. Instead, reconfigurable strings require few switching elements to implement the reconfiguration matrix, while both RSP and RTCT arrays require more elements, or at least they are more complex. In particular, the number of combinations, thus the number of switches, required by the RSP architecture increases significantly with the number of modules in series. Instead, the RTCT architecture is more sensible to the increment of the number of modules in parallel. Hence, for high-voltage applications, RSP solutions require smaller switching matrices in comparison with RTCT solutions, with a smaller number of possible configurations, a simplified control algorithm but with a reduced flexibility. The inverse relation is found for high-current/low-voltage applications. Some papers propose hybrid structures, which are combinations of RST, RSP and/or RTCT architectures. Those applications commonly require a high number of sensors in order to group PV elements subjected to similar irradiance levels, or to isolate those working in mismatched conditions.

Concerning the algorithms controlling the reconfiguration architecture, six basic solutions were identified: PRA, ERA, SRA, DRA, COA and CIA. The PRA option is the simplest and fastest: it is useful for applications with pre-defined configurations. The most reliable option is the ERA, which ensures to find the best configuration, but at the cost of a high number of evaluations. This might be impractical for large PV arrays. Instead, the SRA option does not evaluate all the possible reconfiguration modes, so it is faster. However, SRA does not guarantee to reach the optimal configuration. Similarly the drawback of the CIA approach is that it may also reconfigure to the suboptimal power condition, although the power still increases. However, both SRA and CIA are the viable candidates for large arrays because of reduced reconfiguration evaluations compared to ERA and PRA. COA is a new approach, which assumes that classical optimization theory ensures the tracking of the best configuration. Unfortunately, since complex optimization routines must be adopted, COA solutions may have either low or high complex level of switches, depending on the particular algorithm. DRA is another new approach, which is designed to act on RST architectures only. Moreover, DRA solutions require distributed hardware formed by both control units and switches, which significantly increases the amount of hardware required, but at the same time, it improves classical RST solutions by avoiding the disconnection of shaded modules for long periods of time.

It is also important to remark the lack of comparative studies between reconfiguration solutions and other PV systems optimization techniques, such as DMPPT, differential power processing, among others. Such studies must be developed to ensure that a reconfiguration system is the best option for a given application.

On the other hand, some studies concerning the optimal matching between the PV generator and the load by means of a suitable reconfiguration of the units composing the PV source have also been analyzed. The discussion has focused on the slow-frequency switching PV array that reconfigures only in response to slow varying environmental impacts, such as partial shadings over a PV array, or infrequent changing of DC-load requirements. The periodic switching technique of a switching matrix, involving both DC/AC and DC/DC converters, have also been proposed in some recent literature. The switching frequency of the reconfigurable matrix is the fundamental frequency (50Hz or 60 Hz) in [66] and [67] or the high-switching frequency (e.g. at least several kHz) in [68]–[71]. To address partial shading problems, the multi-level inverter proposed in [68]–[70] controls individual PV-module to work at its own MPP voltage by switching PV units in and out of series connections. Another type of three-phase multi-level inverter connecting each PV module with a particular phase during a specific switching interval is proposed in [67]. This approach not only has the advantages of multi-level inverters but also inherits the flexibility and redundancy from the previously discussed PV reconfigurations for mismatch compensations. To further explore a possibility to merge the reconfiguration concept with power converters, a reconfigurable DC/DC converter reconnecting the PV modules from series to parallel at high frequency is introduced in [71].

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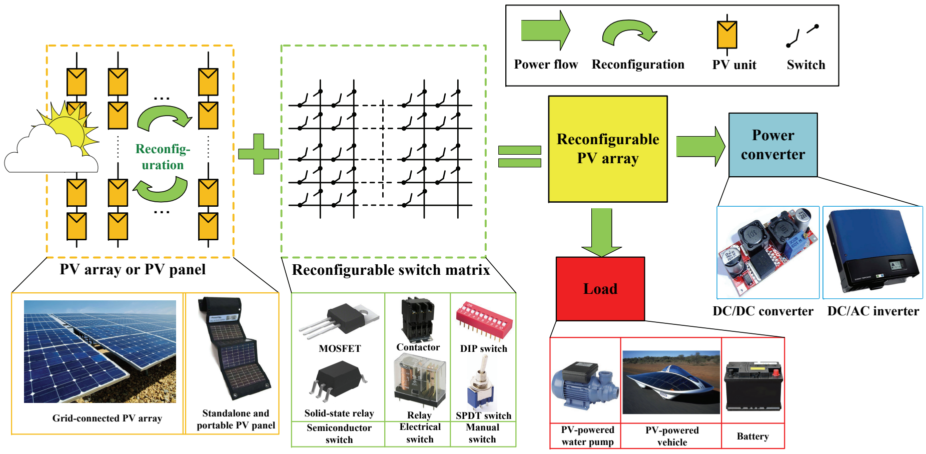


Fig. 1. Schematic diagram and photos of main components in the PV reconfiguration.

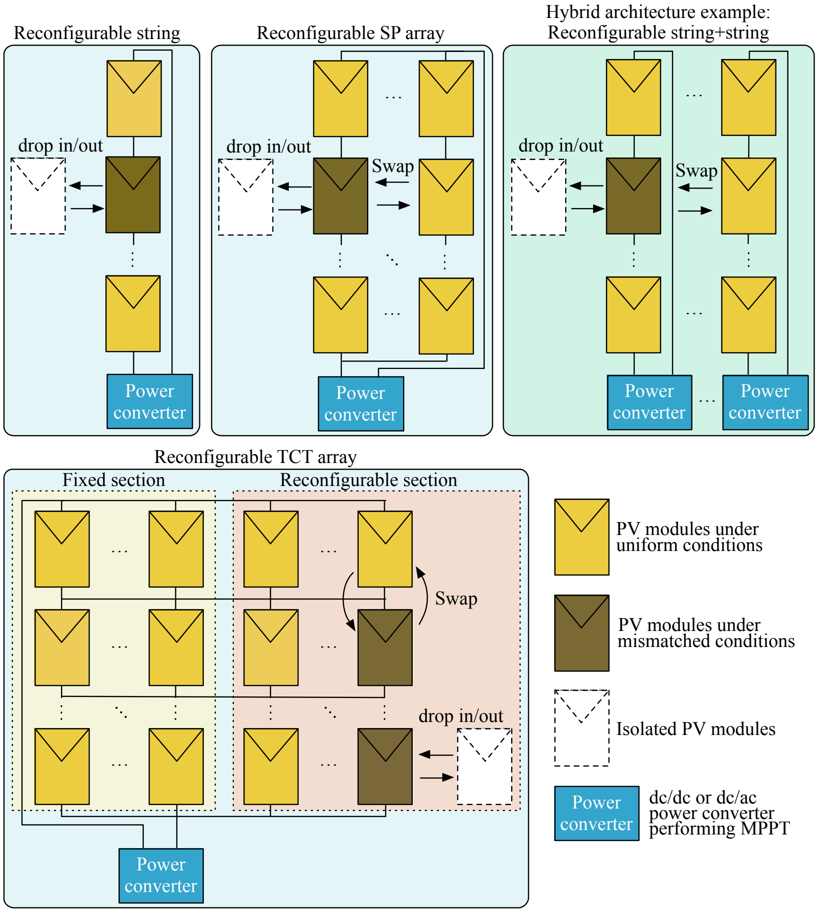


Fig. 2. Architectures for reconfiguration of PV arrays.

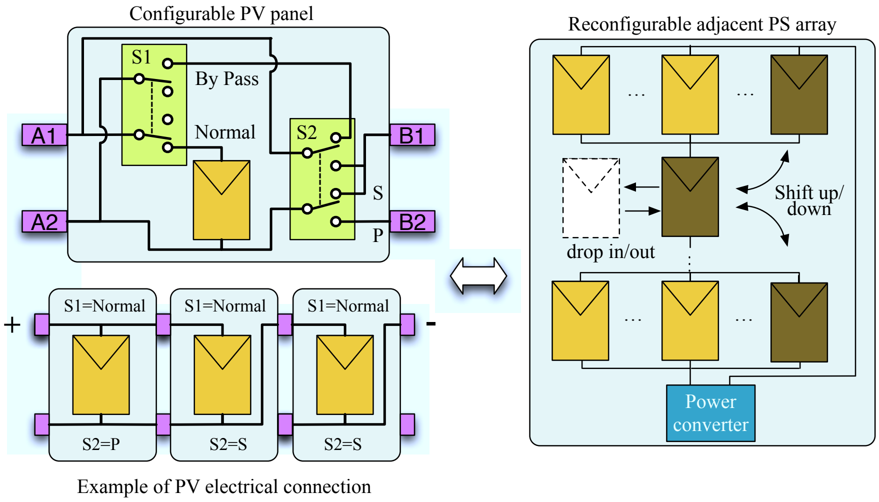


Fig. 3. Electrical connections for adjacent SP array configuration.

TABLE I
RECONFIGURATION ALGORITHM CATEGORIES.

Category	**Analog or digital**	**Convergence speed**	**Algorithm and implementation complexities**	**Performance in tracking the best solution**
PRA	Both	Fast	Low	Low
ERA	Digital	Slow	Medium	High
SRA	Digital	Medium	Medium	Medium
DRA	Analog	Fast	High	Medium
COA	Digital	Medium/Slow	High	High
CIA	Digital	Medium/Slow	Medium	Medium

TABLE II
FEATURES OF THE APPLICATIONS REPORTED IN SCIENTIFIC PAPERS.

Application	**Power Level**	**Architecture/ Level**	**Algorithm**	**Number Sensors /Complexity**	**Number Switches /Complexity**	**Advantage**	**Disadvantage**
Building Integrated [29]	3/90kW	RSP/Module	ERA	High/High	Not-Specified (NS)	Dynamic switching time	Require models
Water Pump [34] [59]	1.44kW	RSP/Module	PRA	Medium/High	High/Low	Simple implementation	Constrained solution
[35]	600W	RSP/Module	PRA/ERA	High/High	Medium/High	Manual/Automatic	Constrained solution
PV-Powered Vehicle [50]	126W	RSP/Module	CIA	NS/NS	NS/NS	Matched Torque/Speed	Constrained solution
Battery Charger [62]	4W	RSP/ Module-Cell	PRA	Low/Low	High/Low	Simple hardware, dedicated	Constrained solution
Portable Systems [33]	1.35mW	RST/Cell	DRA	High/Medium	Medium/Low	Avoid bypassed cells	Many circuits and components
Grid Connected [31]	1.65kW	RTCT/panel	ERA	Low/Medium	Low/High	Reduced searching space	Require models
Urban [47]	1320W	RST Hybrid/Module	ERA	Low/Medium	High/Low	Clustered modules	Extra hardware
Not-specified							
[28]	4kW	RSP/Panel	ERA/CIA	High/Medium	NS	Meet inverter voltage	Heuristic step
[30]	NS	RTCT/Cell	SRA	Low/Low	Medium/Low	Reduced search	Require models
[32]	517W	RSP/Module	ERA	Low/Medium	Medium/Low	Sensor per string	Require models
[41]	1280W	RTCT/Module	SRA	Low/Medium	High/Low	Reduced search	Extra hardware
[42]	2000W	RTCT/Module	COA	High/Medium	NS	Reduced search	Require models
[46]	9W	RST/RSP/Module	SRA	High/Medium	Medium/Low	Simple algorithm	Isolate shaded modules
[51]	NS	RTCT/Cell	CIA	High/Medium	NS	Reduced search	Require models
[55]	100W	RSP/Module	SRA	High/High	Medium/Low	Matched load voltage	Constrained solution

TABLE III
FEATURES OF THE APPLICATIONS REPORTED IN PATENTS.

Application	**Power Level**	**Architecture/ Level**	**Algorithm**	**Number Sensors /Complexity**	**Number Switches /Complexity**	**Advantage**	**Disadvantage**
Energy Spacecraft							
[36]	NS	RSP/Module	PRA	Medium/High	Medium/Low	Simple algorithm	Constrained solution
[37]	NS	RSP/Panel	PRA	NS	NS	Simple algorithm	Constrained solution
Load Matching							
[56]	NS	RSP/Cell	SRA	Medium/Low	NS/Low	Fractional Algorithm	Constrained solution
Battery Charger							
[63]	NS	RSP/Cell	PRA	NS/NS	NS/NS	Simple algorithm	Constrained solution
[64]	NS	RSP/Cell	PRA	NS/NS	NS/NS	Analog implementation	Constrained solution
Smart PV Modules							
[52]	NS	RSP/Cell	DRA/SRA	Medium/Low	NS/Low	Detect faults	Many elements
[53]	NS	RST/Cell	DRA/SRA	High/Medium	NS/Low	Integrated functions	Many elements
[54]	NS	RST/Cell	DRA/SRA	Medium/High	NS/Low	Not local measure	Less elements
[65]	NS	RSP Hybrid/Cell	DRA/PRA	NS/NS	NS/Low	Integrated functions	Many elements
Not-specified							
[43]	2000W	RTCT/Module	COA/SRA	High/Medium	High/NS	Reduced search	Require models
[39]	NS	RSP/Module	PRA	High/Medium	High/Low	Meet inverter voltage	Constrained solution
[44]	NS	RSP/RTCT/Module	PRA	High/Medium	Medium/Medium	Meet inverter voltage	Constrained solution
[45]	NS	RSP/Module	PRA	Medium/Medium	NS/NS	Simple algorithm	Constrained solution
[49]	NS	RSP Hybrid/Module	PRA	NS/NS	NS/NS	Integrated solution	Switch for converters

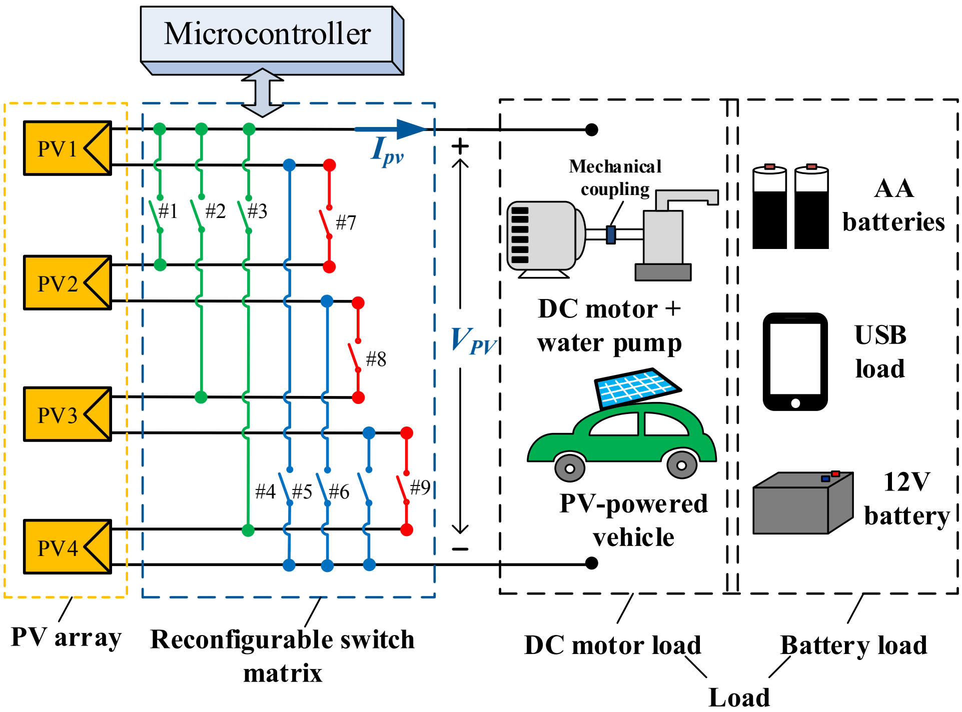


Fig. 4. Schematic diagram of the PV reconfiguration for DCL (demonstration purposes only).

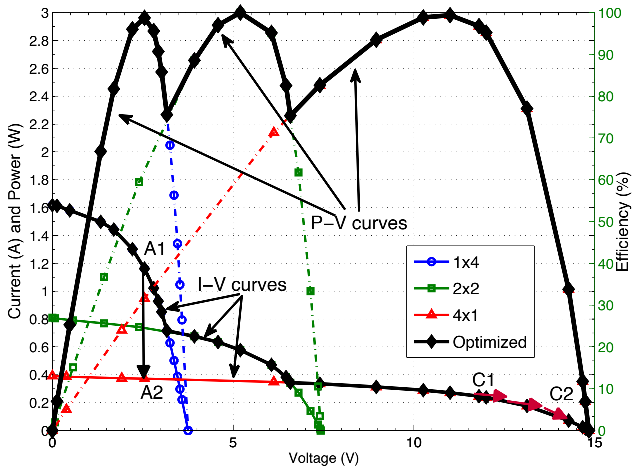


Fig. 5. Experimental results: Current, power, and efficiency vs. voltage curves of the reconfigurable PV array. Black curve represents the optimized *P-V* and *I-V* operation of the panel: it switches from 1×4 to 2×2 to 4×1 configurations as load voltage increases.

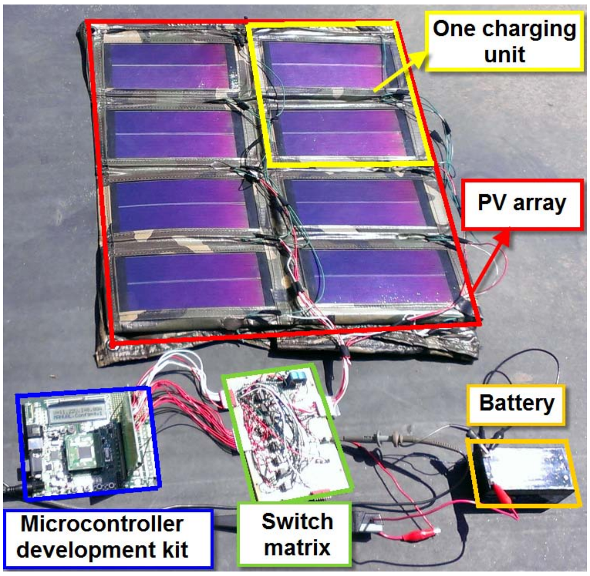
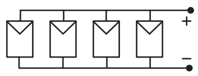
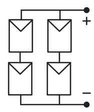
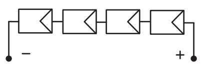


Fig. 6. Experimental prototype of the reconfigurable PV charger for proof of concept.

TABLE IV
SUMMARY OF PV RECONFIGURATIONS FOR DIRECT-COUPLED LOAD (DCL).

DC Loads		**PV-powered water pump [34]**	**PV-powered vehicle [50]**	**PV Battery charger [62]**
Control method	ON switches	Irradiance dependent	Speed dependent	Load-voltage dependent
1x4 (parallel) 	Switches #1 to #6	Low irradiance	To start the vehicle	$2.4V$ battery
2x2 (series-parallel) 	Switches #2, #5, #7 and #9	Medium irradiance	In acceleration	$5V$ USB load
4x1 (series) 	Switches #7 to #9	High irradiance	At full speed	$12V$ battery
PV array (at STC) and switch ratings		PV array 1.44kW (estimated), switch rating is N/A	PV array 126W (estimated), switch rating is N/A	PV array 4W, switches use solid-state relays (ASSR-1611) with ratings 60Vdc, 2.5Adc