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Passive hybridization of a photovoltaic module with lithium-ion battery cells: A model-based analysis

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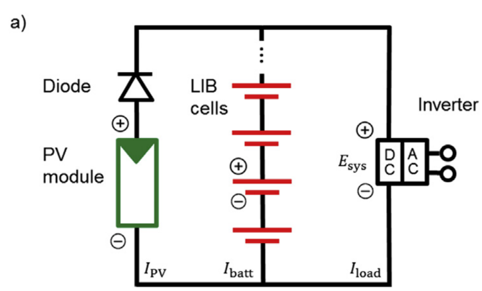
HIGHLIGHTS

- Simple design of a photovoltaic battery system by parallel connection.
- No intermediate ("active") inverters or controllers.
- Model-based study shows a self-regulating behavior avoiding battery overdischarge.
- Predicted self-sufficiency is only 5–10% smaller than that of a MPP-tracked system.

GRAPHICAL ABSTRACT



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ABSTRACT

Standard photovoltaic battery systems based on AC or DC architectures require power electronics and controllers, including inverters, MPP tracker, and battery charger. Here we investigate an alternative system design based on the parallel connection of a photovoltaic module with battery cells without any intermediate voltage conversion. This approach, for which we use the term passive hybridization, is based on matching the solar cell's and battery cell's respective current/voltage behavior. A battery with flat discharge characteristics can allow to pin the solar cell to its maximum power point (MPP) independently of the external power consumption. At the same time, upon battery full charge, voltage increase will drive the solar cell towards zero current and therefore self-prevent battery overcharge. We present a modeling and simulation analysis of passively hybridizing a 5 kWp PV system with a 5 kWh LFP/graphite lithium-ion battery. Dynamic simulations with 1-min time resolution are carried out for three exemplary summer and winter days using historic weather data and a synthetic single-family household consumer profile. The results demonstrate the feasibility of the system. The passive hybrid allows for high self-sufficiencies of 84.6% in summer and 25.3% in winter, which are only slightly lower than those of a standard system.

1. Introduction

The past few years have shown a strong market growth for residential photovoltaic (PV) battery systems, which are about to reach commercial viability in Germany [1]. Batteries bridge the solar day/night cycle and therefore enable the increase of self-consumption and self-sufficiency. Today's systems are based on either DC or AC architectures [2] both of which require (on different levels) power electronics and controllers, including inverter(s), MPP tracker(s), and battery management system. These components add to system cost and complexity. As PV and battery

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represent a hybrid power generation system, we use in the following the term *active hybridization* for the standard architectures.

We investigate here an alternative architecture based on *passive hybridization*. The approach is based on the parallel connection of a PV module and a lithium-ion battery (LIB) without any intermediate ("active") inverters or controllers. The architecture is shown in Fig. 1. It is based on matching the solar cell's and battery cell's respective current/voltage behavior. A battery cell with flat discharge characteristics (such as, LFP/Graphite [3] or NCA/LTO [4] lithium-ion cells) can allow to pin the solar cell close to its maximum power point (MPP) independently of the external power consumption. At the same time, upon battery full charge, voltage increase will drive the solar cell towards zero current and therefore self-prevent overcharge. A diode is used to prevent discharge of the battery into the PV module for low PV voltages (e.g., at night).

The passive hybrid system has several advantages:

- No active battery management system is required due to self-regulating operation preventing battery overcharge.
- Only one single DC/AC inverter is required. The inverter will typically operate demand-based and will shut down when a minimum voltage is reached, therefore preventing battery overdischarge.
- The battery cells may be integrated in a straightforward and modular way into the PV modules outside the house, therefore increasing safety.
- The simple architecture will make the system more robust and cheaper as compared to standard architectures.

The main disadvantage of the passive hybrid, as will be shown and discussed in this article, is the decreased efficiency because the PV module is not always operated at the MPP and surplus solar energy is not fed into the grid.

This approach is not new; as a matter of fact, first patents date back to 1960s and 1970s [5–7]. A recent patent even shows a mathematical analysis [8]. However, there is only a very limited number of scientific publications of this approach. The parallel connection of PV and lithium-ion battery was shown by the US-company GM in the context of vehicle battery charging [9], however without further analysis and without discharge option. Older work exists in the context of lead-acid batteries [10]. Therefore, to the best of our knowledge, the present study is the first systematic modeling and simulation investigation of the PV/ LIB passive hybrid system.

In this article we present a model-based analysis of a PV/LIB passive hybrid system in order to assess feasibility, design options, and performance figures. Section 2 presents the modeling and simulation methodology. Section 3 shows and discusses the results. Section 4 concludes the article.

2. Mathematical model

2.1. Approach

We use a modeling and simulation approach to investigate the behavior of a PV/LIB passive hybrid system. The dynamic system model is shown schematically in Fig. 2. It consists of several submodels that will be described in the following Subsections. Note

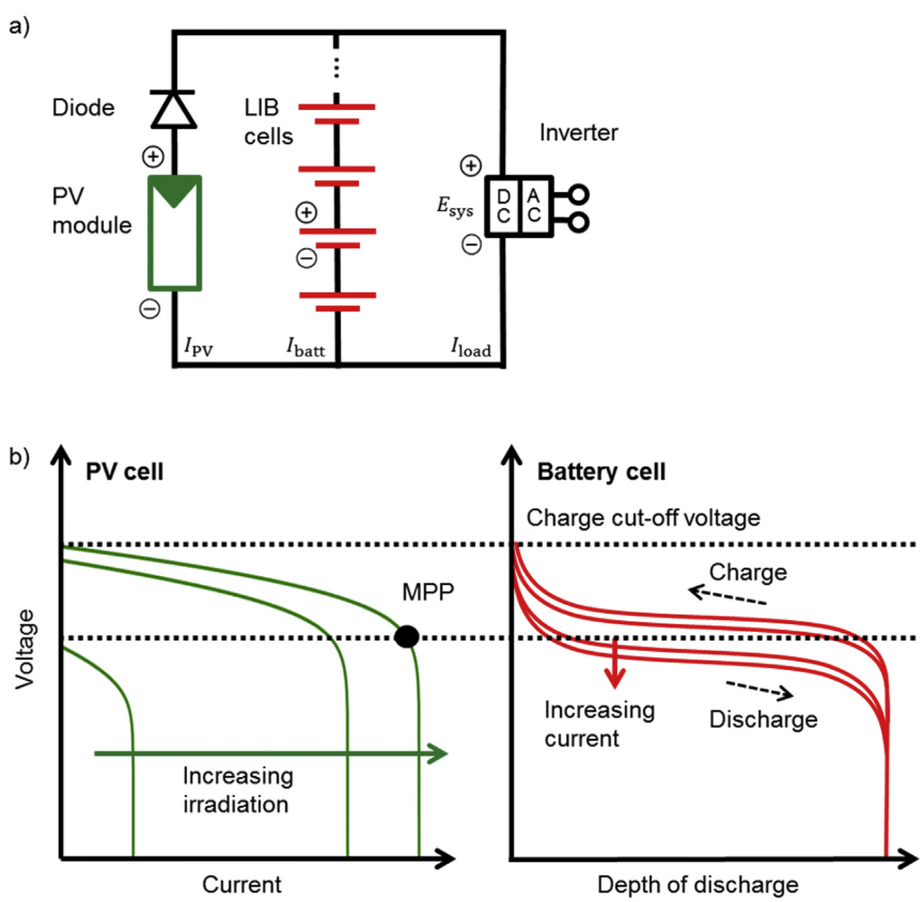

Fig. 1. Passive hybridization approach. a) Parallel connection of photovoltaic (PV) module and lithium-ion battery (LIB) cells, where only one inverter and no battery management system is needed. The additional diode prevents battery discharge over the solar cell overnight. b) Comparison of voltage characteristics of solar cell and battery cell, where the battery characteristics pin the solar cell close to the maximum power point (MPP) while the open-circuit voltage of the PV cell keeps the battery below its charge cut-off voltage.