Technical report

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Abstract

In this report, a genetic algorithm-based method is implemented for the optimal grouping of mismatched photovoltaic (PV) panels. Due to inherent inconsistencies in maximum power point voltage (Vmp) and current (Imp) among individual panels, conventional grouping often results in significant power loss. This work proposes a structured genetic algorithm (GA) to generate valid parallel-series configurations while enforcing voltage and current consistency constraints. The algorithm was evaluated using real-world panel data, and the optimized output power was benchmarked against randomly generated configurations. The result demonstrated a 28.5% increase in total power output compared to the average baseline.

Introduction

In PV systems composed of multiple modules, optimal string and group arrangement becomes increasingly important, especially under mismatched conditions. Real-world PV panels often exhibit nonuniform characteristics such as differing Vmp and Imp, caused by manufacturing tolerances, aging, or environmental factors. Improper grouping of such panels can lead to severe mismatch losses due to current limitations in series strings and voltage unbalance in parallel connections.

To address this issue, specific electrical constraints must be satisfied during panel arrangement:

1. Series string voltage constraint: The total voltage of each series-connected string (sum of Vmp values) must remain within a narrow engineering window, typically 360 V to 400 V, to match DC-DC converters or inverters.
2. String current consistency constraint: Within a series string, all panels must exhibit similar Imp values. Otherwise, the lowest Imp limits the current, causing underutilization of other panels.
3. Group voltage uniformity constraint: For multiple strings connected in parallel (within the same group), their total voltages must be closely matched—voltage deviation exceeding 10% can cause unequal loading and safety issues.

Given these strict constraints, manual arrangement is not feasible for large-scale panel datasets. This report proposes a genetic algorithm (GA) framework that constructs and evolves population-based arrangements, selecting the most efficient groupings based on power output and constraint satisfaction.

System Modelling and Genetic Algorithm Design

Panel Representation and Data Preprocessing:

Each photovoltaic panel is modelled using four electrical parameters derived from its datasheet or experimental characterization:

Voc: Open-circuit voltage

Isc: Short-circuit current

Vmp: Voltage at maximum power point

Imp: Current at maximum power point

Before optimization, the panel data is pre-processed from a CSV file (dataset1.csv). Only complete data rows are retained. Each panel is represented as a Python dictionary and indexed with a unique id.

For example: {'id': 0, 'Voc': 45.2, 'Isc': 9.8, 'Vmp': 37.4, 'Imp': 9.4}

Genetic Algorithm Workflow:

The GA employed in this study follows a standard evolutionary framework consisting of initialization, evaluation, selection, crossover, mutation, and elitism. What distinguishes this implementation is its built-in handling of electrical constraints at each step to ensure realistic PV panel arrangement.

Algorithm Purpose and Challenges:

The GA is designed to optimize the grouping of mismatched PV panels into valid series-parallel configurations that maximize total power output. The key challenge lies in ensuring that each string and group meets strict electrical constraints, which are:

1. Each string must have a total Vmp between 360 V and 400 V
2. All panels in a string must have similar Imp (≤ 10% deviation)
3. All strings in a group must have closely matched voltages (≤ 10% deviation)

Individual Structure (Chromosome Encoding):

Each individual in the population represents a complete layout plan composed of G arrays, where G is the total number of arrays formed based on the number of panels. Each array contains M = 5 parallel strings, and each string consists of 6 to 12 panels connected in series.

Initialization: Panel Selection with Constraints:

Panels are shuffled and sorted by Imp.

For each string, panels are selected that: (1) Have total Vmp between 360 V and 400 V; (2) Have Imp values within 10% range.

No panel is reused across strings.

Repeat until G arrays × 5 strings are constructed for each individual.

Fitness Function: Array-Level Power Evaluation:

For each array:

1. Line current is the lowest Imp among all 5 strings.
2. Array voltage is the sum of Vmp of all strings.
3. Array power = line current × array voltage.

If any string or array violates constraints, a penalty is applied.

Total fitness = sum of valid array powers – penalties.

Evolution: Selection, Crossover, Mutation:

Selection: Tournament selection.

Crossover: One-point crossover at array level.

Mutation: Randomly replace panels within strings (with unused ones).

Elitism: Carry the best individual to the next generation.

Experimental Setup Summary:

A total of 500 PV panels were provided. After cleaning and validation, 10 arrays were constructed, each containing 5 parallel strings. Each string consists of 6–12 series-connected panels, forming a complete GA-optimized configuration.

|  |  |
| --- | --- |
| Metric | Value |
| Total Output Power | 195,573.42 W |
| Number of Arrays (G) | 10 |
| Average Power per Array | 19,557.34 W |
| Max Power among Arrays | 24,995.83 W |
| Min Power among Arrays | 13,217.98 W |

The optimized configuration produced a total output power of 195,573.42 W, with arrays achieving a power range from 13,217.98 W to 24,995.83 W. This confirms the algorithm's ability to form voltage-consistent and current-balanced groups while maximizing usable output.

Random Layout Baseline Comparison:

To verify the effectiveness of the genetic algorithm, 30 random layout schemes were generated using the same number of strings and the same average string length as the optimized result. Each string was formed by randomly selecting panels without considering electrical constraints. The resulting power outputs were as follows:

|  |  |
| --- | --- |
| Metric | Value (W) |
| Average Random Power | 164,798.75 W |
| Maximum Random Power | 168,105.84 W |
| Minimum Random Power | 163,426.83 W |
| Optimized Power | 195,573.42 W |
| Improvement | 24,240.00 W |

Note: Due to the stochastic nature of the GA, the exact optimized result may vary slightly per run. However, the power improvement consistently remains significant.

This report presents a GA-based method for optimizing the electrical grouping of mismatched PV panels. By enforcing realistic engineering constraints—including string voltage limits, current consistency, and group-level voltage uniformity—the algorithm successfully generates valid series-parallel configurations that consistently outperform random layouts. Due to the nature of genetic algorithms—such as stochastic selection and inheritance—and the limited number of generations designed for computational efficiency; the results may vary across runs. Nevertheless, all optimized configurations achieve a total output power improvement exceeding 14% compared to the average of 30 randomized groupings, demonstrating the robustness and practical effectiveness of the proposed method under strict physical constraints.

Several key observations emerged during the experiment:

1. The GA consistently converges to high-performance layouts within 30 generations, suggesting good stability and efficiency.
2. Arrays with well-balanced string voltages tend to dominate the final configurations, confirming the importance of voltage uniformity in parallel connections.
3. Mutation rate and initial pool diversity play an important role in avoiding local optima. Future work can investigate adaptive mutation schemes or hybrid metaheuristics.
4. While the absolute optimized power may slightly fluctuate across runs, the relative advantage over random layouts remains steady, making the algorithm reliable for practical deployment.