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# Investigation on Dynamic PV Array Reconfiguration Performance Enhancement under Non-Uniform Partial Shading Conditions

## Booklet of PhD Theses


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**Miskolc**
**2025**

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# 1. INTRODUCTION

The increasing demand for renewable energy, coupled with growing environmental concerns, has driven significant interest in photovoltaic (PV) systems as a sustainable energy solution. Solar energy has emerged as a viable alternative to conventional energy sources, with PV panels playing a crucial role in electricity generation through the photoelectric effect [1]. The first PV cell, developed by Charles Fritts in 1883, had a low power conversion efficiency (PCE) of 1% [2]. However, advancements in materials and manufacturing have significantly improved PV technology, making it an essential component of the modern renewable energy landscape [3].

## 1.1 Classification and Operation of PV Systems

PV systems are categorized into grid-connected, off-grid, and hybrid types. Grid-connected systems feed excess power into the electrical grid, reducing reliance on battery storage [4]. Off-grid systems utilize battery storage, providing energy independence, particularly in remote locations [5]. Hybrid systems combine grid connectivity with energy storage, ensuring reliability under varying sunlight conditions [6]. PV applications range from household energy generation to industrial power supply, telecommunications, military operations, and satellite systems

[7]. The efficiency and cost-effectiveness of these systems depend on their configuration and the specific application requirements.

## 1.2 Types of Solar Panels

PV panels are classified based on technology generations and the number of layers interacting with sunlight. The three main generations include:

**A. First Generation:** Monocrystalline and Polycrystalline Silicon (Mono-SI and Poly-SI) panels. Monocrystalline panels offer high efficiency (~20%) and longevity but are costly. Polycrystalline panels provide a cost-effective alternative with slightly lower efficiency (~15%) [8].

**B. Second Generation:** Thin-Film Solar Cells (TFSC), which are lightweight and flexible but have lower efficiency (~7-10%) and require more installation space [9].

**C. Third Generation:** Advanced solar cells such as Cadmium Telluride (CdTe) and Concentrated PV (CPV). CPV technology offers the highest efficiency (~41%) using solar concentration techniques but requires precise sun tracking and large installation areas [10].

## 1.3 Modeling of PV Cells

PV cells convert sunlight into electricity using semiconductor materials, typically configured as p-n junctions. The one-diode model is widely used for mathematical representation due to its simplicity [11]. The electrical behavior of PV cells is governed by equations incorporating key parameters such as light-generated current, diode saturation current, series resistance, shunt resistance, and thermal voltage [12].

## 1.4 Challenges and Technological Advancements

Partial Shading (PS) is a significant challenge for PV arrays, leading to power loss and hot spots that can damage solar panels [13]. Bypass diodes are used to mitigate shading effects but introduce multiple peaks in the Power-Voltage (P-V) curve, affecting overall efficiency [14]. Various PV interconnection configurations, including Series-Parallel (SP), Total Cross-Tied (TCT), Bridge-Linked (BL), and Honeycomb (HC), have been developed to minimize mismatch losses [15]. Among these, TCT is considered the most effective in reducing mismatch losses [16][17].

Dynamic PV array reconfiguration is a promising solution to compensate for shading-induced power loss. Unlike static reconfiguration, which rearranges the physical layout of PV panels, dynamic reconfiguration changes electrical interconnections in real time based on shading conditions [18]. This technique requires sensors, controllers, and switching matrices, increasing system complexity but improving efficiency [19]. Heuristic algorithms have been explored to optimize reconfiguration strategies, balancing computational cost and energy gains [20].

## 1.5 Research Objectives

This research aims to:

1. **Develop a Hierarchical PV Array Structure**: Design and implement a novel hierarchical PV array structure integrating automatic switching to mitigate partial shading losses.
2. **Create and Implement a Reconfiguration Algorithm**: Develop a dynamic algorithm to optimize energy harvesting by adjusting electrical connections based on real-time shading conditions.
3. **Conduct Simulation Studies**: Model the hierarchical PV array's performance across different shading scenarios using simulation tools.

4. **Validate Through Experimental Studies**: Set up a controlled experimental PV array to measure power production and system adaptability under shading conditions.
5. **Monitor Environmental Conditions**: Utilize sensors to measure solar irradiance and PV cell temperature for accurate data collection.
6. **Optimize System Design**: Enhance the scalability, efficiency, and cost-effectiveness of the hierarchical PV array structure.

## 2. PROPOSED SCHEME

This research introduces several innovative reconfiguration schemes aimed at enhancing the efficiency of photovoltaic (PV) systems under partial shading (PS) conditions. The proposed methodologies leverage hierarchical switching architectures, advanced real-time adaptation mechanisms, and intelligent control algorithms to optimize PV array performance.

### 1. Model-A: Controller-Based Dynamic Switching Blocks (SBs)

Model-A introduces a hierarchical dynamic system that utilizes switching blocks (SBs) controlled by microcontrollers. Each SB comprises two relays that switch PV panel connections between series and parallel modes based on real-time shading conditions, determined by a solar irradiance sensor cell (SISC). When a panel's power drops below a predefined threshold (e.g., 50% of maximum power), the system dynamically isolates the shaded panel, thereby preventing power losses and potential damage. This model offers a modular structure, allowing seamless scalability and adaptability without requiring a complete system redesign.

### 2. Model-B: Hierarchical Link Block Architecture

Building upon Model-A, Model-B employs an advanced link block (LB) structure to further enhance system scalability and adaptability. This design allows for the integration of multiple PV panels in various configurations, including series-parallel (SP), bridge-linked (BL), and total-cross-tied (TCT), in addition to the Model-A layout. By leveraging real-time data from solar radiation sensors, the system dynamically adjusts interconnections to minimize shading-induced mismatch losses and maximize power output. The scalable architecture makes Model-B a versatile and robust solution for optimizing PV arrays in dynamic environmental conditions.

## 3. Dynamic Probabilistic Reconfiguration Algorithm (DPRA)

The third proposed scheme introduces the Dynamic Probabilistic Reconfiguration Algorithm (DPRA) within a hierarchical switching array to optimize PV performance under partial shading and temperature variations. This system organizes switching blocks (SBs) into multiple layers, assigning probability values to dynamically reconfigure connections based on real-time irradiance and temperature data. The DPRA operates in two stages:

1. Isolating shaded or overheated panels using environmental sensor data.
2. Reintegrating panels into an optimized configuration to track the maximum power point (MPP) efficiently.
3. By excluding inefficient configurations and limiting adjustments to six optimized layouts, DPRA simplifies the reconfiguration process while ensuring high adaptability, reliability, and scalability.

## 4. HLLBE Algorithm: Highest and Lowest Layer-Based Exchange

The Highest and Lowest Layer-Based Exchange (HLLBE) Algorithm enhances the system by redistributing PV panels based on irradiance levels and real-time current output. Using a mathematical model, the algorithm dynamically adjusts the panel positions across different layers to equalize radiation distribution and minimize power mismatches. By mitigating the effects of shaded panels, HLLBE improves energy yield, reduces efficiency losses, and strengthens overall system stability.

Key Advantages of the Proposed Schemes

- Real-Time Adaptability: Dynamic response to shading and temperature fluctuations.
- Optimized Maximum Power Point Tracking (MPPT): Enhanced efficiency with DPRA-based probabilistic reconfiguration.
- Scalability & Modularity: Supports hierarchical expansions without redesigning the entire system.
- Improved Reliability: Prevents hot spots, prolonging PV panel lifespan.
- Hybrid Integration: Seamlessly incorporates traditional and advanced reconfiguration techniques for enhanced performance.

These innovative methodologies provide a comprehensive framework for maximizing photovoltaic system efficiency, ensuring resilient energy generation even in challenging environmental conditions.

## 3. SYSTEM DESIGN

The proposed system architecture dynamically reconfigures PV panels using hierarchical switching blocks (SBs) and real-time sensor data. Key components include:

- PV Array: Nine solar panels configured for dynamic interconnections.
- Microcontrollers: Arduino Mega (PCU) and Arduino Uno (SCU) manage real-time data acquisition, control, and communication.
- Sensors: Solar irradiance (SISC), voltage, current, temperature (DS18B20), and light intensity (BH1750).
- Communication: ZigBee wireless modules enable remote monitoring.
- Software: Arduino IDE for control logic, XCTU for ZigBee, and MATLAB/Simulink for simulations.

Figure 1. This diagram demonstrates how PV panels, microcontrollers, sensors, wireless modules, and software tools come together in a hierarchical design.

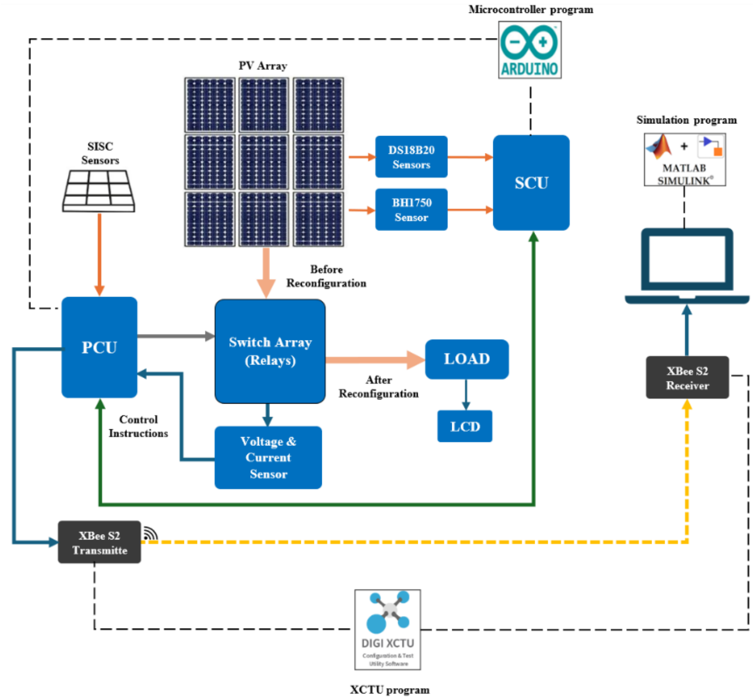


**Figure 1**: System achitecture of the proposed scheme.

## 3.1 Research Methodology

The research employs a hybrid approach involving computer simulation and practical experimentation to evaluate PV system performance.

## A. Computer Simulation

MATLAB Simulink (R2023b) models a nine-panel PV system, assessing performance under varying irradiance (200–1000 $W/m^2$) and temperature (15–45°C). The hierarchical switching model allows flexible PV configurations, including Series-Parallel (SP), Bridge-Linked (BL), and Total Cross-Tied (TCT), for comparative analysis.

## B. Practical Implementation

The hardware setup mirrors the simulated system, ensuring consistency. Key aspects include:

- Dynamic reconfiguration: Implemented via SBs and relay-based switching mechanisms.
- Sensor integration: Continuous monitoring of solar irradiance, voltage, current, and temperature.
- SCU-PCU communication: SCU handles environmental data, while PCU executes reconfiguration algorithms.
- Real-time data acquisition: XBee facilitates wireless monitoring and logging.

### 3.1.1 Simulation & Experimental Analysis

#### A. System Models: Model-A vs. Model-B

Two hierarchical PV models were evaluated:

- **Model-A**: Every two solar panels share one SB, offering basic reconfiguration.
- **Model-B**: Every three panels share two SBs, introducing Link Blocks (LBs) for enhanced flexibility and efficiency. Model-B dynamically emulates traditional PV configurations, ensuring optimal adaptability.

Figure 2 shows how each panel pair is connected via a dedicated SB, allowing dynamic switching between series or parallel modes, while Figure 3 illustrates how LBs build upon the Model-A principle to provide even richer interconnection possibilities.

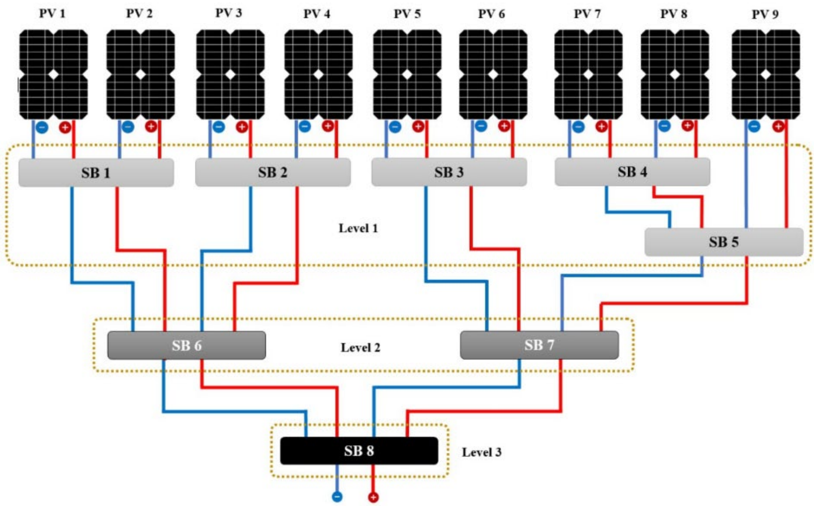


**Figure 2** : Configurable operational modes with switches in Model-A.

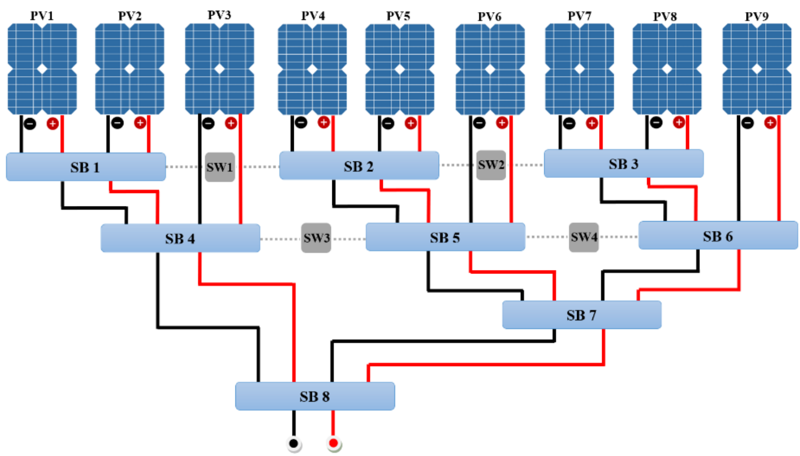


**Figure 3** : Configurable operational modes with switches in Model-B.

### 3.1.2 Practical Implementation

#### A. PV Array & Switching Blocks

- Hierarchical relay-based switching (Figure 4) dynamically adjusts PV connections between series and parallel modes.
- SB Layers:
    - First Layer: 5 SBs (10 relays) – connects panels.
    - Second Layer: 2 SBs (4 relays) – refines connections.
    - Third Layer: Load Block (SB8) – final power output.

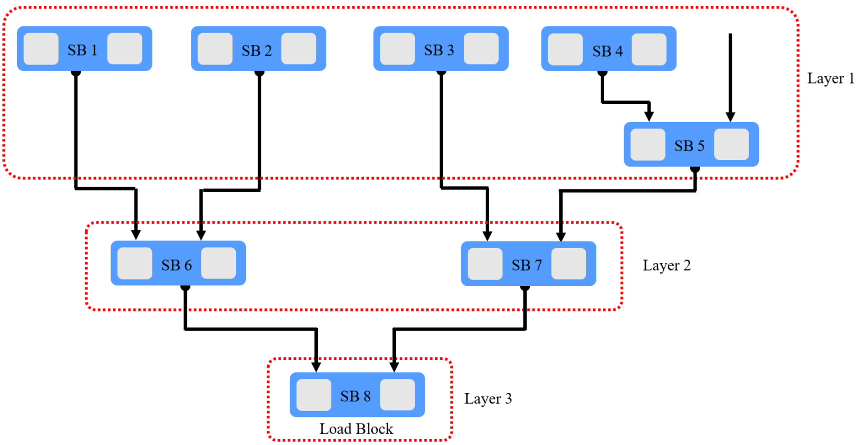


**Figure 4**: The hierarchical structure of SBs in switch array.

## B. Sensor Integration

- SISC Sensors: Measure solar irradiance adjacent to PV panels.
- Voltage/Current Sensors: Monitor real-time power output and efficiency.
- BH1750 Light Sensor: Detects shading and dust accumulation, optimizing maintenance.
- DS18B20 Temperature Sensors: Prevent overheating and maintain panel efficiency.

Figure 5 illustrate sensors placement and circuit integration.

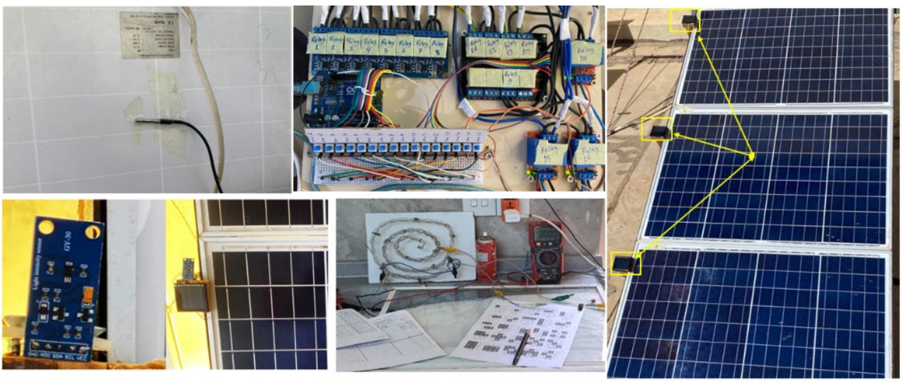

**Figure 5**: Sensor placement and circuit integration.

## C. Software Implementation

### 1. Microcontroller Programming

- SCU Software: Manages light & temperature sensors, triggering alerts for shading anomalies and overheating risks.
- PCU Software: Implements a three-stage reconfiguration process:
    - Shading Threshold Adjustment: Disconnects shaded panels.
    - Layer Probabilities (DPRA Algorithm): Reconfigures SBs dynamically for optimal MPPT.
    - Switching Block Probabilities: Tracks MPPT across 30 optimized configurations.

Figure 6 present algorithm flowcharts for these reconfiguration strategies.

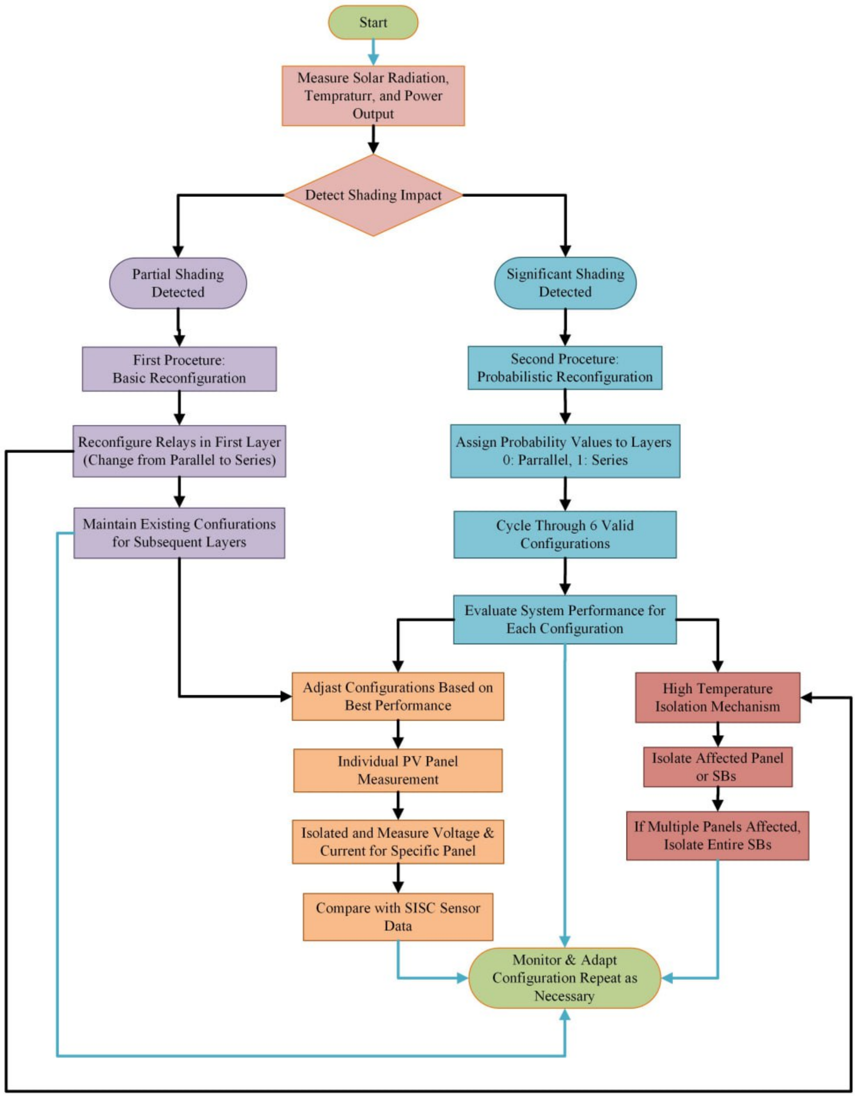


**Figure 6** : Flowchart of the three-stage reconfiguration.

## 2. High-Temperature PV Panel Isolation

- Panels exceeding a critical temperature are isolated to prevent efficiency losses.
- SBs dynamically adjust relay connections to reroute power flow without disrupting operation.
- Voltage/current sensors validate PV performance, ensuring reconfiguration accuracy.

Figuer 7 depicts how a DS18B20 sensor reading triggers the PCU to isolate overheating panels via SBs.

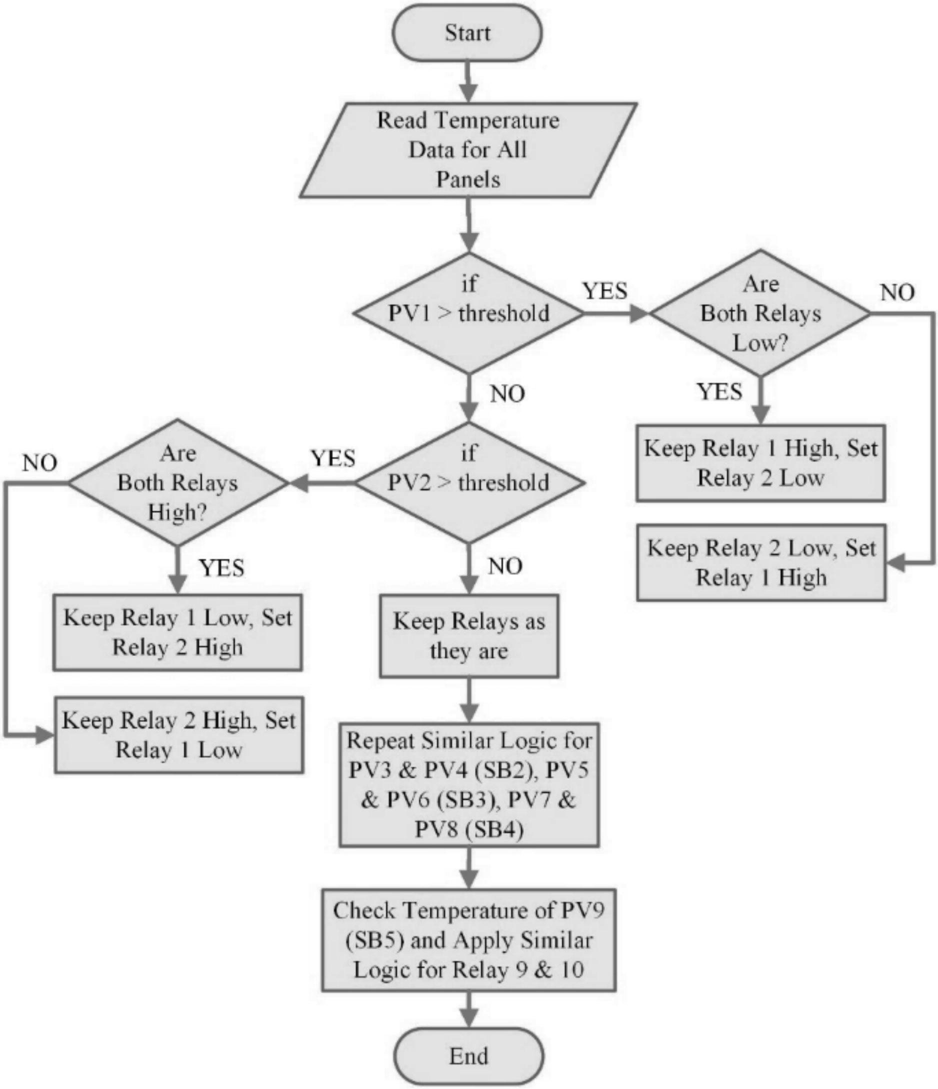


**Figure 7**: Temperature-based isolation logic.

### D. XBee-Based Real-Time Data Monitoring

- PCU transmits data wirelessly via XBee, displaying real-time voltage, current, temperature, and irradiance levels.
- Serial Monitor & MATLAB Interface: Enables remote monitoring & logging for performance analysis.

## 4. SIMULATED AND EXPERIMENTAL PS ANALYSIS

The system's performance under shading was evaluated through simulated and experimental studies, analyzing shading impacts on PV efficiency and optimizing energy output via dynamic reconfiguration.

### A . First Scenario: Two-Stage Simulation

Figures 8 and 9 illustrate random-shading and fixed-shading scenarios, respectively, in a sample case. In both figures, part (a) shows the array before reconfiguration, while part (b) displays the improved distribution after dynamic reconfiguration.

- **Stage 1:** Random shading (200–900 W/m$^2$).

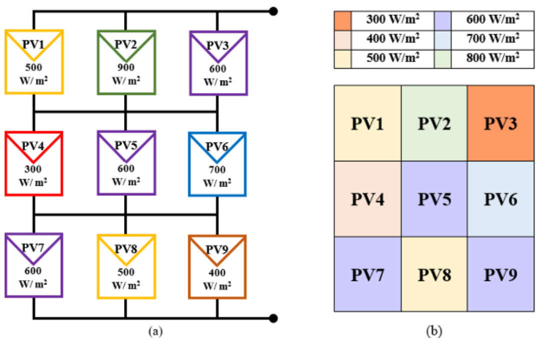


**Figure 8** : Random-shading a) Before reconfiguration. b) After reconfiguration.

- **Stage 2:** Fixed shading (100 W/m²) on shaded panels, 1000 W/m² on unshaded panels.

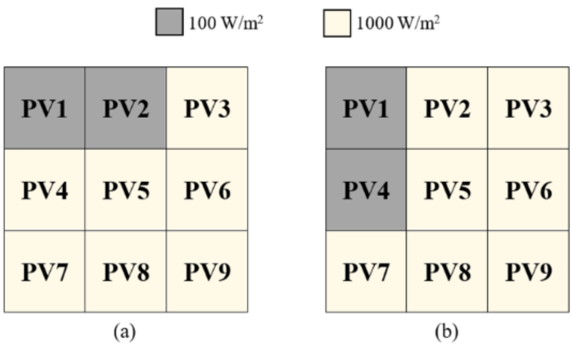


**Figure 9**: Fixed-shading a) Before reconfiguration. b) After reconfiguration.

## B. Second Scenario: 18 Shading Cases

- Tested 18 shading scenarios (shown in Figure 10).
- Used irradiance values 600, 480, 360, 120, 80, and 720 W/m².
- Analyzed MPPT performance with SP, BL, and TCT configurations

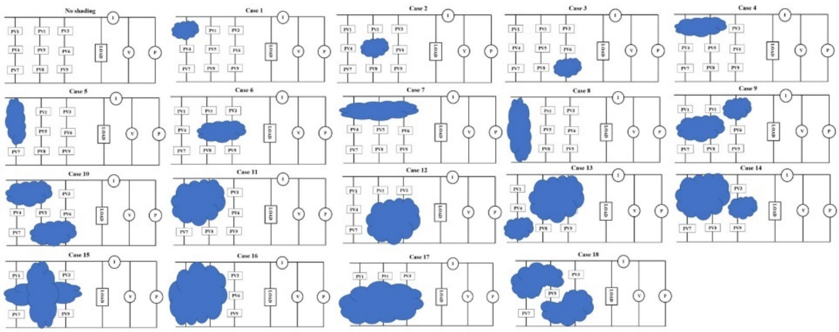

**Figure 10**: Patterns of shading on the solar PV array.

## C. Third Scenario: 25 Shading Cases & System Expansion

3 × 3 PV array tested under 25 PS conditions with irradiance 750, 500, and 250 W/m² is shown in Figure 11.

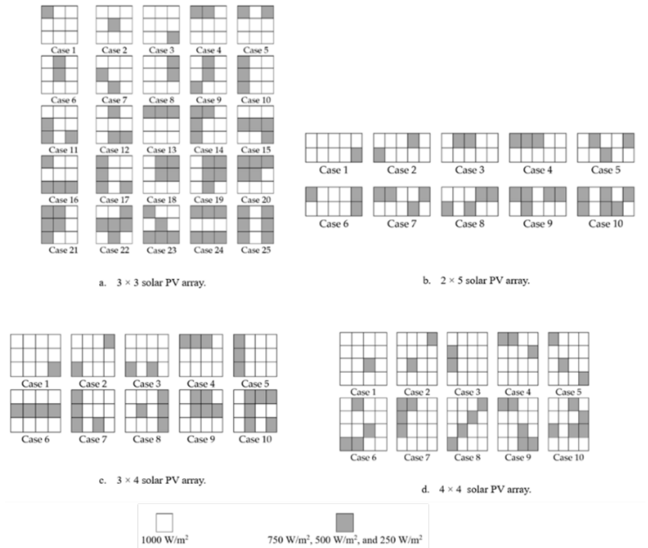


**Figure 11**: Shading patterns for different solar PV array configurations.

- **Stage 1:** Added 1 PV panel (**2 × 5 or 5 × 2**, shown in Figure 12)

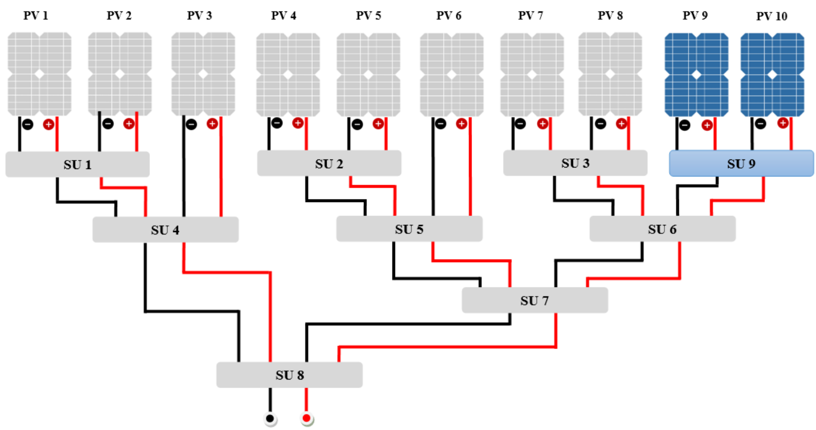


**Figure 12**: Expansion of the proposed system by adding one panel and an SB.

- **Stage 2:** Added 3 PV panels (**3 × 4 or 4 × 3**, shown in Figure 13).

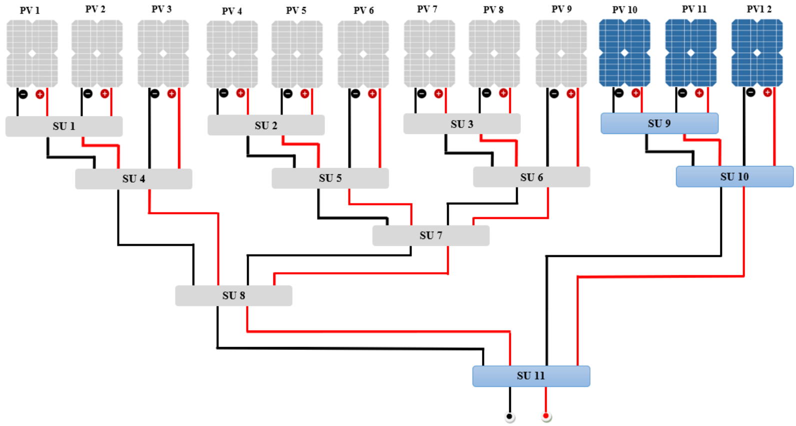


**Figure 13**: Expansion of the proposed system by adding three panels and three SBs.

- **Stage 3: 4 × 4 PV array** (shown in Figure 14).

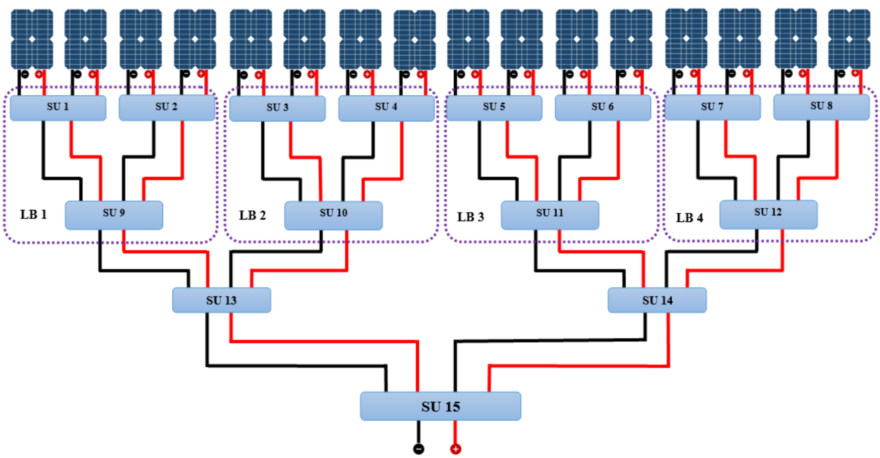


**Figure 14**: New (4 × 4) PV array for the proposed system.

## D. Experimental Scenario: Artificial Shading

The experiment analyzed 25 distinct shading patterns under four irradiance levels:

- 850 W/m² (No Shading) , 680 W/m² (20% Shading), 425 W/m² (50% Shading), 255 W/m² (70% Shading)
- A shading simulation was conducted using white raw fabric, which reduced sunlight by 10% per layer, with up to 80% shading applied (shown in Figure 15).

**Figure 15:** Different stages of shading applied using fabric layers.

# 5. NEW SCIENTIFIC RESULTS – THESES

## THESIS I

I have introduced a comprehensive system design and research methodology to enable dynamic PV array reconfiguration under partial shading conditions. This approach involved developing and comparing two conceptual frameworks: Model-A and Model-B. Model-A, simulated and practically implemented, connected every two solar panels with a single switching block, simplifying the hierarchical structure. Model-B offered a more advanced configuration by linking every three panels through two SBs within a link block, thereby enabling greater flexibility and the option to replicate various conventional PV arrangements such as SP, BL, and TCT.

I have integrated and calibrated essential components—microcontrollers, sensors, and relays—ensuring accurate data acquisition and reliable PV panel reconfiguration. In addition, I have introduced a hybrid simulation environment that combines MATLAB-Simulink with a microcontroller, confirming the practical feasibility and responsiveness of the chosen strategies. These efforts have laid a solid foundation for subsequent optimization and testing phases, ultimately enhancing the system's adaptability and overall performance under non-uniform irradiance conditions.

**Publications related to Thesis I:** [P1],[P3],[P4]

## THESIS II

I proposed the Highest and Lowest Layer-Based Exchange (HLLBE) Algorithm, a novel approach for dynamic reconfiguration of PV arrays to tackle partial shading issues. The HLLBE algorithm employs a reconfigurable switch matrix to equalize irradiance levels across PV array layers, optimizing power output while minimizing switching operations. This method significantly reduces multiple peaks in power-voltage curves and enhances system adaptability to varying shade patterns. Simulation results demonstrated that the HLLBE algorithm improved efficiency by up to 116.6% compared to traditional TCT configurations, all while maintaining a streamlined and cost-effective switch design, ultimately enhancing the efficiency and reliability of PV systems.

**Publications related to Thesis II:** [P2]

## THESIS III

I developed a scalable hierarchical switching block architecture, Model-A, for dynamic PV array reconfiguration under partial shading. The system integrates SISCs and employs a threshold-based switching mechanism, enabling real-time adjustments of PV module connections to optimize MPPT performance. Simulations conducted in MATLAB–Simulink demonstrated superior results, with the system achieving an average power output improvement of 13.6% compared to SP, BL, and TCT configurations under partial shading conditions. When compared to advanced techniques such as TCT, Sudoku, and other dynamic proposals, the system achieved up to 39.37% improvement in power generation and 39.32% in efficiency. Its hierarchical architecture ensures scalability, adaptability, and enhanced energy harvesting, effectively addressing the challenges of partial shading.

**Publications related to Thesis III:** [P1]

## THESIS IV

I proposed Model-B, an optimization-driven dynamic PV array reconfiguration system that adapts electrical connections in real time based on irradiance sensor data. The system dynamically switches between series and parallel configurations, maximizing energy output and outperforming traditional methods such as SP, BL, and TCT. Simulations demonstrated scalability with seamless asymmetric and symmetric expansions, achieving an efficiency gain of up to 6.04% over TCT, Zig-Zag, and HPSO, while reducing the switch count by up to

79.17% compared to DES. This approach simplifies connections, reduces complexity, and enhances system robustness under diverse shading conditions.

**Publications related to Thesis IV:** [P3]

## THESIS V

I proposed a Dynamic Probabilistic Reconfiguration Algorithm (DPRA) to optimize PV system performance under partial shading and temperature variations. The DPRA employs a hierarchical switch array with SISCs and DS18B20 temperature sensors to dynamically adjust electrical connections in real time, minimizing mismatch losses and mitigating thermal degradation. By integrating minimal hardware, the system optimizes voltage and current flow, enhancing energy harvesting efficiency.

Simulation and experimental results demonstrated that the DPRA improved energy output compared to conventional configurations such as Series-Parallel (SP), Bridge-Link (BL), and Total-Cross-Tied (TCT). It achieved an average energy improvement of 32% in simulations and 39% in experimental results. The DPRA offers a scalable, cost-effective solution to enhance PV efficiency, extend panel lifespan, and adapt to diverse environmental conditions.

**Publications related to Thesis V:** [P4]

# 6. PUBLICATIONS RELATED TO THE DISSERTATION

[P1]. Ameen, F., Siddiq, A., Trohák, A., & Benotsmane, R. (2023). A Scalable Hierarchical Dynamic PV Array Reconfiguration under Partial Shading. Energies, 17(1), 181.

[P2]. Ameen, F., Trohák, A., Siddiq, A., & Benotsmane, R. (2024, May). Enhancing Photovoltaic Array Performance under Partial Shading through Dynamic Reconfiguration and Layer Equalization Algorithm. In 2024 25th International Carpathian Control Conference (ICCC) (pp. 1-6). IEEE.

[P3]. The paper titled "Scalable Dynamic Photovoltaic Array Reconfiguration Scheme for Mitigating Partial Shading" has been accepted for publication in the Tikrit Journal of Engineering Sciences (TJES), a Q3-ranked journal.

[P4]. The paper titled "Dynamic Probabilistic Reconfiguration for Optimized Photovoltaic Performance under Shading and Temperature Variations" has been accepted for publication in the International Journal of Intelligent Engineering and Systems (IJIES), a Q2-ranked journal.

[P5]. Ameen, F. N., Trohák, A., & Siddiq, A. (2023, November 23). Dynamic PV Array Reconfiguration for Maximized Power Generation under Partial Shading. Doktoranduszok Fóruma, University of Miskolc, Hungary.

[P6]. The paper titled "Review of Photovoltaic Array Reconfiguration Techniques for Mitigating the Effects of Partial Shading" has been submitted to Multidiszciplináris Tudományok. The submission is currently under review.

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