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# SYSTEM-LEVEL CONCEPTUAL ANALYSIS OF THERMAL BEHAVIOR IN SOLAR MICROGRIDS WITH FUZZY LOGIC PERSPECTIVE

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**Abstract.** Temperature control plays an important role in the performance of solar panel grids. At the system level, three key components are sensitive to thermal effects: solar panels, DC-DC converters, and storage batteries. In panels, increasing temperature reduces conversion efficiency, while in converters, it increases electrical losses and device stress, and in batteries, it accelerates capacity fade and shortens lifespan. Most research considers these effects in isolation. However, the thermal behavior of the grid is interconnected, and the heating of one element influences the performance of the others. This paper discusses temperature control strategies from a system-wide perspective by analyzing the sources of uncertainty and the ways thermal effects in one component influence others. Fuzzy logic is considered a possible solution for handling nonlinear behavior and overlapping operating conditions. The discussion highlights where thermal stress occurs in the grid and how more system-level control strategies may contribute to more effective temperature management in solar energy systems.

**Keywords**: solar microgrid, thermal management, fuzzy logic, DC–DC converter, battery, renewable energy.
**AMS Subject Classification:** 93C42, 93C15, 80A20.
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## 1 Introduction

Microgrids have emerged as a promising solution to meet the growing demand while improving reliability and sustainability. Unlike traditional centralized grids, microgrids can operate independently or in coordination with the main grid (Ashok Kumar & Amutha Prabha, 2022). Their flexibility allows them to provide continuous power even under variable conditions, making them increasingly relevant for remote communities, industrial sites, and modern smart city applications (Kermani et al., 2021). A typical solar microgrid integrates solar panels, DC-DC converters, and batteries (Albarakati et al., 2022). Each of these components presents unique thermal challenges. Solar panels lose efficiency as temperature increases, converters experience increased electrical losses and stress, and batteries degrade faster at elevated temperatures (Pérez Escobar et al., 2021). Moreover, thermal effects on one component can propagate and influence the performance of others, creating a complex network of interactions that complicates temperature management.

Most existing studies focus on individual components, such as cooling strategies for solar panels or thermal management of batteries, without considering the system as a whole. Few works take a system-level perspective that examines how thermal interactions between components affect overall performance (Yusubov & Bekirova, 2023). This gap makes it challenging to develop control strategies that account for uncertainty and the interconnected nature of microgrid operation.

This paper presents a system-level analysis of temperature control in solar microgrids, emphasizing the sources of uncertainty in the interactions between components. Conceptual fuzzy logic strategies are proposed to address the unpredictable behavior of each element. By considering the microgrid as an integrated system, the work offers a comprehensive perspective on temperature management, providing a foundation for future research and the development of potential control strategies.

## 2 Objective

The primary objective of this work is to examine how operational and environmental factors impact the performance of key components in a solar microgrid and to illustrate the importance of thermal control for system efficiency and reliability. Focusing on solar panels, DC–DC converters, and batteries, the study analyzes the sources of thermal variability and their effects on component behavior. Through this analysis, the paper provides a system-level perspective on temperature-related challenges and highlights the thermal interactions between components within the microgrid.

## 3 Materials and Methods

Figure 1 illustrates the general block diagram of a solar microgrid. The power generated by photovoltaic (PV) panels passes through DC-DC converters to regulate voltage and current for storage or local consumption. The converters feed a common DC bus, which interconnects the generation, conversion, and storage elements, ensuring voltage stability throughout the system (Ashok Kumar & Amutha Prabha, 2022).

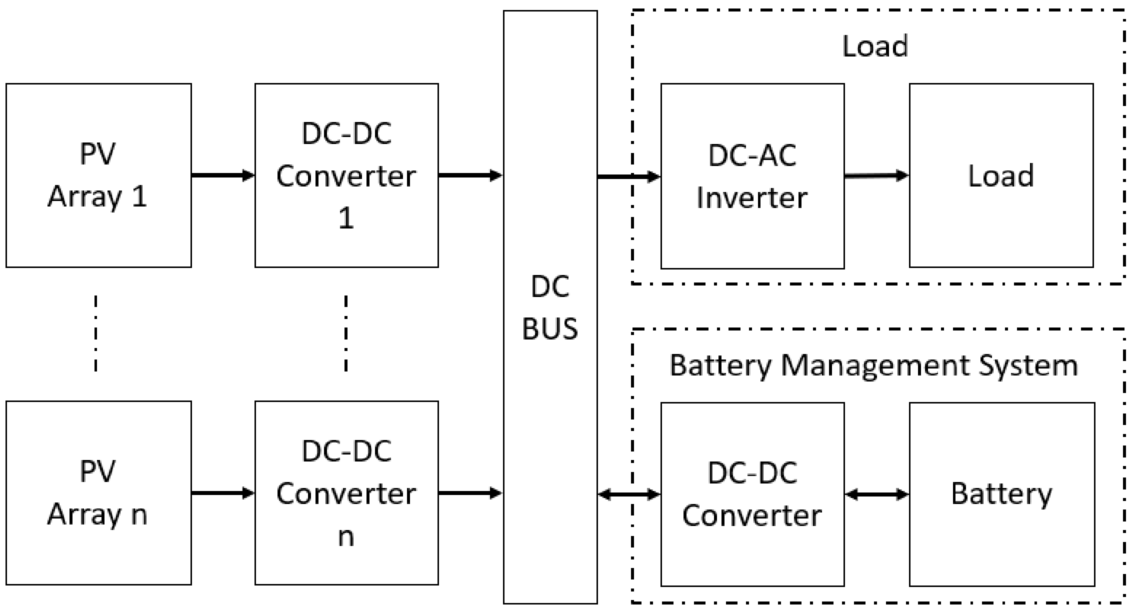


**Figure 1:** Block Diagram of a DC–DC Solar Microgrid

Thermal control in microgrid components is mainly determined by surface area, the specific thermal properties of the materials used, and the employed cooling mechanisms. Understanding the interactions, inputs, outputs, and thermal behavior of these components is a necessary foundation before exploring temperature management strategies and flexible control methods (Mammadov, 2025).

- Solar PV arrays: They convert sunlight into electrical energy, producing voltage and current that depend on irradiance and temperature. Variations in their output affect downstream converters and battery performance, making it important to monitor and understand their thermal behavior in the context of overall system operation.

- DC–DC converters: These regulate the power received from solar panels to match storage or load requirements. Their efficiency is influenced by temperature, load changes, and switching dynamics. Thermal stress in converters can reduce performance and propagate effects to both the generation and storage components.

- Batteries: They store excess energy when generation exceeds demand and supply energy when generation is insufficient. State of charge, temperature, and internal resistance influence their charge and discharge performance. Improper thermal management can not only degrade battery lifespan but also impact the stability of the connected system.

The thermal behavior of each component in the microgrid can be represented by the general heat balance equation, which relates heat generation, accumulation, and dissipation to describe temperature variation over time:

$$C\frac{dT}{dt} = Q_{\text{in}} - Q_{\text{out}} \tag{1}$$

Where $C$ is the thermal capacitance, $T$ is the component temperature, $Q_{\text{in}}$ is the heat input from generation or losses, and $Q_{\text{out}}$ is the heat dissipated to the environment. In Figure 2, the solar panel's layered structure is shown. Accounting for the thickness and material properties of each layer is essential, as they influence thermal resistance and the distribution of heat within the panel.

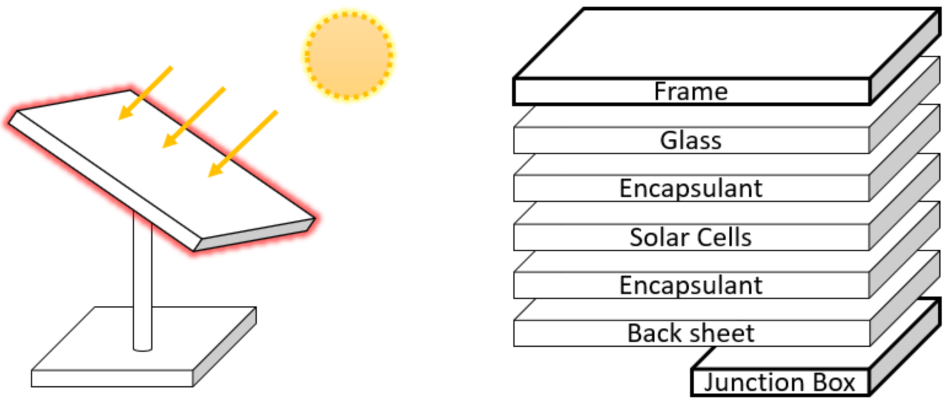


**Figure 2:** Thermal Distribution in the Solar PV Array

In the solar panels, heat is mainly dissipated through natural convection and thermal radiation from the module surface, with materials such as glass and aluminum frames influencing the transfer rate, and passive cooling is generally sufficient due to the large surface area and moderate operating temperatures (Borunda et al., 2022). Heat generation arises from absorbed sunlight that is not converted into electrical energy and from resistive losses in the current flow. The main factors include solar irradiance, panel area, conversion efficiency, and output current:

$$Q_{\text{in,Panel}} = (1 - \eta_{\text{pv}})\, GA + I^2 R_{\text{int}} \tag{2}$$

Where $\eta_{pv}$ is the panel conversion efficiency, $G$ is the solar irradiance, $A$ is the panel area, I is the current output, and $R_{int}$ is the internal resistance of the panel. In Figure 3, the N-channel region of a MOSFET inside a Zeta converter is marked as the primary hot spot.

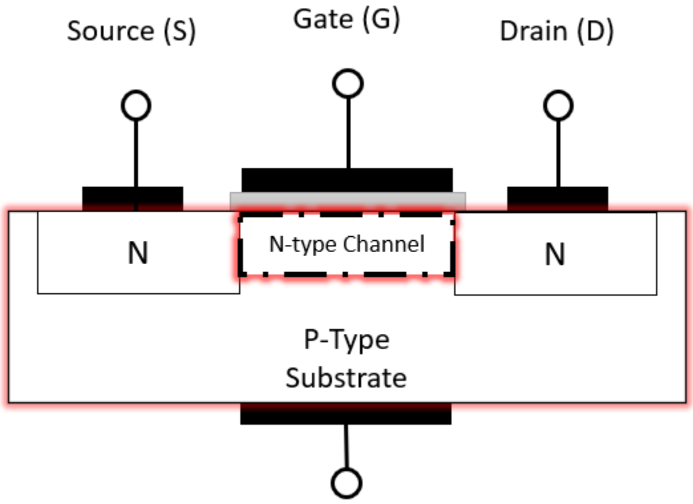


**Figure 3:** Thermal Distribution in DC–DC Converter MOSFETs

DC-DC converters often generate higher localized heat due to switching losses and conduction in semiconductor devices (Yusubov & Bekirova, 2023). Dissipation depends on the thermal conductivity of the semiconductor and packaging materials, with active cooling such as heat sinks combined with forced air or liquid systems often required to maintain safe operating conditions. Heat production is determined by load current, conduction resistance, switching frequency, and overall device efficiency. This can be expressed as:

$$Q_{\text{in,Converter}} = I^2 R_{\text{eq}} + P_{\text{switch}} \tag{3}$$

Where $I$ is the current through the converter, $R_{eq}$ is the equivalent conduction resistance of the devices, and $P_{switch}$ represents switching losses during operation. In Figure 4, the thermal behavior of a battery pack is shown, where middle cells often heat up more (red) than side (yellow) or corner (blue) cells due to limited airflow and thermal pathways.

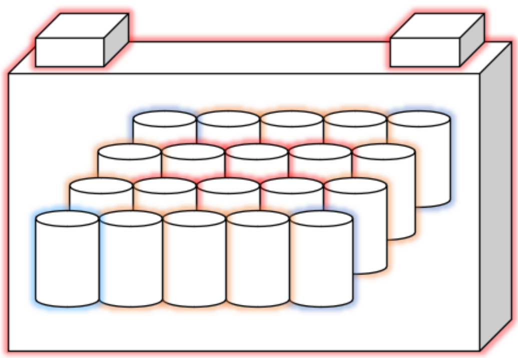

**Figure 4:** Thermal Distribution in Battery Pack

In batteries, heat is generated inside each cell, and dissipated through the casing and electrolyte, with pack surface area and casing thermal conductivity being important parameters (Sun et al., 2023). Passive cooling is sufficient for smaller packs, while larger systems or high-power applications often require forced air or liquid cooling to maintain uniform temperatures and prevent hot spots. This is especially critical when cell-level control is necessary to avoid accelerated degradation. Heat is generated during both charging and discharging by internal resistance and electrochemical polarization, represented as:

$$Q_{\text{in,Battery}} = I^2 R_{\text{int}} + I\left(V_{\text{OC}} - V_{\text{ter}}\right) \tag{4}$$

Where $I$ is the battery current, $R_{\text{int}}$ is the internal resistance, $V_{\text{oc}}$ is the open-circuit voltage, and $V_{\text{ter}}$ is the terminal voltage under load. Having discussed the heat generation mechanisms for the key components of the microgrid, it is evident that a common factor among all components is the resistive heating associated with current flow, which often depends nonlinearly on temperature. This relationship can be expressed as:

$$R(T) = R_0\left[1 + \alpha\left(T - T_0\right)\right] \tag{5}$$

Where $R$ is the resistance at temperature $T$, $R_0$ is the reference resistance at temperature $T_0$, and $\alpha$ is the temperature coefficient specific to each component. The resistance–temperature dependence is fundamentally nonlinear, but over the moderate temperature ranges relevant to most electronic devices, a linear approximation is frequently used to simplify analysis. Apart from resistive losses, it is also evident that each component of the microgrid exhibits unique thermal characteristics influencing heat generation:

- In solar panels, efficiency determines how much of the incoming solar irradiance is converted to electrical energy, with the remaining irradiance being absorbed by the panel. Modern high-efficiency panels, such as those utilizing n-type back-contact (IBC) cells, achieve module efficiencies up to 25% and higher. However, further significant increases in efficiency are challenging due to the material and physical limitations.

- In DC-to-DC converters, heat generation is strongly influenced by switching losses in semiconductor devices such as MOSFETs. These losses occur due to the overlap of voltage and current during transitions between on and off states, and the frequency and type of switching further impact the amount of heat produced. Modern MOSFETs typically operate at switching frequencies from 20 kHz to 100 kHz, with some high-performance devices capable of up to 1 MHz. The maximum junction temperature for most MOSFETs is typically around $150°C$ to $175°C$, beyond which thermal runaway and permanent damage can occur. Other semiconductor switches, including IGBTs (Insulated-Gate Bipolar Transistor) and GaN (Gallium Nitride) transistors, exhibit similar phenomena, with device-specific characteristics affecting thermal performance.

- Batteries exhibit complex thermal and electrical behavior due to coupled electrochemical and thermal dynamics. Total capacity, ranging from a few ampere-hours for small packs to several hundred Ah for large energy storage systems, determines the charge and discharge currents, directly influencing the magnitude of heat generated. Operating temperature ranges depend on chemistry: lead-acid batteries typically operate safely between $-20°C$ and $50°C$, while lithium-ion batteries are limited to roughly $0°C$ to $45°C$ during charging, with high temperatures accelerating degradation and low temperatures restricting ion mobility. Unlike converters, battery packs are generally managed as integrated units without direct cell-level control, so the behavior of a single cell can impact the entire pack. Monitoring must capture the nonlinear relationships among state of charge, current, voltage, and temperature, with special attention to uneven heating that could reduce lifespan or compromise safety.

## 4 Solution Approach

Thermal monitoring in solar microgrids is important because conditions rarely stay constant. Sunlight, load demand, and switching activity all change over time, and each shift leaves a trace in the form of temperature rise, voltage fluctuation, or efficiency loss. These changes do not remain confined to a single device. For example, a drop in panel output can raise stress on the DC–DC converter, which then alters the charging profile of the battery. For this reason, the first step is to illustrate how these uncertainties manifest in measurable signals and propagate across the system. Figure 5 shows the main thermal and electrical pathways linking the solar panel, DC–DC converter, and battery.

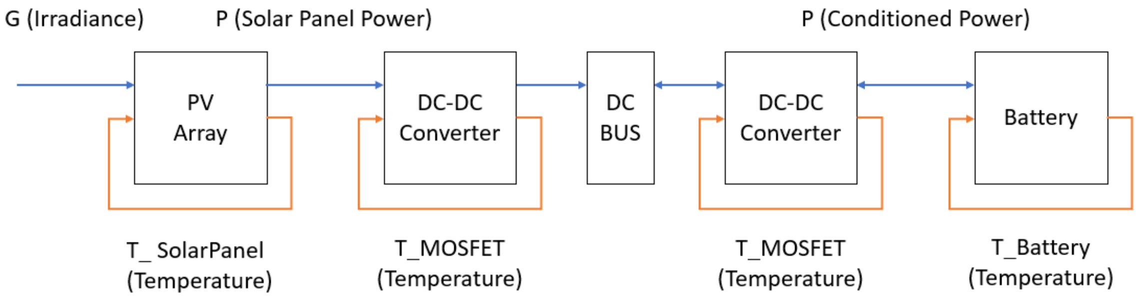


**Figure 5:** Multidomain Block Diagram of Thermal and Electrical Pathways in a DC Microgrid

In the following, we outline the main contributors to these shifts before discussing their role in fuzzy-logic–based monitoring.

- The primary source of initial fluctuation in the system originates from the PV array, where power output is strongly dependent on temperature and irradiance. As panel temperature rises, conversion efficiency drops, and this effect is more severe for panels with higher power ratings, since their absolute losses are greater. When efficiency falls, the output power fluctuates, creating mismatches with the expected operating point of the DC–DC converter. This not only lowers the available power but also increases the stress on downstream components, which must adjust to maintain stable energy flow.

- The DC–DC converter acts as the balancing stage between fluctuating panel output and the relatively stable requirements of the load and battery. Its thermal stress arises from two sources: variations in switching behavior and mismatches caused by unpredictable PV output. Converters such as buck, boost, or buck–boost are commonly used, but since the panel can operate above or below the required voltage, the Zeta converter is particularly suited to handle these bidirectional shifts. When the converter struggles to track the shifting maximum power point, it either overdraws from the panels or delivers fluctuating power to the battery pack, amplifying the effect of PV fluctuations further into the system.

- The battery introduces its own challenges due to nonlinear charging behavior, state-of-charge estimation errors, and temperature sensitivity. Heat buildup during charging can accelerate aging, reduce capacity, and in extreme cases, lead to thermal runaway. These risks grow if the DC–DC converter delivers irregular current, as temperature rise within the cells becomes uneven and harder to control. In turn, a stressed battery reflects its instability back to the converter, which must compensate with higher duty cycles or switching rates, further destabilizing the PV-converter-battery chain. Thus, the battery is both a receiver and an active contributor to the overall thermal stress of the microgrid.

Fuzzy logic offers a flexible approach for monitoring thermal and electrical conditions in a DC–DC microgrid, especially when precise mathematical models are difficult to obtain (Aliyeva, 2025). In the microgrid, solar panels generate power subject to temperature and irradiance variations, DC–DC converters regulate this power while experiencing localized heating and switching-related stress, and batteries store energy with coupled electrothermal dynamics influenced by state of charge and cell imbalances. By applying tailored strategies, fuzzy logic can be used to handle the thermal behavior of each component more effectively, providing a foundation for more detailed control approaches.

Solar panels present modeling challenges because their efficiency is strongly affected by temperature and irradiance, which fluctuate throughout the day and across environmental conditions. Fuzzy logic offers a way to observe performance changes and assess thermal stress in a practical manner without relying on detailed physical models. Using irradiance and temperature as initial inputs may simplify the fuzzy logic execution while leaving room for more advanced controller development if needed.

- Efficiency loss monitoring: Observes output power and notes when high temperatures could significantly reduce power output. Lookup tables relating irradiance to output power at different panel temperatures can help construct the fuzzy logic rule table, supporting decisions for preventive actions
- Thermal stress assessment: Observes panel surface temperature relative to its rated limits and changes over time. Alerts are generated when temperatures approach critical levels, ensuring potential thermal stress is flagged without relying on complex irradiance data, as the focus is purely on temperature-based safety thresholds.

DC–DC converters are difficult to predict because junction heating is highly nonlinear and influenced by both switching activity and current flow. Fuzzy logic could provide a conceptual framework to monitor these thermal dynamics and guide potential cooling strategies:

- Junction temperature and load monitoring: Observes current junction temperature along with expected heat from switching and conduction losses. Fuzzy rules could identify rising thermal stress and suggest when to apply sufficient cooling to maintain safe operating temperatures.
- Topology-aware assessment: In converters with multiple switching elements, such as MOSFETs, fuzzy logic could conceptually coordinate the switching schedule for each element. By considering the load on individual devices, the system could anticipate localized heating, increase the effectiveness of natural convection to reduce hotspots, and apply additional cooling mechanisms as needed to balance thermal stress.

Battery packs present monitoring challenges due to coupled electrothermal behavior, nonlinear charging dynamics, and variable current from upstream converters. Unlike semiconductor switches, cells cannot generally be individually turned on or off, so monitoring must consider the weakest cell to prevent system-wide issues:

- Cell-Level Input Adjustment: Observes estimated cell temperatures and state of charge to identify the cell under the most stress. Fuzzy logic could then be used to adjust the charging current to protect the weakest cell, balancing performance while avoiding hot spots or accelerated degradation.
- Flooded Lead-Acid Battery Evaporation Monitoring: In microgrid applications, flooded lead-acid batteries are often used because of their low internal resistance. However, excessive heating can accelerate water evaporation, increasing electrolyte acidity and potentially causing battery failure. Fuzzy rules can track temperature and charging patterns to anticipate evaporation risks and trigger preventive measures, such as scheduling maintenance.

Together, these methods demonstrate how fuzzy logic can assist in monitoring the microgrid by interpreting nonlinear, coupled, and component-specific behaviors. It provides a framework to assess panel efficiency, converter junction stress, and battery state-of-charge trends, while anticipating risks. Rather than replacing conventional sensors or models, fuzzy inference complements them by offering adaptive interpretation of data, bridging the gap between raw measurements and actionable insights.

# 5 Conclusion

This study analyzes the coupled thermal and electrical behavior of solar panels, DC–DC converters, and battery packs within a photovoltaic microgrid. It highlights how fluctuations in irradiance and temperature propagate through converters and influence the battery response, revealing dependencies that are often overlooked when components are examined separately. The objective is to clarify how these interactions shape overall thermal behavior rather than claim direct performance improvements. Fuzzy logic is introduced as a practical framework for interpreting these nonlinear effects using inputs such as panel temperature, irradiance, converter junction temperature, and battery state of charge. The findings illustrate how thermal stresses spread across generation, conversion, and storage, forming a conceptual basis for future work on monitoring, cooling, and adaptive control in DC–DC microgrids.

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