A Rapid Feasibility Checking for Reconfiguration of Mismatched PV Arrays

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***Abstract*—Power generation efficiency of photovoltaic (PV) arrays is significantly affected by partial shading and PV cell damage. Partial shading or PV cell damage induces mismatched power generation among PV panels and causes an efficiency loss of power generation. Power generation of mismatched PV arrays can be recovered by reconfiguring connection of PV panels. In this paper, we introduce a *feasibility check problem* of PV panel configuration. The problem identifies whether a connection among PV panels can be configured from a given PV module level solution. We also propose an algorithm for the feasibility check problem. The experimental results demonstrate that the proposed method can identify feasible configurations more than 32,000X faster than the exhaustive search with around 0.6% errors.**

I. Introduction

As fossil fuel depletion and environmental pollution become more serious, green and renewable energy has become necessary for a sustainable society and environment and photovoltaic (PV) systems receive significant attentions. However, due to the nature of a PV cell, which is a basic component of a PV array, PV arrays are sensitive to partial shading and PV cell damage. PV cells could not uniformly generate power when PV cells experience a mismatching where cells have different irradiances or some of cells have physical defects, and it causes a significant loss of power generation.

There are two types of PV arrays, *series-parallel* arrays and *total-cross-tied* arrays, and this paper considers series-parallel PV arrays (PV array hererafter). Figure 1 shows an example of a PV array. A PV array is a parallel connection of (PV) strings where a string is a series connection of PV panels. A PV panel is a series connection of PV modules, and a PV module is a parallel connection of a series of PV cells and a bypass diode. A typical PV panel is composed of three PV modules each of which has 12 - 36 PV cells.

When PV arrays are mismatched, power could not be effectively generated, and such a loss of power generation can be recovered by reconfiguring connection among PV panels. Figure 2 shows an example of power generations of a PV array with a partial shading before and after reconfiguration. We distributed shading cells non-uniformly to a PV array with 3 $\times$ 4 PV panels (3 strings with 4 PV panels) and applied power simulation. After reconfiguring PV panel connection, the PV array generates more power than before reconfiguration.

Though several reconfiguration methods have been proposed, most works consider reconfiguration in PV cell or PV module level [1], [2]. However, from a practical view, reconfiguration of connection among PV panels is a realistic

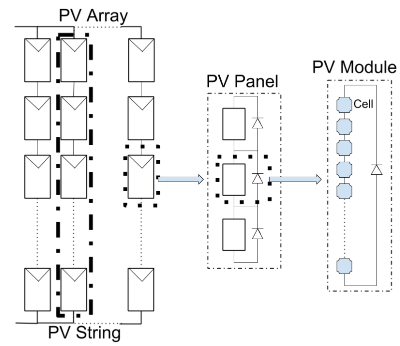


Fig. 1: PV array, string, module and panel

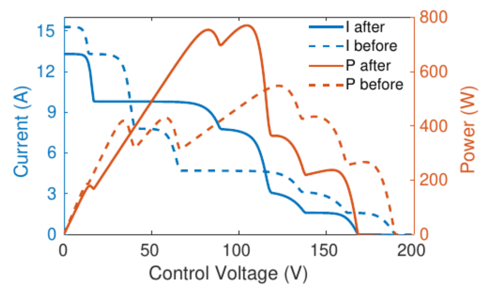
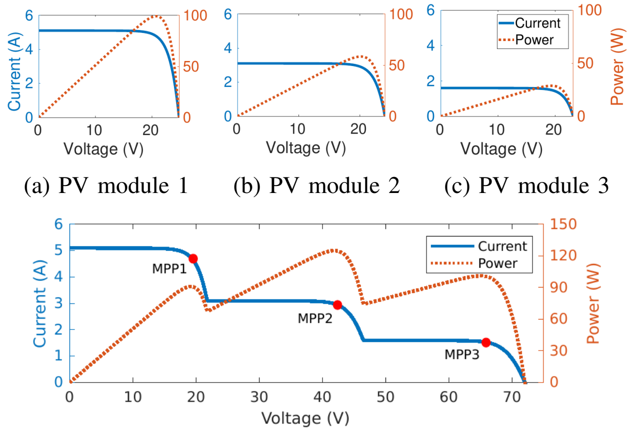


Fig. 2: Power generation before and after reconfiguration

solution since a PV panel is manufactured as a physical one panel with two terminals and PV panels can be flexibly interconnected. However, since one PV panel is composed of several PV modules, a reconfiguration problem for PV panels has a constraint that a series connection of PV modules in the same PV panel have to be kept, and this constraint makes the PV panel level reconfiguration complicated.

Reconfiguration at PV panel level has been investigated [3]–[5]. Some methods are based on genetic algorithm (GA) [3] or a nonlinear integer programming [4]. Orozco-Gutierrez et al. proposed a reconfiguration method [5] where they first consider PV module level balancing with approximated values and select feasible PV panel connections as candidates for further analysis. Though they showed a simple necessary condition to check feasibility, the condition is not sufficient and it is not clear how the method accurately identify the feasibility of PV panel connections.

In this paper, we introduce a *feasibility check problem* that identifies whether a PV panel connection can be configured



(a) PV module 1 (b) PV module 2 (c) PV module 3

(d) PV panel

Fig. 3: I-V characteristics

from a given PV module level specification, and propose an algorithm to solve the problem. The proposed algorithm efficiently and effectively checks the feasibility by configuring PV panel connections. The proposed method is useful to identify the feasibility required in [5] and also configure PV panel connections from solutions at PV module level.

II. Feasibility Check Problem

A PV module can generate power for a given voltage according to its I-V characteristics. The I-V characteristics is affected by an irradiance level and physical damage of a PV cell. Figure 3(a-c) show typical degradations of I-V characteristics where irradiance levels decrease in the order of Fig. 3(a), (b), and (c).

When a PV panel has a partial shading, the PV panels might have multiple peaks (maximum power points, MPPs) in power generation as shown in Fig. 3(d). The I-V characteristics of a series connection of PV modules like a PV panel or a string can be roughly understood as follows. In Fig. 3, one PV panel has three PV modules with different I-V characteristics with MPPs at current and voltage pairs of around (4.5A, 22V), (3A, 22V), and (1.5A, 22A), respectively as shown in Fig. 3(a-c). The PV panel has three MPPs at around (4.5A, 22V), (3A, 44V), and (1.5A, 66A) as shown in Fig. 3(d). When a control voltage is 22V, a PV module with the highest maximum current (module 1) is active while other PV modules (modules 2 and 3) are inactive with turning on their bypass diodes. When a control voltage is 44V, PV modules 1 and 2 are active with current level 3A. That is if a PV module can be active with current level IA, the PV module also can be active with current level IA or less.

We introduce a *feasibility problem* for a requirement of currents of strings. In a PV array, current levels of active PV modules should be the same for each string and voltage levels of strings should be the same. The latter implies that the number of active modules should be the same for all the strings. When information of MPPs of PV panels is given like Table I, we consider if it is feasible to configure a PV array

TABLE I: MPP information

		Panels			
		$P1$	$P2$	$P3$	$P4$
MPP1		3A	3A	0.5A	2.5A
MPP2		3A	2.5A	0.5A	1.5A
MPP3		1.5A	2.5A	0.5A	0.5A
Max Number of Active Modules	3A	2	1	0	0
	2.5A	2	3	0	1
	1.5A	3	3	0	2
	0.5A	3	3	3	3

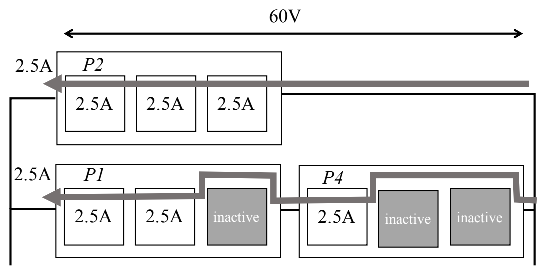


Fig. 4: Feasible configuration

with current levels of $Q = (Q_1, Q_2, \ldots, Q_s)$ for s strings with m active modules per string. Table I also shows the maximum number of active modules for each required current level and PV panel (this information is obtained from MPP information). For example, for a current requirement (2.5A, 2.5A) with 3 active modules is realized by assigning panel $P2$ to the first string and panels $P1$ and $P4$ to the second string as shown in Fig. 4. However, we could not find a feasible assignment for a current pair (3A, 2.5A) with 3 active modules.

For a PV array A with s strings, let $M_{A,i}(I)$ denote the number of modules that can be active with a current level I in the i-th string. Let $Q = (Q_1, Q_2, \ldots, Q_s)$ be a sequence of currents required for strings.

Definition 1 (Feasibility):
A sequence of currents Q is feasible with m modules if and only if it is possible to configure a PV array A such that

$$M_{A,i}(Q_i) \geq m \tag{1}$$

holds for each string $i (1 \leq i \leq s)$.

Definition 2 (Feasibility Check Problem):
Input: information of MPPs, a current sequence Q, and the number m of active modules per string.
Output: Whether Q with m modules is feasible or not.

III. Algorithm

A. Outline

In the proposed algorithm, we try to configure a PV array and identify the feasibility. For a given current sequence $Q = (Q_1, Q_2, \ldots, Q_s)(Q_i \geq Q_j$ if $i \leq j)$, we will assign PV panels to strings in the order of $Q_1, Q_2, \ldots, Q_s$. When selecting a PV panel to a string, we will consider how much we lose an opportunity that the panel is more effectively used for other current levels. For example, if we select a panel $P1$ in Table I for a string with current level 3A, two modules can

TABLE II: An example of the proposed method ($m = 5$)

	Panels							
	$P1$	$P2$	$P3$	$P4$	$P5$	$P6$	$P7$	$P8$
$M_p(Q_1)$	1	1	1	1	2	2	1	2
$M_p(Q_2)$	1	2	2	2	3	3	1	2
$M_p(Q_3)$	1	2	2	2	3	3	2	3
$Loss(p, 2)$	0	1	1	1	1	1	1	1
$Loss(p, 3)$	0	0	0	0	0	0	1	1
step 2	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$			
step 3	$\surd$	$\surd$	$\surd$		$\surd$			
step 4	$\surd$				$\surd$	$\surd$		

TABLE III: Swap rule

The numbers of active modules	
selected panels	unselected panels
1, 1, 1	3
1, 1	2
1, 2	3

be active while the remaining one module becomes inactive. The remaining one module still is not active if $P1$ is used for current level 2.5A, while it can be active if it is used for current level 1.5A or 0.5A.

Let $M_p(I)$ denote the number of modules that can be active at current level I in a PV panel p. For a given current sequence $Q = (Q_1, Q_2, \ldots, Q_s)(Q_i \geq Q_j$ if $i \leq j)$, a loss of selecting a panel p at the $(k-1)$-th string for the k-th string is defined as $Loss(p, k) = M_p(Q_k) - M_p(Q_{k-1})$.

To assign panels for the n-th string, the following steps are applied. Let m be the required number of active modules.

1) Sort unselected PV panels in a lexicographically ascending order of $Loss(p, n+1)$, $Loss(p, n+2)$,. . ., $Loss(p, s)$ and $M_p(Q_n)$.
2) Select PV panels until selecting m or more active modules for current level Q_n in the sorted order.
3) Cancel redundant PV panels so that the number of active modules at current level Q_n is minimized.
4) Swap selected PV panels with unselected PV panels so that the number of selected PV panels is minimized.

Table II shows an example of how to select (at least) 5 PV modules for the first string. Panels are sorted by $Loss$ and $M_p(Q_1)$ and a sequence $P1$, $P2$, . . ., $P8$ is obtained. First, panels are selected in this order. After selecting until $P5$, the number of active modules exceed $m(= 5)$. Then, some redundant panels ($P4$ in this case) are canceled. Finally, some of selected PV panels are swapped with unselected panels according to a swap rule in Table III. In the example, $P2$ and $P3$ are swapped with $P6$. Consequently, three panels $P1$, $P5$ and $P6$ are selected.

B. Evaluation

We evaluated the proposed algorithm for 100 randomly generated PV arrays. These PV arrays have 3 - 8 strings and 3 - 6 PV panels in each string. We applied the method [5] to select candidate configurations and identify their feasibility. We also apply an exhaustive search algorithm for comparison.

Table IV shows the results for the proposed algorithm and the exhaustive search. From 100 PV arrays, 486 configuration candidates are selected where each candidate is specified with a required current sequence for strings and the number of active modules per string. Since the exhaustive search checks all the combinations of panel connections for each configuration candidate, it accurately identify the feasibility but takes a lot of time. On the other hand, the proposed algorithm rapidly (more than 32,000X faster) checks feasibility while misidentifying only 3 feasible cases. Each PV array has 4 or 5 candidates and our algorithm indeed found PV panel connection for each PV array.

TABLE IV: Experimental Results

	Proposed Algorithm	Exhaustive Search
Number of PV Array	100	
Number of MPP candidates	486	
Feasible Candidates	324	327
Infeasible Candidates	162	159
Error Rate	0.62%	0%
Ave. times per Array	0.003s	98s

IV. CONCLUSIONS

Power generation of mismatched PV arrays can be recovered by reconfiguring connection of PV panels. In this paper, we introduce a feasibility check problem to configure PV panel connections from PV module connections and proposed an algorithm that efficiently and effectively solve the problem. The experimental results shows that the proposed algorithm can identify feasible configurations more than 32,000X faster than the exhaustive search with around 0.6% errors. The proposed method is useful to identify or configure actual PV panel connections from PV module level specifications or connections. Since there are many works of PV module level reconfiguration and PV panel level reconfiguration using PV module level optimization as an intermediate solution, the proposed algorithm is useful to actually find PV panel connections from PV module level solutions. PV panel level reconfiguration is a practical and realistic solution for PV arrays composed of standard PV panels, and the proposed method contributes to find efficient and effective solution for PV panel level reconfiguration.

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