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Design-Time Optimization of Reconfigurable PV Architectures for Irregular Surfaces

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***Abstract*—Compared to flat PV arrays, PV cells on curved surfaces such as vehicles, wearable devices and building rooftops have varying inclination angles and therefore, non-uniform operating conditions. Dynamic reconfiguration techniques used for tackling partial shading effects can also be deployed for non-uniform operating conditions on curved surfaces. However, designing a reconfigurable PV system for irregular surfaces is significantly different because the placement of reconfiguration switches should account for the curvature, not just random partial shading patterns. In this paper, we propose a design-time framework for identifying the optimal placement of reconfiguration switch sets as well as a dynamic reconfiguration algorithm for a PV array on a given irregular surface. Case studies performed for different irregular surfaces show that our proposed technique reduces the number of reconfiguration switches by 83% while still generating 81% power compared to having reconfiguration switches on all PV atomic units. While the cost reduction due to the reduced number of switches is marginal in most applications because the PV panel cost dominates the total cost, the technique helps in significantly reducing the wiring harness required for dynamic reconfiguration switches, which is a burden for manufacturing.**

***Index Terms*—Photovoltaic Array, Reconfigurable Architecture, Partial Shading, Design-Time Optimization**

I. Introduction

Photovoltaic (PV) cells are being adopted to a wide range of applications from small scale systems such as energy harvesting for wearable devices, mobile devices, portable charging systems to larger systems such as solar powered vehicles [10], streets lights, rooftop installations [3] and solar power plants. Figure 1 is such an example where four PV modules are mounted to form a non-uniform PV array. The power generation capability of the PV array depends on the solar irradiance that each PV cell receives, temperature and its operating points (voltage, current). Maximum power point tracking (MPPT) is a well known technique used to maintain the operating point of the individual PV cell such that the power generated from each PV module is maximum (see Figure 2).

Conventional PV installations are typically on a flat surface such as rooftop or large solar farms. By contrast, installations on curved surfaces such as aerial vehicles, electric vehicles, wearable devices and building integrated PVs (BIPV) are gaining more attention recently [16]. Recent advances in flexible PV cells offer additional opportunities to fit PV arrays on various non-uniform surfaces [12]. The major difference between PV modules on irregular surfaces to those on flat surfaces is that the amount of solar irradiance that each module will receive and operating temperature vary depending on their position on the surface. As a result, typical circuit architectures for a flat PV installation are not really effective for PV modules on irregular surfaces.

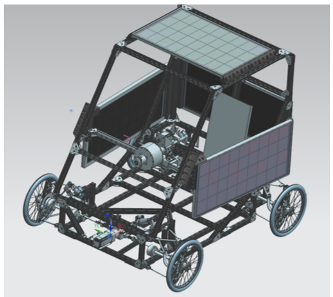


Fig. 1: A custom designed EV with four PV modules.

One of the well-known control technique to maintain power generation capability of a PV array under non-uniform operating conditions (solar irradiance and temperature) is dynamic reconfiguration using switches. In a typical PV farm installed on a flat surface, reconfiguration switch modules will be uniformly distributed in the PV array as partial shading could occur to any modules and limit the power generation of the whole PV string connected in series. If partial shading occurs, the associated PV module is either isolated or provided with an alternative current path by the reconfiguration switches.

Problem motivation: Implementing such dynamic reconfiguration for PV arrays on an irregular surface is not straightforward and has not been sufficiently analyzed in the literature. Installing reconfiguration switch sets uniformly will not result in an energy- and cost-efficient system since the geometry information of the irregular surface, which can be known at design time, is not being utilized. For the purpose of tackling irregular surfaces, such a uniform setup could be an overkill as adjacent PV cells need not be considered separately. Therefore, a detailed analysis of the geometry of the irregular surface and possible incidence angles of light

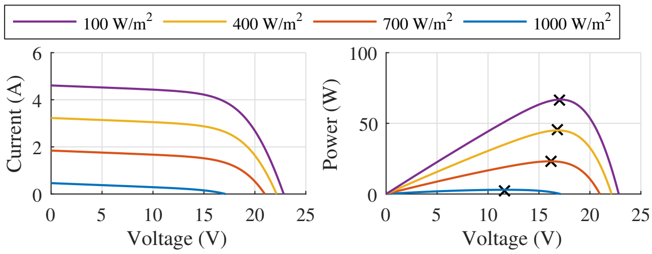


Fig. 2: VI curve of a PV module.

is required to determine the number and the location of the reconfiguration switches such that the energy and the overall system cost are optimized. Performing such an analysis is non-trivial since runtime reconfiguration problem and design-time problem have to be solved together while the former alone is already known to be quite challenging [7].

Contributions: In this paper, we propose, for the first time, a design automation framework that will enable us to identify the required number and the location of reconfiguration switches for a given surface geometry. The main idea of our proposed framework stems from the fact that the locations and inclination angles of the individual PV cells on the irregular surface, and therefore, the statistical correlation among their solar irradiance values are known at design time. Our specific contributions in this paper are as follows:

- For the first time, we propose a design automation framework that utilizes the geometry of the irregular surface to identify the required number and location of reconfiguration switches.
- Our proposed approach offers a significant reduction in complexity (wiring harness as well as cost) of PV systems promoting their usage on applications previously deemed impractical, e.g., irregular surfaces of commercial vehicles, artistic buildings and wearable devices.
- Our case studies show that the number of reconfiguration switches required for an irregular surface is reduced up to 83% compared to a full reconfiguration approach whereas the maximum power generated still remains at 81%.

II. Related Work

Recently, advances in the materials for PV manufacturing have stimulated the study on flexible PV cells [12]. The curved surfaces of PV array can be realized at the cell level as well as at the multi-module level. This paper does not restrict the scale of the curvature and can be applied to both cell-level and module-level granularity of reconfiguration approaches.

Various techniques exist to mitigate the partial shading problem [2]. One static way of handling the partial shading problem is to make use of blocking diodes and bypass diodes [14]. They provide alternative current paths and block reverse currents to enhance the power generation and ensure the safe operation of the PV cells even without active control. MPPT for such an array is a difficult problem due to multiple local optimum values in the power-voltage graph [15]. But of course, their flexibility and adaptability to changing irradiance patterns are limited compared to reconfiguration approaches.

Dynamic reconfiguration of PV arrays is a well researched topic as the technique is useful in coping with partial shading [7], [5], [4] and fault-detection [8]. While the previous works assume a uniform placement of reconfiguration switches, this work focuses on the importance of taking the curvature into consideration for better placement of the switches. A recent paper solves a very similar problem of reducing the number of reconfiguration switches for rooftop PV installations [11]. But, the paper focuses on tackling partial shading while this paper looks into irradiance patterns due to the curvature potentially on a moveable surface such as vehicles.

One work has tackled the problem of partial shading at *design time* [1]. The work proposes a shading-aware PV cell string layout, and locations of the reconfiguration switches. However, the technique is for simple shading patterns rather than holistic optimization for irregular surfaces. Another work solves a similar problem to the one in this paper [9]. But, the work only compares different reconfiguration topologies on a non-uniform surface rather than deriving a customized reconfiguration topology for a given irregular surface itself. Another recent work targeted the same problem of PV arrays on an irregular surface, but the control knob is the static series-parallel electrical placement of PV cells on a PV array, which is orthogonal to our paper here [13]. In this paper, we solely focus on utilizing the dynamic reconfiguration switches for solving the same problem.

III. PV Arrays on Irregular Surfaces

In this section, we introduce an analytical model of a PV cell used in this work. We also explain the differences between installing the PV modules on an irregular surface compared to the conventional flat surface installation.

A. PV model

PV arrays require power converters in order to operate and maximize the energy generation. Fig. 2 shows the relationship between output voltage, current and solar irradiance of an example PV module. While the output power is mainly dictated by the solar irradiance, it is also influenced by the voltage-current curve. A power converter controls the operating current, which results in power output changes shown in the right hand side figure. The maximum power points (MPP) are marked with $\times$.

Different architectures for PV inverters exist such as micro-inverters, string inverters, central inverters, etc. Among those, we consider a central inverter architecture, which has only one inverter connected to the PV array at the output. It is predominantly used due to low cost and its simplicity. In this architecture, bypass and blocking diodes are often used i) to provide an alternative current path for modules suffering from partial shading, and ii) to prevent damage from reverse currents flowing back into the module, respectively.

B. PV Array on Irregular Surface

Both a PV array under partial shading and a PV array on an irregular surface suffer from non-uniform operating conditions, but there are two distinguishing features, which necessitate different approaches for energy output optimization. These features distinguish this work from existing works

1) While the partial shading effect happens mainly due to the runtime anomalies, e.g., dust or nearby obstacles, a PV array on an irregular surface suffers from non-uniform solar irradiance due to different inclination angles of PV cells, which can be predicted at design time.
2) The partial shading entails a small number of cells receiving distinctly different solar irradiance values, while all the cells on an irregular surface receive a continuous spectrum of solar irradiance values, which is largely determined by the curvature.

Bypass diodes reasonably handle a small number cells with distinctively different irradiance values. They isolate the affected cells from the PV array to reduce the amount of power output of the entire array. However, this approach cannot be used for PV arrays on irregular surfaces as they do not handle well the PV cells receiving a continuous spectrum of irradiance. Alternatively, design-time approaches such as in [13] cluster the PV cells that exhibit high correlation in solar irradiance, operating temperature, etc., to form PV strings rather than simply connecting the physically adjacent cells in series.

C. Runtime Variations

Nevertheless, a PV array on an irregular surface also faces variations in the operating conditions, apart from the partial shading effect, during runtime. First, the solar irradiance and incidence angles change over time due to both the change of position of the sun in the sky (dominant in the stationary PV arrays) and the movement of the PV array itself (dominant in wearable/mobile devices, vehicular systems.). Due to the curvature of the surface, the patterns of solar irradiance values each cell receives will be non-uniform and time-varying, but somewhat predictable at design time. Second, the temperature of the cells changes significantly due to the amount of solar irradiance they receive and cooling factors such as heat removal due to the wind. However, we leave the effects of temperature as a future work and assume constant temperature of 25°C throughout this paper.

Figure 3 shows an architecture which allows dynamic reconfiguration. There are three switches connected to each PV cell to form a *reconfiguration switch set*. A series switch connects the neighboring PV cells in series while two parallel switches connect them in parallel. Two parallel switches always open and close together while the series switch operates in a complementary fashion. This architecture allows great flexibility in dynamically reconfiguring the series-parallel connection of a PV array. A near-optimal algorithm to tackle the partial shading effect using this architecture has been proposed in [7].

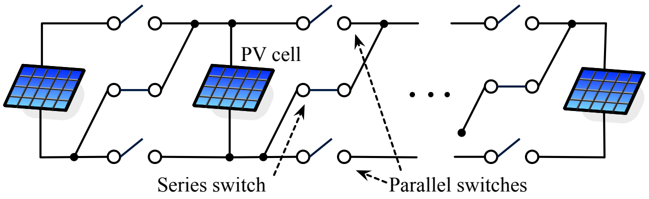


Fig. 3: Reconfigurable PV array architecture.

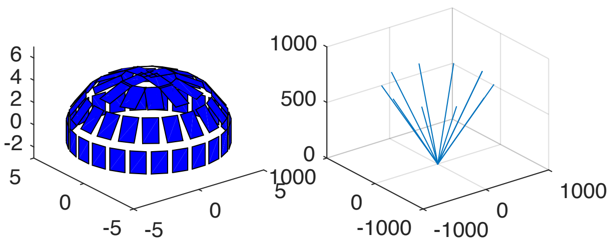


Fig. 4: An example PV array on a sphere surface and 11 light vectors for the motivational example.

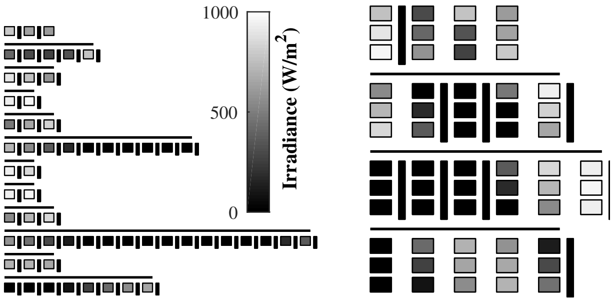
The architecture could be utilized to combat other anomalies such as temperature fluctuations.

IV. Reconfigurable PV Array on Irregular Surface

In this section, we discuss how the reconfigurable switch insertion could improve the overall energy generation and reduce the costs of a PV array on an irregular surface. Dynamic reconfiguration provides great flexibility to adapt to the changing operating circumstances. However, the flexibility comes at the cost of a large number of switches. It is not cost-effective to add reconfiguration switches between every PV cell. In this paper, as the main motivation of using reconfiguration is to cope with the non-uniform irradiance due to the curvature, we consider design-time options for customizing the reconfigurable PV array for specific curvatures. We motivate the problem first by providing an example.

Motivational example: We assume that 60 PV cells are placed on a sphere shown in Fig. 4. Conventional approaches deploy reconfiguration switches for all individual PV cells/modules in a uniform manner as shown in Fig 3 as partial shading could affect any cell uniformly. However, for our purpose, we can expect much fewer reconfiguration switch would be needed to sustain high power generation.

Fig. 5(a) is an extreme and an impractical setup with the maximum number of reconfiguration switch sets, i.e., one set of switches between every cell totaling 59 sets. Horizontally wide rectangles denote PV cells, and black vertical bars denote a set of series-parallel switch (shown in Fig. 3) between adjacent cells/modules. Narrow horizontal black lines denote parallel electrical connections. The vertical direction denotes series connections. The different amount of solar irradiance



(a) 59 SW, 25.21 W @ 7.12 A (b) 9 SW, 19.24 W @ 5.12 A

Fig. 5: (a) PV array on a sphere surface with max. number of reconfiguration switches, and (b) reduced number of switches.

a PV cell receives is described in gray scale. Such a setup provides much flexibility. The output power of the PV array on the sphere is 25.21 W at 7.12 A, which is the MPP. However, such a fine-grained placement is unnecessary in our problem setup due to the aforementioned reasons.

Fig. 5(b) shows an alternative approach. We perform a design-time analysis of the array for 11 directions of light source and remove infrequently used switch sets. Furthermore, we group a number of cells in series, in this case 3, to form an atomic unit, and then leave only 9 most utilized switch sets. While the number of switch sets is barely above 15%, the average power generation for over 11 different light angles is over 19.24 W/25.21 W=76.3%. Note that the total number of cells in series, 12, is the same for both cases. By analyzing the geometry of the irregular surface, the required number of reconfiguration switch sets can be significantly reduced without sacrificing the total power generation capability.

There are a number of configurable parameters, which can be already seen from this motivational example. There are two ways to reduce the number of reconfiguration modules. First, we could connect more cells in series (vertical direction) to form an atomic string. Second, we could connect atomic strings in parallel (horizontal) to form an atomic array. Both actions can reduce the number of reconfiguration switches, but they have to be carefully exercised with regards to the shape of the surface relative to the PV cell sizes, and the light patterns. In the following, we will analyze these constraints in detail and propose a design automation framework that will determine the required number of reconfigurable PV modules.

V. PV Reconfiguration Switch Insertion Algorithm

In this section, we propose a design-time algorithm that determines the locations of the reconfiguration switches considering the shape of the surface on which the PV array is installed, and the statistical patterns of the light source.

A. Problem Statement

The objective of the reconfiguration switch insertion problem is to maximize the average power generation of a PV array for a given set of light sources. The objective is

$$P_{avg} = \frac{\sum_{n=1}^{N} P_{n,mpp}}{N}, \quad (1)$$

where $P_{n,mpp}$ is the maximum power generation of the array for n-th light vector. We assume that the problem is solved for N number of light vectors, which represent the dynamic changes in angles of the sunlight during operation.

The given values are a set of light vectors $G_N = \{g_1, g_2, g_3, \cdots, g_N\}$, a set of PV cells $PV_M = \{pv_1, pv_2, pv_3 \cdots, pv_M\}$, irregular surface CS, a set of PV cells whose locations and inclination angles on CS are given, N_s the number of desired PV cells in series, and K the number of reconfiguration switch sets. N_s is required because DC-DC converters or inverters for a PV array have certain limits in operating voltage.

The input variables for the problem are the electrical locations of the reconfiguration switch sets represented by a set of binary variables LOC_i where the value is 1 if the reconfiguration switch set is placed between atomic unit i and $i+1$ and 0 otherwise.

B. Observations

It is apparent that there exists a trade-off between the number of reconfiguration switches and the power output. The more flexible an array is, it can cope better with the direction changes in the light source. However, it is not a trivial problem to determine the optimal locations of the reconfiguration switches. There are two ways to reduce the number of switches as we briefly mentioned in the previous section, vertically (series) or horizontally (parallel) bind cells together to form an atomic unit.

Let us assume an example of an irregular surface with 120 PV cells. If we were to place 9 sets of reconfiguration switches to the array in a uniform manner, there will be 10 atomic units each comprising 12 cells (dashed rectangle in Fig 6). There are six options for atomic units, 12×1 (12 cells in series and 1 cell in parallel), 6×2, 4×3, 3×4, 2×6, and 1×12. We aim at constructing an array having the same number of cells in series, 24, as in Fig. 6.

In order to cope with dynamically changing incidence angles, more flexibility of the array is preferred. We can quantify the flexibility in terms of the number of possible configurations with different atomics units. The last two options 2×6, and 1×12 are not feasible because they cannot comprise an array with 24 cells in series even if they connect all atomic units in series. The number of available configurations for the remaining four options can be calculated using *combination with repetition* usually denoted using the symbol ${}_nH_k = {}_{n+k-1}C_k$. We are allocating the atomic units to first fulfill the N_s requirement. For 12×1, at least two atomic units should be connected in series, and remaining 8 units can be connected parallel to any of the two units as shown in Fig. 6. This is drawing G1 (Group 1) or G2 (Group 2) eight times while *repetition* is allowed. So, the number of available

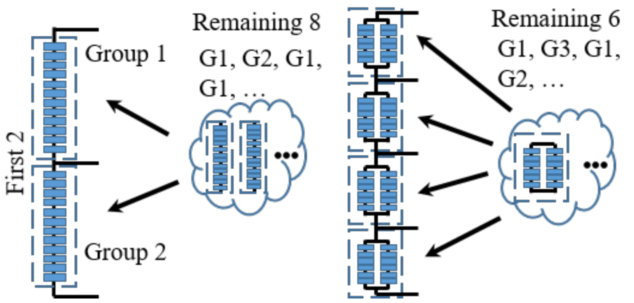


Fig. 6: Flexibility according to the size of atomic unit for reconfiguration. 12×1 (left) and 6×2 (right).

configurations becomes ${}_2H_8 = {}_9C_8 = 9$. Likewise, the numbers of available configurations for other options are ${}_4H_6 = 84$, ${}_6H_4 = 126$, ${}_8H_2 = 36$. Therefore, it is wise to choose 4×3 atomic unit to maximize number of configurations, and hence, the flexibility to cope with dynamic light variations given 9 reconfiguration switch sets. This is leads to increased power generation as will be presented in the experiments section.

C. Heuristic Algorithm

The algorithm consists of multiple sub-algorithms. First, we assume a reconfiguration algorithm based on [7]. The work takes a cue from the fact that MPP voltage values do not differ significantly among different irradiance values as can be seen from Fig. 2. The algorithm tries to group atomic units into parallel connections such that the sum of respective maximum power currents are similar among groups. The details of algorithm are shown in Algorithm 1. It starts with calculating MPP for each atomic unit (12×1, $6\times2,\cdots$) disregarding inter-atomic unit connections. Then, $\mathbb{CUTS}$ is initialized to contain $N_G - 1$ random integers between 1 and $|\mathbb{LOC}|$ (line 2). By having $N_G - 1$, the number of serious connected modules are guaranteed to be N_G. which also means the output voltage of the whole PV array is maintained to be not too low. The $\mathbb{CUTS} = \{1,4,5\}$ denotes, for example, the first, fourth and fifth reconfiguration switches in series connection and the rest in parallel. After the cuts are obtained, the function calcSum() (line 3) calculates the sum of I_{MPP} for each atomic unit in the group (parallel connected atomic units). Then, the algorithm tries to equalize the sum of I_{MPP}s among groups iteratively by enlarging the group with the smallest sum and reducing the one with the largest sum (lines 4 to 8). The sizes of the groups in between are maintained the same in line 6. This algorithm is sub-optimal compared to prior works such as [7], but provides good enough quality and speed to serve as a subroutine for the main algorithm Algorithm 2.

Then, we need a way to find the MPP of the respective configurations. While MPPT of an irregular array itself is a complex optimization problem with multiple local maximum, we circumvent the difficulty of finding the MPP numerically from various initial guesses. We use MATLAB's *fmincon* function to find the MPP. This approach is time-consuming and cannot be used for real-time MPPT, but is fast enough for our purpose of conducting design-time exploration.

Algorithm 1: Heuristic reconfiguration algorithm when locations of K reconfiguration switch sets are given.

Input: Solar irradiance g, Number of atomic units in series N_G, set denoting the locations of switch sets $\mathbb{LOC}$, set of PV cells $\mathbb{PV}_M$

Output: Vector, $\mathbb{SW}$, indicating S/P status of switches

1: For all atomic unit $\mathbb{PV}^i$, calculate the MPP: $I_{MPP,i}$ =findMPP(g, $\mathbb{PV}^i$)
2: Randomly initialize the set of series-configured reconfiguration switches, $\mathbb{CUTS}$: $\mathbb{CUTS}$ =randsample($|\mathbb{LOC}|$,$N_G - 1$)
3: Calculate the set, $\mathbb{I}_{sum}$, of current values, where each element is the sum of MPP currents of parallel-connected atomic units: $\mathbb{I}_{sum} \leftarrow$calcSum($\mathbb{I}_{MPP}$,$\mathbb{CUTS}$)
4: **while** the difference between min($\mathbb{I}_{sum}$) and max($\mathbb{I}_{SUM}$) is larger than 10% **do**
5:     i =minIdx($\mathbb{I}_{sum}$), j =maxIdx($\mathbb{I}_{sum}$)
6:     Configure switches s.t. one more atomic unit is connected in parallel to the group i and one less to the group j: $\mathbb{CUTS}$ =adjustCuts(i,j,$\mathbb{CUTS}$)
7:     Update $\mathbb{I}_{sum}$ with new series-parallel switch configuration: $\mathbb{I}_{sum}$ =calcSum($\mathbb{I}_{MPP}$,$\mathbb{CUTS}$)
8: **end while**
9: All switches in $\mathbb{CUTS}$ is configured as series, and all other as parallel connections: $SW_i = 1$, $\forall i$ s.t. $i \in \mathbb{CUTS}$
10: **return** $\mathbb{SW}$

The main design-time algorithm for reconfiguration switch insertion is shown in Algorithm 2. It finds the locations of K reconfiguration switch sets for a given set of solar irradiance inputs $\mathbb{G}_N$. The algorithm first calculates L the average number of PV cells in an atomic unit. Based on the observation from the previous subsection, it tries to find S, the number of cells in series in an atomic unit, also a divisor of L, which maximizes the flexibility (line 2). Then, the algorithm starts with a superset, $M/S-1$ reconfiguration switch sets – M is the total number of PV cells/modules – utilizing $S\times1$ atomic units. For each solar irradiance vector g_i, reconfiguration is performed to find the often utilized switch sets to be recorded in the vector $\mathbb{SW}_{hist}$ (lines 5 to 8). If a switch set is most of the times parallel connected (SW_i=0), the switch becomes fixed parallel connection, and the other way around when it is series connected. For the switch sets alternating between series and parallel connections, i.e., those having a value close to $N/2$ (line 10), we place switch sets there (lines 9).

VI. Experiments

In this section, various quantifiable simulation results are presented to justify the algorithm. PV cell behaviors are modeled using the equivalent circuit model in [6]. The MPP voltage and current values of the reconfigured array are obtained by formulating a non-linear optimization problem using

Algorithm 2: Heuristic algorithm to determine the locations of K reconfiguration switch sets.

Input: Number of switch sets K, set of irradiance $\mathbb{G}_N$, set of PV modules $\mathbb{PV}_M$, Total number of modules in series N_s

Output: Number of modules in series, S, in an atomic unit, and a set denoting locations of switch sets $\mathbb{LOC}$

Calculate the average number of modules in an atomic unit: $L = M/(K+1)$

Assuming the size of every atomic unit is L, determine S, which maximizes the flexibility using *combination with repetition*. s is a factor of L: $S = \mathbf{argmax}_s({}_{N_s/s}H_{K+1-N_s/s})$, $\forall s$ such that $s|L$

Now, assume an atomic unit of size $S \times 1$ and a reconfiguration switch is between every atomic unit, i.e., $\mathbb{LOC} = \{1, 2, \cdots, M/S-1\}$

Initialize a log vector variable, $\mathbb{SW}_{hist}$, of length $M/S-1$: $\mathbb{SW}_{hist} = (0, \cdots, 0)$

for $\forall g_n \in \mathbb{G}_N$ **do**

  Derive a vector, $\mathbb{SW}_n$, the output of Algorithm 1: $\mathbb{SW}_n$ = Reconfigure(g_n,N_s/S,$\mathbb{LOC}$,$\mathbb{PV}_M$)

  Record the usage of switches: $\mathbb{SW}_{hist} = \mathbb{SW}_{hist} + \mathbb{SW}_n$

end for

Identify K switches that are switching between S and P the most often, i.e., $\mathbb{SW}_{hist}$ value close to $N/2$: $\mathbb{LOC}$ =argmin$K$(abs($\mathbb{SW}_{hist} - (N/2, \cdots, N/2)$))

return S, $\mathbb{LOC}$

MATLAB's *fmincon* function. First, the observation regarding the relationship between the atomic unit selection and the PV power generation is validated. We have performed simulation on a pyramid with four surfaces containing 30 cells each (120 in total). The mean power generation for 12×1, 6×2, 4×3, and 3×4 are 38.25 W, 46.12 W, 60.37 W, and 53.62 W, respectively. There is a clear trend that more flexibility leads to higher power generation.

Fig. 7 shows the power generation of three techniques, the proposed, uniform placement with 3×5 atomic units and with 5×3 atomic units, using 7 switch sets and aiming $N_s = 15$. We applied Algorithm 1 to obtain the results for the two baseline cases assuming that the quality is not too distant from [7] as it follows the same principle. While we have aggressively set the baselines to use the same number of reconfiguration switches, the proposed algorithm outperforms them by 7.2% and 14.8% for the 11 different light source vectors over 600 seconds. A semisphere with 60 PV cells shown in Fig. 4 is also studied. Fig 8 shows that the proposed technique outperforms the baselines by 8.6% and 31.3%, respectively. This is due to better placement of reconfiguration switches as shown in Fig. 9. Even though they all use the same number of switch sets, different sizes of their atomic units lead to different results. One thing to note is that the second atomic unit from the bottom row from the proposed technique has 3×1 size because it helps to balance the sum of I_{MPP} among groups. Here, we find a non-trivial observation that simply

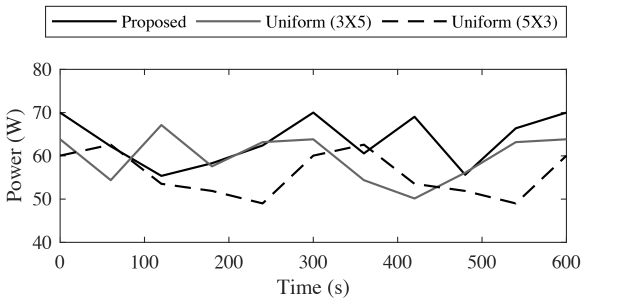


Fig. 7: Power generation over solar irradiance profiles for 120 cell array on a pyramid surface. Mean power is 63.63 W, 59.37 W, and 55.41 W, respectively for three cases.

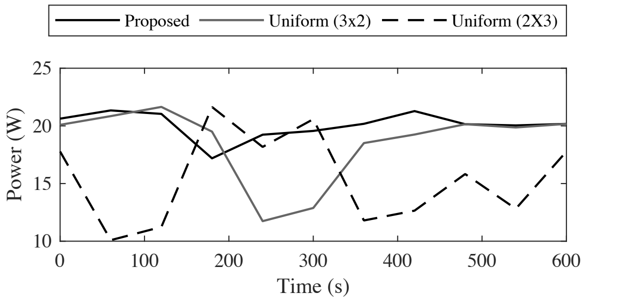


Fig. 8: Power generation over solar irradiance profiles for 60 cell array on a semisphere surface. Mean power is 20.04 W, 18.45 W, and 15.26 W, respectively for three cases.

grouping the similar irradiance cells might not be optimal. The location of switch sets in the figure ($\mathbb{LOC}$) is fixed over the evaluation, but the series parallel configuration ($\mathbb{SW}$) will change according to Algorithm 1.

Finally, Fig. 10 shows the impact of number of reconfiguration switches. It is quite clear that the more number of switches provide more flexibility. However, careful placement of the switches plays an important role as can be seen from the figure. Uniform placement of $X \times 1$ atomic units performs okay when the number of switches is large, but their performance degrades as fewer switches are available. On the other hand, the proposed technique is able to retain 80% of power while

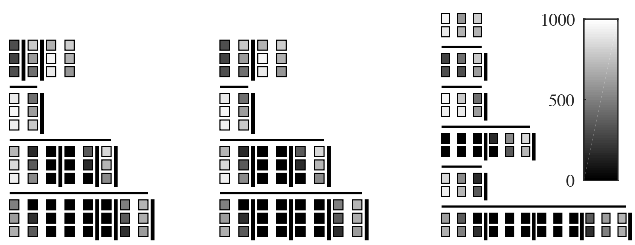


Fig. 9: Switch location and configuration for the first irradiance vector on 60 cell sphere array. Left: proposed, center: uniform 3×2, right: uniform 2×3. Color denotes irradiance in (W/m^2)

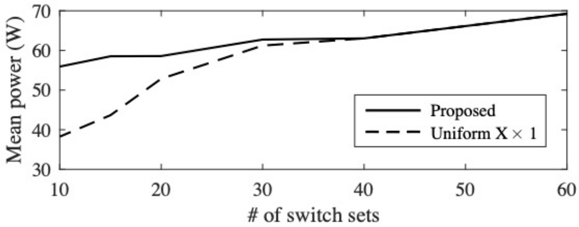


Fig. 10: Trade off between the number of reconfiguration switch sets and the power output for the pyramid example.

the number of switch sets are reduced from 60 to 10.

Cost analysis: The cost of power generation from PVs has come down dramatically recently. The actual cost savings due to the reduction in the number of reconfiguration switches depends on the size of the atomic units relative to the number of reconfiguration switches. In the electric vehicle example, we are assuming the usage of four panels, M536100, each capable of generating 100 W, which roughly translates to the cost of 800 to 1,000 USD. For this application, our assumed cost of a conservatively selected MOSFET switch, BUK9M24-40E, with the maximum drain current of 30 A is around 0.18 USD. If 60 switch sets (3 switches each) are used then the total cost of reconfiguration switches would be 32.4 USD plus the costs for MOSFET drivers [17]. In this application, the reduction of switch cost reduction is only a fraction of 32.4 USD because it the technique only affect the switch costs. However, there will be a significant reduction in the wiring harness, which results in easier manufacturing and cost reductions. This is in line with the findings of previous works such as [11].

VII. Concluding Remarks

In this paper, we propose a design time framework to maximize the power generation of a PV array on an irregular surface. The proposed method offers complexity reduction in wiring harness of reconfigurable PV systems on irregular surfaces of vehicles, buildings or wearables by suggesting the best locations for reconfiguration switches, which best cope with runtime changes of solar incidence angles. In contrast to most previous dynamic reconfiguration techniques assuming a uniform placement of switches to mitigate partial shading effect or to detect faults, this is the first work to tackle non-homogeneous operating conditions due to the irregular surface using dynamic reconfiguration. While the proposed technique is highly effective in reducing the number of switches and wiring harness, joint consideration with electrical placement of the PV cells themselves on the irregular surface can be done in the future to further optimize the power generation and reduce the complexity of the system.

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References

[1] M.-I. Baka, F. Catthoor, and D. Soudris. Near-static shading exploration for smart photovoltaic module topologies based on snake-like configurations. *ACM Trans. Embed. Comput. Syst.*, 15(2):27:1–27:21, 2016.

[2] S. K. Das, D. Verma, S. Nema, and R. Nema. Shading mitigation techniques: State-of-the-art in photovoltaic applications. *Renewable and Sustainable Energy Reviews*, 78:369 – 390, 2017.

[3] X. Gong and M. Kulkarni. Design optimization of a large scale rooftop photovoltaic system. *Solar Energy*, 78(3):362 – 374, 2005.

[4] M. Jazayeri, K. Jazayeri, and S. Uysal. Adaptive photovoltaic array reconfiguration based on real cloud patterns to mitigate effects of non-uniform spatial irradiance profiles. *Solar Energy*, 155:506 – 516, 2017.

[5] J. Kim, Y. Wang, M. Pedram, and N. Chang. Fast photovoltaic array reconfiguration for partial solar powered vehicles. In *ISLPED*, 2014.

[6] W. Lee, Y. Kim, Y. Wang, N. Chang, M. Pedram, and S. Han. Versatile high-fidelity photovoltaic module emulation system. In *ISLPED*, 2011.

[7] X. Lin, Y. Wang, S. Yue, D. Shin, N. Chang, and M. Pedram. Near-optimal, dynamic module reconfiguration in a photovoltaic system to combat partial shading effects. In *DAC*, 2012.

[8] X. Lin, Y. Wang, D. Zhu, N. Chang, and M. Pedram. Online fault detection and tolerance for photovoltaic energy harvesting systems. In *ICCAD*, 2012.

[9] P. Manganiello, M. Baka, H. Goverde, T. Borgers, J. Govaerts, A. van der Heide, E. Voroshazi, and F. Catthoor. A bottom-up energy simulation framework to accurately compare pv module topologies under non-uniform and dynamic operating conditions. In *IEEE PVSC*, 2017.

[10] NASA. Helios Prototype. https://www.dfrc.nasa.gov/Gallery/Photo/Helios/HTML/ED01-0209-3.html, 2001.

[11] D. J. Pagliari, S. Vinco, E. Macii, and M. Poncino. Irradiance-driven partial reconfiguration of pv panels. In *Design, Automation Test in Europe Conference Exhibition (DATE)*, pages 884–889, March 2019.

[12] J. Park, H. Joshi, H. G. Lee, S. Kiaei, and U. Y. Ogras. Flexible pv-cell modeling for energy harvesting in wearable iot applications. *ACM Trans. Embed. Comput. Syst.*, 16(5s), 2017.

[13] S. Park and S. Chakraborty. Design optimization of photovoltaic arrays on curved surfaces. In *Design, Automation Test in Europe Conference Exhibition (DATE)*, 2018.

[14] H. Patel and V. Agarwal. Matlab-based modeling to study the effects of partial shading on pv array characteristics. *IEEE Transactions on Energy Conversion*, 23(1):302–310, March 2008.

[15] K. Sundareswaran, V. Vignesh kumar, and S. Palani. Application of a combined particle swarm optimization and perturb and observe method for mppt in pv systems under partial shading conditions. *Renewable Energy*, 75:308 – 317, 2015.

[16] J. Urbanetz, C. D. Zomer, and R. Rüther. Compromises between form and function in grid-connected, building-integrated photovoltaics (bipv) at low-latitude sites. *Building and Environment*, 46(10):2107 – 2113, 2011.

[17] Y. Wang, X. Lin, M. Pedram, J. Kim, and N. Chang. Capital cost-aware design and partial shading-aware architecture optimization of a reconfigurable photovoltaic system. In *Design, Automation Test in Europe Conference Exhibition (DATE)*, pages 909–912, March 2013.