Optimal Switch Configuration Design for Reconfigurable Photovoltaic Modules

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***Abstract*—PV module reconfiguration techniques have been proposed to combat the partial shading effect. These techniques can adaptively change the PV module configuration according to the partial shading pattern. A reconfigurable PV module is designed by integrating three programmable switches with each PV macro-cell. The PV module reconfiguration is then realized by controlling the ON/OFF states of the switches. To reduce the additional capital cost induced by the switches, we propose to optimize the switch configurations, i.e., derive the required number of MOSFETs in each switch based on the maximum current passing through that switch, in a reconfigurable PV module. The optimal switch configuration design combined with the optimization of PV macro-cell size can make the reconfigurable PV module achieve the maximum performance enhancement under partial shading while satisfying the capital cost constraint of the PV module.**

Keywords—photovoltaic; reconfiguration; partial shading.

I. INTRODUCTION

Utilization of renewable energy has attracted more and more attention due to increasing prices of fossil fuels and the associated environmental effects. Among renewable energy resources, photovoltaic (PV) energy has been widely utilized in PV power plants, satellites, and PV powered household appliances. The output power of a PV system largely depends on solar irradiance, which varies significantly during daytime and falls to zero at night. Therefore, standalone PV systems need to be equipped with electrical energy storage devices (e.g., batteries, supercapacitors) to store excess energy when solar irradiance level is high and to complement insufficient energy when solar irradiance level is low[1][2].

PV cells exhibit highly non-linear current-voltage (I-V) output characteristics, under a given solar irradiance level. Therefore, power converters are necessary in PV systems for controlling the output voltage and current of PV modules[3]. The maximum power point tracking (MPPT) and maximum power transfer tracking (MPTT) techniques have been proposed to maximize the output power of PV systems under changing solar irradiance[4][5][6].

A PV module is comprised of $m \times n$ identical PV cells connected in a series-parallel manner. Ideally, all PV cells in a PV module receive uniform solar irradiance, and they can be set to operate at their maximum power points (MPPs) simultaneously, in which case the whole PV module achieves the maximum output power [7]. However, in reality, PV cells in a PV module may receive non-uniform solar irradiance, which is usually caused by moving clouds and shadows of nearby obstacles. Such a phenomenon is known as *partial shading*. Under partial shading, not only the maximum output power of the shaded PV cells is reduced, but also the non-shaded or less-shaded PV cells may deviate from their MPPs. Therefore, the maximum output power of the PV module reduces significantly under partial shading.

To overcome the partial shading effect, PV module reconfiguration techniques have been extensively investigated to adaptively change the PV module configuration according to the partial shading pattern[8][9][10][11]. Compared with other reconfiguration techniques, the technique we proposed in [11] can achieve better flexibility and higher output power improvement under partial shading. In this technique, a reconfigurable PV module was designed by integrating three programmable switches with each PV cell, and a reconfiguration control algorithm was provided to make all PV cells work near their MPPs, thereby improving the PV module output power under partial shading. To justify the economic feasibility of PV module reconfiguration, we further proposed to group a number of PV cells into a PV macro-cell and to integrate three programmable switches for each PV macro-cell instead of each PV cell[12]. In [12], we derived the optimal PV macro-cell size such that the highest performance under partial shading can be achieved while satisfying the capital cost constraint of a reconfigurable PV module.

In this work, we focus on the optimal design of the programmable switches in a reconfigurable PV module, such that the PV module can achieve the maximum performance enhancement under partial shading while satisfying the capital cost constraint of a reconfigurable PV module. The programmable switch used in a reconfigurable PV module consists of a gate driver and a number of MOSFETs. We first derive the required number of MOSFETs in every switch based on the maximum current passing through that switch. In this way, we minimize the numbers of MOSFETs in the switches, thereby reducing the capital cost of the switches. Furthermore, we observe that the number of PV groups in a PV module should be larger than a value g_{min} to increase the efficiency of the power converter, thus increasing the efficiency of the whole PV system. Considering the fact that the PV group number is larger than g_{min}, the required numbers of MOSFETs in the switches can be further reduced. Therefore, for a given

PV macro-cell size, we can derive the g_{min} value such that the total capital cost of a reconfigurable PV module is within a limit. Then we solve the PV system design optimization problem, which determines the optimal PV macro-cell size such that the PV system achieves the highest performance enhancement for combating partial shading effect under a constraint of the reconfigurable PV module capital cost. Experimental results show that the PV system can achieve up to86% performance enhancement under partial shading with a capital cost increase less than 20%.

II. Component Models

A. PV Cell Modeling and Characterization

Every PV module is comprised of multiple PV cells. Let V_{pvc} and I_{pvc} denote the output voltage and current of a PV cell, respectively. The relationship between I_{pvc} and V_{pvc} (i.e., the I-V characteristics) under a given solar irradiance G is provided by Eqn. (2) in[7]. Figure 1 illustrates the PV cell I-V and P-V characteristics under different solar irradiance levels, where G_{STC} stands for the irradiance ($1000\ \mathrm{W/m^2}$) at standard test condition. One can observe that the PV cell exhibits a non-linear output current and voltage relationship. There is a MPP under any solar irradiance level, where the output power of the PV cell is maximized. MPPs are labeled by black dots in Figure 1.

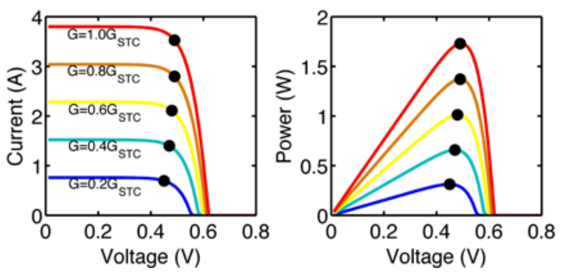

Figure 1. I-V and P-V characteristics of a PV cell.

B. Power Converter Model

We use a power converter between the PV module and the energy storage or load device. The power converter model is provided in [13]. Let V_{in}, I_{in}, V_{out}, andI_{out} denote the input voltage, input current, output voltage and output current of the power converter, respectively. The input ports of the power converter are connected to the PV module, and the output ports are connected to the storage or load device. The system controller adjusts the power converter output current, thereby controlling the operating point of the PV module. The power consumption of the power converter i.e., P_{conv} is a function of V_{in}, I_{in}, andV_{out}[13]. Based on the power converter model, we can calculate the power converter output current as a function of V_{in}, I_{in}, andV_{out}: $I_{out} = Chg\_Out\_I(V_{in}, I_{in}, V_{out})$.

III. Reconfigurable PV Module

A reconfigurable PV module takes place of the conventional PV module with fixed configuration, in order to combat the partial shading effect. In a reconfigurable PV module, the physical locations of PV cells/macro-cells are fixed, but the electrical connections of them can be changed by controlling the ON/OFF states of programmable switches. Figure 2 shows the structure of a reconfigurable PV module. Please note that Figure 2 does not represent the actual physical locations of PV cells/macro-cells. The reconfigurable PV module consists of N PV macro-cells, and each PV macro-cell consists of $s \times p$ PV cells, where s PV cells are in series and p PV cells are in parallel. In Figure 2, the PV macro-cell consists of four PV cells i.e., has a size of 2×2. Each PV macro-cell (except for the N-th PV macro-cell) is integrated with three programmable switches: a top parallel switch TPS_i, a bottom parallel switch BPS_i, and a series switch SS_i.

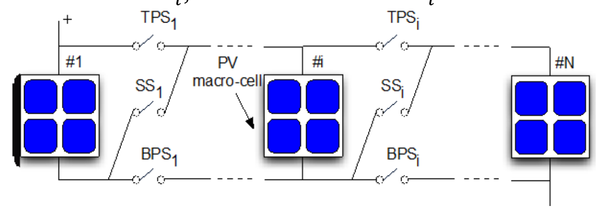

Figure 2. The structure of a reconfigurable PV module.

The PV module reconfiguration can be conducted by controlling the ON/OFF states of the programmable switches. The two parallel switches of a PV macro-cell are always in the same state, and the series switch of a PV macro-cell must be in the opposite state of its parallel switches. The parallel switches connect PV macro-cells in parallel to form a *PV group*, and the series switches connect PV groups in series. Figure 3 shows an example of PV module reconfiguration. The first four PV macro-cells are connected in parallel forming PV group 1; the next three PV macro-cells form PV group 2; and the last five PV macro-cells form PV group 3. These three PV groups are series-connected by the series switches of the fourth and the seventh PV macro-cells. We call such a PV module configuration as $\mathcal{C}(3; 4,3,5)$, where there are 3 PV groups and the PV groups consist of 4, 3, and 5 PV macro-cells, respectively. This kind of imbalanced PV module configuration is useful in combating partial shading effect. More details can be found in[12].

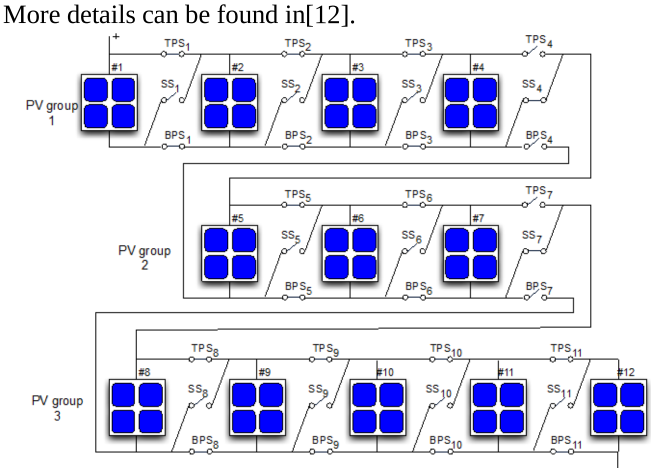

Figure 3. An example of PV module reconfiguration.

Now we provide the formal definition of the configuration of a reconfigurable PV module. Considering a reconfigurable PV module consisting of N PV macro-cells, it can have an arbitrary number (less than or equal to N) of PV groups. The number $r_j (> 0)$ of parallel-connected PV macro-cells in the j-th PV group should satisfy

$$\sum_{j=1}^{g} r_j = N, \tag{1}$$

where g is the number of PV groups. We denote such a configuration by $\mathcal{C}(g; r_1, r_2, \ldots, r_g)$. This configuration can be viewed as a partitioning of the PV macro-cell index set $\boldsymbol{A} = \{1,2,3,\dots,N\}$, where the elements in $\boldsymbol{A}$ denote the indices of PV macro-cells in the PV module. This partitioning is denoted by subsets $\boldsymbol{B}_1$, $\boldsymbol{B}_2$, …, and $\boldsymbol{B}_g$ of $\boldsymbol{A}$, which correspond to the g PV groups consisting of r_1, r_2, …, and r_g PV macro-cells, respectively. The subsets $\boldsymbol{B}_1$, $\boldsymbol{B}_2$, …, and $\boldsymbol{B}_g$ satisfy

$$\cup_{j=1}^{g} \boldsymbol{B}_j = \boldsymbol{A}, \tag{2}$$

and

$$\boldsymbol{B}_j \cap \boldsymbol{B}_k = \emptyset, \text{ for } \forall j,k \in \{1,2,\dots,g\} \text{ and } j \neq k. \tag{3}$$

The indices of PV macro-cells in PV group j must be smaller than the indices of PV macro-cells in PV group k for any $1 \le j < k \le g$ due to the structural characteristics of the reconfigurable PV module, i.e., $i_1 < i_2$ for $\forall i_1 \in \boldsymbol{B}_j$ and $\forall i_2 \in \boldsymbol{B}_k$ satisfying $1 \le j < k \le g$. A partitioning satisfying the above properties is called an *alphabetical partitioning*.

The PV cells in a PV module are usually physically placed into an $m \times n$ array, where there are m rows and n columns of PV cells. This is the physical layout of a PV module. The PV macro-cell has a size of $s \times p$, i.e., s PV cells connected in series and p PV cells connected in parallel to form a PV macro-cell. s and p must be factors of m and n, respectively. The PV macro-cells (from 1 to N) are physically placed in a zigzag manner within a PV module. In this way, the total length of wires connecting the PV macro-cells and switches can be minimized. The PV module reconfiguration method only changes the electrical connection of the PV macro-cells, whereas the electrical connection of PV cells within a macro-cell is fixed after PV system installation in the field.

IV. PV Module Reconfiguration Problem

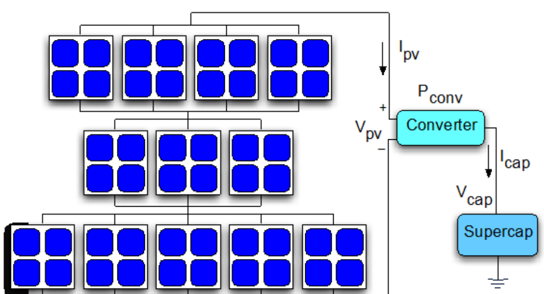

Figure 4. The architecture of a reconfigurable PV system.

In this section, we discuss the PV module reconfiguration problem for maximizing the output power of the PV system under partial shading. In this problem, we assume that the size of the PV macro-cell is given. Figure 4 shows the architecture of a reconfigurable PV system, consisting of a reconfigurable PV module, a power converter and a supercapacitor as the energy storage device. The PV cells in the module are placed into an $m \times n$ PV cell array (not shown in Figure 4.) The PV macro-cell has a size of $s \times p$. Then the total number of PV macro-cells is $N = (m \times n)/(s \times p)$. The output voltage and current of the PV module are V_{pv} and I_{pv}, respectively. The power consumption of the power converter is P_{conv}. The terminal voltage of the supercapacitor is V_{cap}, and the charging current of the supercapacitor is I_{cap}. We assume that the PV module reconfiguration controller has no access to the solar irradiance on every PV cell for the realistic consideration. Instead, it has only an estimate $\hat{G}_i^m$ of the solar irradiance on each i-th PV macro-cell. This estimation causes certain performance degradation since PV cells in a macro-cell may receive different irradiances. The formal statement of the PV module reconfiguration problem is:

Referring to Figure 4, **given** the instantaneous solar irradiance estimate $\hat{G}_i^m$ of the i-th $(1 \le i \le N)$ PV macro-cell and the supercapacitor terminal voltage V_{cap}, **find** the optimal PV module configuration $\mathcal{C}^{opt}$ and the optimal PV module operating point $(V_{pv}^{opt}, I_{pv}^{opt})$, **such that** I_{cap} is maximized.

The detailed algorithm can be found in[12]. Generally, the algorithm consists of a kernel algorithm and an outer loop. The kernel algorithm finds the optimal $r_1, r_2, \dots, r_g$ values with a given g value in a configuration $\mathcal{C}(g; r_1, r_2, \dots, r_g)$ to maximize the MPP power of the PV module. The kernel algorithm is a dynamic programming algorithm. In the outer loop, the optimal g value is decided. In general, the reconfiguration algorithm will ensure that (i) all PV macro-cells operate near their MPPs and (ii) the MPP voltage of the PV module and the terminal voltage of the supercapacitor are close to each other (so that the power converter efficiency is high.)

V. Optimal Switch Configuration Design

The programmable switch used in the reconfigurable PV module consists of one MOSFET gate driver and one or multiple pairs of n-type MOSFETs. The two MOSFETs in one MOSFET pair are connected back to back. Figure 5 shows the detailed circuitry of a programmable switch. The number of MOSFET pairs in a switch depends on the maximum current passing through the switch.

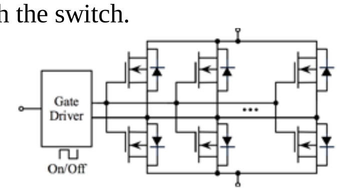

Figure 5. The circuitry of a programmable switch.

A. Case I: No Constraint on the PV Group Number

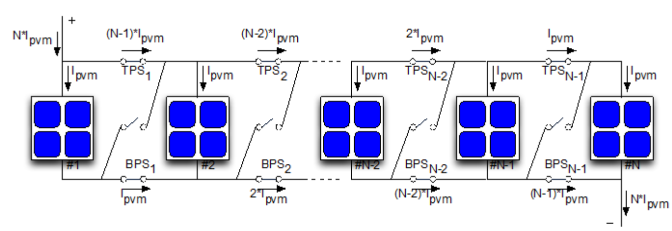

Figure 6. The maximum currents of top and bottom parallel switches.

In a reconfigurable PV module, the maximum current passing through a switch depends on the position of the switch. For the top and bottom parallel switches (i.e., TPS_i and BPS_i), when all the PV macro-cells are connected in parallel (i.e., the PV module has a $\mathcal{C}(1; N)$ configuration), the top and bottom parallel switches need to conduct the maximum currents. The maximum current passing through a top or bottom parallel switch is shown in Figure 6, where $I_{pvm} = p \cdot \max(I_{pvc})$, and p is the number of PV cells connected in parallel in a PV macro-cell. We can see the maximum current that TPS_i needs to conduct is $(N - i) \cdot I_{pvm}$ and the maximum current that BPS_i needs to conduct is $i \cdot I_{pvm}$. Therefore the required number of MOSFETs in a top parallel switch TPS_i is calculated by

$$Num_{TPS_i} = 2 \cdot \left\lceil \frac{(N-i) \cdot I_{pvm}}{I_D} \right\rceil, \quad (4)$$

where I_D is the maximum drain current of a MOSFET. The required number of MOSFETs in a bottom parallel switch BPS_i is calculated by

$$Num_{BPS_i} = 2 \cdot \left\lceil \frac{i \cdot I_{pvm}}{I_D} \right\rceil. \quad (5)$$

For a series switch (i.e., SS_i), it needs to conduct the maximum current when the PV module has two PV groups: the first PV group consists of PV macro-cells $1 \sim i$, and the second PV group consists of PV macro-cells $(i+1) \sim N$ (i.e., the PV module has a $\mathcal{C}(2; i, N-i)$ configuration.) In this case the two PV groups are series-connected by SS_i. The maximum current of SS_i is calculated by

$$I_{SS_i}^{max} = \min(i, N-i) \cdot I_{pvm}, \quad (6)$$

which is due to the structural characteristics of a reconfigurable PV module. Then, the required number of MOSFETs in a series switch SS_i is calculated by

$$Num_{SS_i} = 2 \cdot \left\lceil \frac{I_{SS_i}^{max}}{I_D} \right\rceil. \quad (7)$$

B. Case II: The PV Group Number Has a Constraint

The power converter power consumption P_{conv} is a function of its input voltage, input current, and output voltage, which are V_{pv}, I_{pv}, and V_{cap}, respectively, as shown in Figure 4. Generally speaking, when V_{pv} is too low (compared with V_{cap}) or equivalently the PV group number g is too small, the power converter efficiency is low. Therefore, in reality the optimal PV module configuration, produced by the reconfiguration algorithm in Section IV, usually has a PV group number g larger than a certain value g_{min}. That is to say, the method we use to calculate the required number of MOSFETs in a switch is pessimistic. For example, the PV module reconfiguration algorithm may never generate a configuration as shown in Figure 6. In this section, we calculate the required number of MOSFETs in a switch considering $g \geq g_{min}$.

With the PV group number constraint, the current of the PV module (which is also the current of each PV group) cannot be larger than $\lceil N/g_{min} \rceil \cdot I_{pvm}$. Therefore, the maximum current a top parallel switch needs to conduct is the minimum one between $\lceil N/g_{min} \rceil \cdot I_{pvm}$ and $(N-i) \cdot I_{pvm}$. Please note that $(N-i) \cdot I_{pvm}$ is the maximum current a top parallel switch needs to conduct when there is no constraint on the PV group number. The required number of MOSFETs in TPS_i is then calculated by

$$Num_{TPS_i} = 2 \cdot \left\lceil \frac{\min\left(\lceil N/g_{min} \rceil, (N-i)\right) \cdot I_{pvm}}{I_D} \right\rceil. \quad (8)$$

Similarly, the required numbers of MOSFETs in BPS_i and SS_i can be calculated by

$$Num_{BPS_i} = 2 \cdot \left\lceil \frac{\min(\lceil N/g_{min} \rceil, i) \cdot I_{pvm}}{I_D} \right\rceil, \quad (9)$$

and

$$Num_{SS_i} = 2 \cdot \left\lceil \frac{\min(\lceil N/g_{min} \rceil, i, N-i) \cdot I_{pvm}}{I_D} \right\rceil. \quad (10)$$

VI. PV System Design Optimization

The PV system design optimization problem aims to find the optimal size (i.e., the optimal s and p) of the PV macro-cell, the optimal switch configuration, and the constraint value g_{min}, such that the PV system can achieve the highest performance for combating partial shading under a constraint on the total capital cost of the reconfigurable PV module. If the PV macro-cell has a relatively small size, more switches are needed in the reconfigurable PV module, thereby increasing the total capital cost of the PV module. On the other hand, if the PV macro-cell has a large size, fewer switches are needed, thereby decreasing the total capital cost of the PV module. However, a larger PV macro-cell size results in lower performance for combating partial shading effect. The reasons are: (i) the PV module with a larger PV macro-cell size has less reconfiguration flexibility and (ii) the use of a single solar irradiance level for each PV macro-cell in the PV module reconfiguration algorithm causes performance degradation. Similarly, as discussed in Section V.B, when the constraint g_{min} of PV group number is smaller, the reconfigurable PV module has higher performance but also higher capital cost due to the potentially larger required number of MOSFETs in every switch.

The PV system design optimization problem is formulated as follows:

Given a PV module with fixed physical layout of $m \times n$ PV cells, **find** the optimal s, p, g_{min}, and the associated optimal switch configurations, **such that** the PV system performance (output power) is maximized under partial shading and the PV module capital cost is within a certain limit. s and p should be factors of m and n, respectively.

The proposed PV system design optimization algorithm is provided in Algorithm 1. Please note that we use the binary search method to effectively find the constraint value g_{min}. We evaluate the performance of each PV system design by executing partial shading benchmarks (comprised of extreme-case partial shading, random shading, and block shading, as shall be discussed in the experimental results section) and taking into account the probability distribution of the supercapacitor terminal voltage V_{cap}.

Algorithm 1: PV System Design Optimization Algorithm

Input: PV module physical layout $m \times n$, PV module capital cost limit.

Output: optimal PV macro-cell size s^{opt} and p^{opt}, optimal constraint g_{min}^{opt} on PV group number, and associated optimal switch configurations.

$Perf^{max} \leftarrow 0$.

For each (s, p) ,where s and p are factors of m and n, respectively:

Use binary search to find the smallest g_{min} and associated switch configurations that satisfy the capital cost limit.

Run the partial shading benchmarks and obtain the

performance $Perf$.
If $Perf > Perf^{max}$
$Perf^{max} \leftarrow Perf$.
$(s^{opt}, p^{opt}) \leftarrow (s, p)$.
$g_{min}^{opt} \leftarrow g$.
End
End

VII. Experimental Results

We consider a PV module with a physical layout of 12×12 PV cells. There are 36 possible PV macro-cell sizes. We employ real-world examples of the PV cells, switch gate driver, and switch MOSFET, with the specifications and prices shown in Table I. There are commercial PV cells in the price ranges of ~\$1, ~\$5, and ~\$20, which we name as low price, medium price, and high price PV cells, respectively.

Table I. Specifications and prices of PV cells, gate driver, and MOSFET.

PV Cell	I_{sc}	P_{MPP}	**Price**
SZGD6030	302mA	134.4mW	\$1.2
SZGD10040-10	115mA	575mW	\$5.5
SZGD196156-10	720mA	3250mW	\$21.9
Gate Driver	V_{max}	T_{on}	**Price**
MAX15054AUT	65V	11ns	\$0.70
MOSFET	V_{DS}	I_D	**Price**
DMG4406LSS-13	30V	10.3A	\$0.09

We effectively evaluate the performance of reconfigurable PV module using PV module partial shading benchmarks. The proposed benchmarks consist of (i) extreme-case partial shading patterns as those in [11] for testing the robustness of the PV module reconfiguration architecture, (ii) random shading over each PV cell to mimic the effect of dusts on the PV module, and (iii) block-based partial shading on the PV module to mimic the effect of moving clouds.

Table II. Maximum performance enhancement under capital cost increase constraint.

Capital Cost Increase	$\leq 10\%$	$\leq 20\%$	$\leq 30\%$
Low price cell	42.38%	53.07%	53.70%
Medium price cell	60.44%	65.57%	77.86%
High price cell	77.86%	86.56%	86.56%

Table II provides experimental results on the PV system design optimization problem. It shows the maximum performance enhancement when the PV module capital costs are 10%, 20%, and 30% higher than a PV module without any reconfiguration method. Experimental results on the low price, medium price, and high price PV cells are provided. According to Table II, the high price PV cell-based module achieves more than 86% performance enhancement with a capital cost increase less than 20% compared with a PV module without any reconfiguration method. For the low price PV cell-based module, about 53% performance enhancement can be achieved with a capital cost increase less than 20%.

VIII. Conclusion

The PV module reconfiguration techniques have been proposed to combat partial shading effect, which adaptively change the PV module configuration according the partial shading pattern. The PV module reconfiguration method in [11] can recover the PV module output power loss to the maximum extend under partial shading. The reconfigurable PV module is designed by integrating three programmable switches with each PV macro-cell. To reduce the additional capital cost induced by programmable switches, we propose to optimize the switch configurations according their functions in the reconfigurable PV module. The optimal switch configuration design combined with the optimal PV macro-cell size determination can make the reconfigurable PV module achieve the maximum performance enhancement under partial shading while satisfying the capital cost constraint of the PV module.

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