Evaluation and Improvement of Photovoltaic Power Systems

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Chapter 1

Introduction

In order to reach net zero emissions targets set by the United Nations (UN) at the 2015 Paris Agreement [4] before 2050, the International Energy Association (IEA) estimates that nearly 630 Gigawatts (GW) [3] of photovoltaic (PV) energy generation capacity need to be added annually by 2030. As of 2022, we observed that at least 175 GW were installed in 2021 [2] [1], a 22% year over year growth. With large policy and geopolitical tailwinds behind major economies like the United States and Europe, solar is expected to be one of the, if not the major driver of new energy generation within the next two decades.

However, in order to achieve this target generation capacity in a sustainable way, engineers and PV designers need to maximize the electrical efficiency of the overall power system, as opposed to just improving the solar cell efficiency. According to the U.S. Energy Information Administration (EIA) [5], the capacity factor of PVs as an energy source in the United States reached a monthly maximum of 33.4% in June of 2022; *capacity factor* is defined by the EIA as a measure of the generated output by the electric generator versus the maximum possible output. It is clear that system inefficiencies in PV generation provide large constraints, and optimistically, equally large opportunities, in allowing us to increase our pace towards reaching net zero carbon emissions by 2050.

This thesis takes a holistic evaluation of the PV power generation system in a unique use case that necessitates maximizing the capacity factor: solar powered vehicles. We evaluate the modeling, creation, and optimization of a solar powered vehicle for the University of Texas at Austin's Longhorn Racing Solar team, and attempt to identify and address inefficiencies and bottlenecks whose improvements will help the larger PV industry as a whole.

In particular, this thesis will focus on three important and active areas of development within the PV field: solar array modeling and prediction, solar cell binning processes and heuristics, and maximum power point tracking algorithms. In each of these areas, we look at the state of the art techniques, propose novel ideas to improve our understanding of the system and its inefficiencies, and see if we can translate it lateral applications like rooftop solar or industrial PV. Note that in this thesis we refer to photovoltaics and solar without distinction.

The second area of development may be more generalized then this.

In the first major section, **Modeling Photovoltaics**, this thesis discusses how can solar cells can be modeled at various abstraction layers, from idealized cells at standard conditions using the 3-parameter model to non-idealized cells that incorporate parasitic resistances using the 7-parameter model. These solar cell models are then evaluated against a dataset of several hundred solar cell current-voltage (I-V) curves generated from our custom testing setup to see how well the model fits real cells at different conditions. We build upon these models to form larger units of PVs, such as solar modules and solar arrays, which may consist of strings of cells in series with bypass diodes across them, among other configurations. Some important topics that are explored using these multi-cell models include PV mismatch and bypass activation. Insights from these topics lead to heuristics that are proposed in the next section, **Optimizing Photovoltaics**.

The second major section, **Optimizing Photovoltaics**, takes the aforementioned models and dataset created to propose a process to bin, match, and combine solar cells and modules, with the end goal of maximizing the performance of the solar array that will be attached to the solar vehicle. In this section, we propose design criteria, heuristics, and methodologies to generate designs for the solar vehicle that fit the unique constraints of the application, which center around the dynamism of the system as it moves in transit across the real world.

In the third and final major section, **Optimizing Photovoltaic Infrastructure**, this thesis investigates the operation of the PV system in the context of the solar vehicle. We observe the energy conversion process from incident light on the solar array to electricity captured by the battery protection system (BPS) and present a PV system simulator and a suite of maximum power point tracking (MPPT) algorithms to minimize energy losses from the aforementioned conversion process. We demonstrate custom hardware developed by the Longhorn Racing Solar team and evaluate in real world settings a select set of MPPT algorithms. We compare these results with existing research and our digital twin model of the solar vehicle, and finally discuss conclusions from the three sections that can be translatable to the wider PV industry.

Along with these three major sections, we also provide a large set of appendices corresponding to the development of the main body of work in this thesis. Among them include manufacturing procedures for testing, assembling, and laminating solar cells into solar modules, schematics and accompanying documentation for hardware that was used for characterizing and validating parts of the thesis, software diagrams with relevant open source software repositories developed by our team, and extra insights into the design of the Longhorn Racing Solar's phovoltaic array that are not directly applicable to the major sections, such as thermal models performed of the vehicle topshell that influenced our simulation models, among others.

Chapter 2

Modeling Photovoltaics

Chapter 3

Optimizing Photovoltaics

Chapter 4

Optimizing Photovoltaic Systems

Chapter 5

Conclusion

Appendix A

Acronyms and Abbreviations

UN United Nations

IEA International Energy Association

GW Gigawatts

EIA U.S. Energy Information Administration

PV photovoltaic

I-V current-voltage

P-V power-voltage

BPS battery protection system

Bibliography

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