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PHD IN PHOTOVOLTAICS

Dottorato di interesse nazionale in Photovoltaics

Curriculum: Power Electronics and Control

PhD Thesis Title

A Subtitle if Needed

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Introduction

Although photovoltaic (PV) panels and battery energy storage systems are essential to this transition, a lack of unified models and integrated diagnostic tools frequently prevents their optimal performance. The integration of second-life batteries, while offering significant sustainability benefits, further complicates system modeling, state estimation, and control, posing unique challenges that demand advanced solutions. At the moment, most PV models are either static, which means they only show DC characteristics in steady state, or dynamic, which means they show behavior in the time domain but don't work with steady state power flow simulations. This fundamental divide restricts their utility in critical applications such as converter design, advanced control strategy development, and accurate fault detection. Similarly, most diagnosis methods operate independently of the models used for system design and control. This not only creates redundancy but also diminishes overall system transparency and effectiveness. Addressing these critical gaps is essential for the advancement of truly intelligent, adaptive, and fault-tolerant PV-battery systems.

1.1 Research Problem

Despite significant progress in renewable energy technologies, a critical gap persists in the integrated modeling and diagnosis of PV systems combined with energy storage. Conventional PV models often offer a limited scope, focusing either on static I-V behavior or dynamic transient simulations. This binary approach prevents a unified representation that can seamlessly transition between both domains, thereby impeding accurate system-level simulation and the realistic design of power electronic converters, where both dynamic and steady-state interactions are crucial.

Power electronic converters are very important because they connect PV panels to energy storage devices. However, they are usually designed and tested using simplified PV models that don't take into account high-frequency or nonlinear effects. Critically, these converters are rarely equipped with integrated diagnostic functionality, despite their strategic role as both energy controllers and potential sensor hubs. This absence of embedded diagnostic features results in limited fault awareness, reduced operational resilience, and suboptimal performance.

The complexity of this problem is further magnified when these systems incorporate second-life batteries, whose aging characteristics and operational behavior are inherently more variable and less predictable than new batteries. Without integrated diagnosis and more realistic, adaptive modeling, the performance, safety, and long-term reliability of such hybrid energy systems remain significantly suboptimal. This research aims to bridge these critical gaps by developing a holistic framework for unified modeling and advanced diagnostics.

1.2 Objectives

The primary aim of this research is to develop a unified modeling and diagnostic framework specifically tailored for PV systems integrated with energy storage. To achieve this overarching goal, the research will pursue the following key objectives:

This study will create a new photovoltaic model based on the physics of PN junctions. The model will be able to simulate both steady-state and transient behavior in a single framework. At the same time, it will focus on getting the model parameters it needs from experimental data, using diode-based SPICE-compatible representations to make sure they are physically relevant and ready for simulation right away. A crucial step will be to integrate this unified PV model into the simulation and design process of a high-performance interleaved synchronous power converter. In addition, the project wants to create and use a converter that can not only get energy from PV panels efficiently but also make system diagnosis easier by allowing small-signal stimulus injection. The proposed PV model and converter behavior will then be rigorously tested using experimental data. The main focus will be on making sure that the power conversion is accurate and that the diagnostic response works well in real-world settings. Finally, the research will explore the potential for extending this advanced diagnostic methodology to battery systems, leveraging preliminary data obtained from modified commercial converters to demonstrate its broader applicability.

1.3 Contributions

This thesis presents several original contributions to the modeling, simulation, and diagnosis of PV-based energy systems. The key contributions are as follows. A novel unified photovoltaic model is developed based on PN junction theory, implemented using a SPICE-compatible diode description. This model is specifically designed to enable consistent steady-state and dynamic simulations, effectively bridging the gap between static I-V representations and time-domain behavior. The most important thing is that the model parameters come straight from measurements of PV panels. This makes sure that the model accurately shows how real devices work in different situations. The combined PV model is then added to power converter simulations to check how the whole system really works. This lets us see things like switching transients, the effects of partial shading, and changes in dynamic load. Building on this, an interleaved synchronous DC-DC converter is designed and evaluated for efficient power harvesting. This converter is engineered to support simultaneous energy conversion and diagnostic signal injection without interrupting normal operation. Adding a model-based diagnosis method in which a small signal stimulus is sent through the converter to get the PV system excited is a big step forward. This lets you see when the model behavior doesn't match what you'd expect, which makes it easier to find faults and keep an eye on the system in real time using a known-good model baseline. The proposed PV model and the converter's diagnostic capabilities are thoroughly subjected to experimental validation. This means using experimental data to make sure the PV model works well in both static and dynamic situations. It also means doing more converter-level tests to make sure the small-signal injection and model-based diagnostic approach work well. Lastly, the diagnosis method is shown to work in theory for battery systems using early data from a modified commercial converter, though it hasn't been fully tested in the lab. This outlines a clear pathway for future work, particularly concerning the integration of second-life batteries into energy systems.

1.4 Scope and Limitations

The research presented in this thesis primarily focuses on PV systems and their interaction with power electronic converters, with a particular emphasis on modeling, simulation, and diagnosis. The scope and boundaries of this work are defined by several key considerations. Firstly, the unified PV model is specifically designed for crystalline silicon solar cells and may require adaptation for other PV technologies, such as thin-film or multi-junction cells. Second, the modeling framework and diagnostic ideas can be used for batteries in a basic way, but the experimental validation has only been done on the PV-side system. It has not been possible to do full experimental testing on second-life battery systems as part of this work. Third, the converter design allows for small-signal injection for diagnostic purposes. However, implementing diagnosis algorithms in real time is not a core part of this thesis; it is suggested as a project for the future. Lastly, environmental factors such as temperature variation and long-term aging effects are not explicitly modeled, although it is acknowledged that these factors can significantly influence parameter stability and diagnostic sensitivity.

1.5 Thesis Structure

This thesis is systematically organized into five chapters, each meticulously addressing a core component of the research, building logically from foundational concepts to experimental validation and future outlook. Chapter 1, the Introduction, sets the stage by providing the context, motivation, research problem, objectives, contributions, and an outline of the thesis structure. Chapter 2: Literature Review gives a complete look at different ways to model PV systems, the best converter topologies, and the best ways to diagnose problems with PV battery systems. Following this, Chapter 3, Methodology, has two sections. unified PV model development that goes into the theoretical formulation of the unified PV model, explaining how the parameters were extracted from experimental data, and showing the first results of validating the model. And Converter Design and Integration, which talks about how the interleaved synchronous converter was designed and built, how it works with the PV model, and how the design process is based on simulations. The next chapter, Results and Discussion, goes into great detail about how the model-based diagnostic framework was made, how small signals were injected, and how the experimental validation results were presented. Finally, Chapter 6, Conclusion and Future Work, summarizes the research findings, discusses the implications of the results, and outlines possible directions for future work, with a particular emphasis on second-life battery systems and the challenges of real-time implementation.

2

Literature Review

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Figure 2.1: Example caption for a figure.
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Parameter	**Unit**	**Test 1**	**Test 2**	**Test 3**
Input Voltage	V	12.0	11.8	12.2
Output Current	A	1.5	1.6	1.4
Efficiency	%	92.3	91.8	93.1
Temperature Rise	°C	32	34	31

Table 2.1: Performance comparison of the table caption.

2.3 Leveraging power convertis and on-line diagnosis

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Methodology

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Results and Discussion

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