Photovoltaic System Reconfiguration Strategy For Mismatch Condition

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***Abstract*—Power generation efficiency of photovoltaic(PV) system is reduced significantly under partial shading or solar cell damage conditions. This efficiency losses affected by turning on bypass diode of PV panels, which called mismatch losses. Reconfiguration technology to reconfigure electrical series or parallel connection among PV panels can maximize power generation. Recently, an efficient reconfiguration method of PV panel connection to optimize power generation is proposed. The method first list candidate configurations and applies precise power simulations to the candidates. However, some of candidates might not be realized by given PV panels and the paper does not show any systematic way to identify such a feasibility. In this paper, we propose a very fast algorithm to check the feasibility with high accuracy.**

***Index Terms*—Photovoltaic system, mismathed power loss, reconfiguration, dynamical reconfiguration.**

I. Introduction

As constant fossil energy generation is increasing the crisis of fossil fuel depletion and serious pollution problems for the environment, research and utilization on a green and renewable energy have become necessary for sustainable society and environment. Photovoltaic (PV) energy has received a significant attention since it is unlimited and easy to be scaled up. Thanks to extensive technology and research on photovoltaic energy generation, large scale photovoltaic energy generation systems have been deployed into many practical applications. However, PV arrays are sensitive to shading and PV cell's fault or aging. This means that when PV cells or modules do not uniformly generate power or experience different irradiance conditions from one another, the PV array is in mismatch condition and could not efficiently generate power. In addition, the photovoltaic arrays under mismatched conditions will accelerate the aging and heating of PV cells and cause a short circuit of photovoltaic cells to further damage the PV array. In order to maximize power generation and also avoid damaging PV cells, we propose an algorithm that can reconfigure photovoltaic arrays.

In this paper, we use non-uniform irradiance levels to represent mismatch condition and analyze the efficiency of a PV system. Photovoltaic arrays operating in mismatch conditions could not efficiently generate power, and reconfiguration of panel connection has been widely investigated to solve this problem [2].

Some of works proposed optimized or efficient algorithms to reconfigure the connection of PV cells [3] [4]. However, these works assume a full reconfiguration ability among PV cells. In general, a PV array is a connection of multiple PV panels, each PV panel has multiple PV modules, and each PV module consists of multiple PV cells. One typical PV panel has 3 PV modules with 24 PV cells. To realize reconfiguration in PV cell level, a new PV panel architecture is required.

Recently, as practical solutions, reconfiguration in PV panels have been investigated [5] [8]. One PV panel typically has two (plus and minus) terminals, and a PV array is configured by connecting PV panels in series and/or parallel. Such a configuration is also realized using a switch among PV panels, and reconfigurations in PV panel level can be regarded as practical solutions. However, the reconfiguration in PV panel level is more difficult than that in PV cell level. PV modules in the same PV panel can be individually bypassed by bypass diodes when some mismatch condition occurs, and it causes multiple maximal power points (MPPs) for one PV panel.

A PV panel level reconfiguration using genetic algorithm is proposed in [5]. Though this can generate a new configuration, computing cost is too significant and the algorithm cannot generate the best configuration precisely. A fast reconfiguration strategy for minimizing power losses is presented in [8]. In this strategy, candidates for PV array configurations are first listed by some fast estimation method, and, for each candidates, precise power simulations are applied. However, some candidate configurations might not be feasible, that is, it is impossible to realize a designated PV array configuration with given PV panels, and there is no description of a systematic way to identify the feasibility.

In this paper, we propose an algorithm to identify feasibility for a given configuration with less computational time and high accuracy.

II. Photovoltaic Array

In this paper, we use the following model of PV arrays, modules, strings and panels as showed in Fig. 1. A PV array is formed by several parallel connected (PV) strings, and a string is formed by several series-connected PV panels. A PV panel is formed by three PV modules. And each bypass diode is connected in parallel with a module. Fig.2a shows I-V curves for PV panels. PV panel generates a currents according to a provided control voltage within some range. PV cells in a PV panel may have different conditions (irradiance or fault) and hence have different upper limits for their generated currents. Therefore, for lower control voltage, only PV cells that can generate higher currents can work and the other PV cells do not generate current with their bypass diodes switching on. As a result, PV panel might have multiple maximal power points (MPPs, points where power curve has extreme values). Fig.2b and 2c show I-V curves for series and parallel connections of two PV panels. The series connection accepts wider range of control voltage, and the parallel connection can generate higher current.

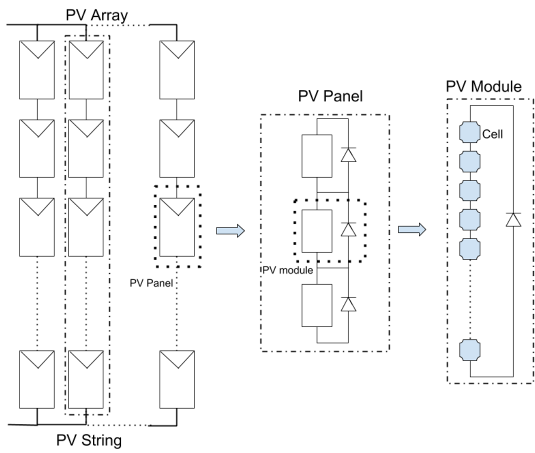

Fig. 1: PV arrays, strings, and panels.

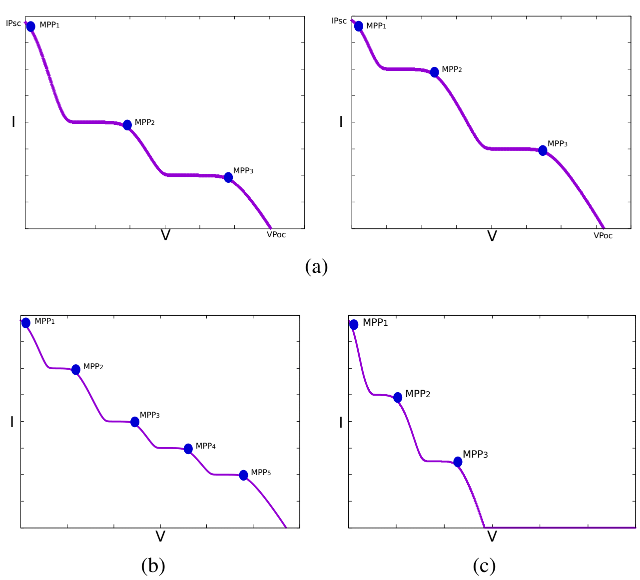

Fig. 2: I-V curves, (a) 2 panels, (b) strings (series connection of PV panels), and (c) parallel connection of PV panels

When understanding complete I-V characteristics of some parallel and/or series connection of PV panels, we may need I-V characteristics of the PV panels. However, to find out the (near) maximum generated power, it is enough to considers some restricted information including maximal power points (MPPs). The algorithm in [6] analyzes the current versus voltage (I-V) curves of panels and finds MPPs, short circuit current, open circuit voltage of each panel in mismatched conditions. These values form a fingerprint of the connection.

III. Related Works

Carotenuto et al. proposed a online recording method of PV module fingerprint [6]. In their method, a fingerprint including the current and voltage at open- and short-circuit points and multiple MPPs are obtained from several samples from a monitored PV panel. Orozco-Gutierrez et al. proposed a method to estimate multiple MPPs of a PV array from fingerprints of PV panels in the PV array [7].

Orozco-Gutierrez et al. further proposed a Fast reconfiguration algorithm to optimize power generation by reconfiguring the connection of PV panels [8], where the online monitoring [6] and the power estimation [7] are utilized. In the method in [8], first, close values of fingerprints from monitoring of PV panels are grouped with some representative values, and then possible combinations of reconfiguration are enumerated. Their power values are estimated by [7] along with careful estimation of possible errors. The method presented a simple feasibility check and obtains estimated power values for all the possible connections for representative values with some error rate *err*, and then select configurations within *err* difference from the largest estimated value as candidates of the optical configurations.

The method [8] needs to check feasibility since their method designate a configuration with number of strings, the number of active modules for one string and current value of each string where the active module means a module whose bypass diode is not working and the number of active modules of strings are common for all the strings have the common control voltage. For example, if a connection requires two strings with two active modules with 3A and 5A for these strings respectively, we might not find possible combination of PV panels. In [8], a simple feasibility check based on the number of active modules for each representative current values. However, we found out that the feasibility check proposed in [8] is optimistic and does not always identify infeasible cases.

TABLE I: Dataset of Each PV Panel

	P1	P2	P3	P4	P5	P6	P7	P8	P9
0.5A	**	***	***	**	**	***	***	***	***
2A	*	**		**	*	**	**	***	**
3A		**					*		*

IV. Feasibility

As an example, we consider a PV array where nine panels are connected in three strings. We assume that, in this example, this Fast reconfiguration algorithm estimate number of working module on different current candidate for each panel as shown in Table I. The dot in table in form of a PV module. We set N_C as the meaning of not candidate, set infeasible MPPs as zero. Though the procedure in Fast reconfiguration algorithm and simple feasibility check, MPPs are presented in matrix below. [C1, C2, C3, C4] indicate 4 MPP candidates.

To execute a power simulation, we have to assign panels to each string to realize a candidate configuration. However, the way is not given in [8] and some candidate configurations are infeasible. The definition of feasibility in (1). When a configuration needs working modules in a string (M_S) are less than number of working module per-string (Q_{M_n}), then this configuration is infeasible.

$$\begin{cases} M_S < Q_{M_n} & \text{Infeasible} \\ M_S \geqslant Q_{M_n} & \text{Feasible} \end{cases} \tag{1}$$

For an configuration example [C2] {0.5A, 0.5A, 2A}, there are 8 PV modules working on each string. According to Table I, for a string current on 2A at least need 4 panels, remaining panels can not provide enough PV module working on 0.5A for another two strings. Of course we can compute it by using an exhaustive search. However, it is time-consuming. So, we need an algorithm to efficiently identify feasibility of a configuration and realize the configuration if it is feasible.

V. An Algorithm to Identify Feasibility

In this section, we propose an algorithm to identify feasibility.

A. The Input And Output Of Algorithm

The input of our algorithm is information of a PV array and a configuration. The information of a PV array is given as a set of panels and the number of working modules in each panel for each current candidate. Table II shows the information of a PV panel given in Table I.

For example, this table shows panel P2 includes three, two, and two modules that work in current 0.5A, 2A and 3A, respectively. Recall that a configuration is a combination of a current assignment and the number of working modules in each string, and a current assignment specifies a current for each string. The output of our algorithm is feasibility of the given configuration. That is, the algorithm determines whether there exists assignment of panels to strings that realizes the configuration.

TABLE II: Information of a PV array

	P1	P2	P3	P4	P5	P6	P7	P8	P9
0.5A	2	3	3	2	2	3	3	3	3
2A	1	2	0	2	1	2	2	3	2
3A	0	2	0	0	0	0	1	0	1

B. Algorithm

Let s be the number of strings, and i_h ($0 \leq h < s$) be the current assigned to the h-th string. Without loss of generality, we assume $i_0 \leq i_1 \leq \cdots \leq i_{s-1}$ holds. In our algorithm, we first determine the assignment of panels for the $(s-1)$-th string (i.e., the string with the highest current), and then determine assignments for $(s-2)$-th string, $(s-3)$-th string, and so on.

To assign panels in the right string, following steps are required:

(1) Select panels in Panel Selection Order Table. The detail explanation are described next pargraph.
(2) If the element in Table is 0, release corresponding panel, $m_p(i)$ = 0.
(3) Replace selected panels if summations of selected panels' contain modules are equal to unselect panel. The replacement will following servious priorities.
(4) If replacement approved, step 3 will be repeated till summations of selected panel contain modules are large or equal to Q_{M_n}.
(5) Otherwise, none of the replacement will be approved. Evaluate selected panels with feasibility requirement in IV equation (1).
(6) If there remain any unselect panel, assign unselect panel to a string with minimum length.

$\frac{Current\rightarrow}{Number\ of\ modules\downarrow}$	{0.5,0.5,0.5}	{0.5,0.5,2}	{0.5,0.5,3}	{0.5,2,2}	{0.5,2,3}	{0.5,3,3}	{2,2,2}	{2,2,3}	{2,3,3}	{3,3,3}
≥ 1	N_C	N_C	N_C	N_C	N_C	N_C	N_C	N_C	N_C	N_C
≥ 2	N_C	N_C	N_C	N_C	N_C	N_C	N_C	N_C	N_C	0
≥ 3	N_C	N_C	N_C	N_C	N_C	0	N_C	N_C	0	0
≥ 4	N_C	N_C	N_C	N_C	N_C	0	N_C	C4	0	0
≥ 5	N_C	N_C	0	N_C	0	0	C3	0	0	0
≥ 6	N_C	N_C	0	N_C	0	0	0	0	0	0
≥ 7	N_C	N_C	0	C2	0	0	0	0	0	0
≥ 8	N_C	C1	0	0	0	0	0	0	0	0

We explain step (1) that determine the assignment of the h-th string. To do this, we consider the number of working modules of each panel for currents less than i_{s-1}. Let $m_p(i)$ be the number of working modules of Panel p that work in current i. For each panel p, we consider the difference vector $D_p = (m_p(i_{s-2}) - m_p(i_{s-1}), m_p(i_{s-3}) - m_p(i_{s-2}), \ldots, m_p(i_0) - m_p(1))$. The first element d_1 of D_p means, if we use panel p in current i_{s-1}, we lose d_1 working modules in current i_{s-2}. Then we sort panels in lexicographic order by vector D_p. This means, a panel with minimum module losses should firstly assign to the string with the highest current.

TABLE III: Panel selection Table

	P3	P2	P1	P5	P7	P9	P4	P6	P8
2A	0	2	1	1	2	2	2	2	3
2A	0	2	1	1	2	2	2	2	3
3A	0	2	0	0	1	1	0	0	0
d_1	0	0	1	1	1	1	2	2	3
d_2	0	0	0	0	0	0	0	0	0

Table III shows the panel selection order of MPP candidate {2A, 2A, 3A} by given panel information from Table I. For this example, this table shows panel P7 includes two, two and one modules that work in current 2A, 2A and 3A, respectively. So choosing panel P7 working on 3A will lose one module that can work on 2A.

In the step (3), to obtain optimal panel selection need swap undesired panel. The replacement policy follows priorities are:

1- Swap a panel contain 3 working modules ($m_p(i)$ = 3) to **three** panels each contain 1 working module ($m_p(i)$ = 1).

2- Swap a panel contain 3 working modules ($m_p(i)$ = 3) to **one** panel contain 1 working module ($m_p(i)$ = 1) and **one** contain 2 working modules ($m_p(i)$ = 2).

3- Swap a panel contain 2 working modules ($m_p(i)$ = 2) to **two** panels each contain 1 working module ($m_p(i)$ = 1).

VI. EVALUATION OF OPTIMIZATION ALGORITHM

Although the pilot example refers to three strings only, the extension of the method to any number of parallel connected strings is the same.

To evaluate the performance of proposed algorithm, we compare the proposed algorithm with exhaustive search algorithm for 300 different partial-shading PV arrays. For each PV array, contain 2-15 PV panels connected into 2-5 strings. The PV panels will have contain 2-20 different current candidates.

The computational time required to find the best configuration and accuracy of configuration in the proposed and exhaustive search algorithm are compared and summarized in Table IV. As shown in Table IV, proposed algorithm achieved less computing time compare with exhaustive search algorithm and with high accuracy.

The calculation time used by the proposed algorithm for one MPP candidate was 157 ms, which is significantly lower compared with exhaustive search 1hour 12min 50s and accuracy are higher than exhaustive search algorithm.

TABLE IV

COMPARISON BETWEEN EXISTED METHODS AND PROPOSED ALGORITHM

	Proposed Algorithm	Exhaustive search Algorithm
Number of PV Array	300	
Number of MPP candidates	10961	
Feasible Candidates	1180	1278
Infeasible Candidates	9781	9683
Error Rate	0.89%	0%
Ave. times per Array	0.157s	4370s

VII. CONCLUSIONS

The existing PV reconfiguration methods either have high accuracy but suffer from long computational time such as exhausted searching algorithm or GA, or they have short computational time but do not guarantee the best configuration as described in [8]. This paper proposed a new PV system reconfiguration algorithm with feasibility check function and have high accuracy and less computational time. Proposed algorithm's effectiveness has been validated using Matlab simulation. The algorithm was tested though un-uniform shadow distribution among PV array and shows its effectiveness in finding optimal configuration. The proposed algorithm also compared with existed method in terms of accuracy and computational time. The result shows that proposed algorithm has high accuracy and less computational time.

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