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Optimal charge control strategies for stationary photovoltaic battery systems

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HIGHLIGHTS

- Optimal charge control strategies for PV battery system are mathematically defined.
- Charging performance with two exemplary days and annual profiles are analyzed.
- A multi-objective function is proposed to take all optimization goals into account.
- Battery lifetime is prolonged by minimizing the dwell time at high states of charge.
- Curtailment of PV peak powers is minimized by optimal storage capacity planning.

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ABSTRACT

Battery systems coupled to photovoltaic (PV) modules for example fulfill one major function: they locally decouple PV generation and consumption of electrical power leading to two major effects. First, they reduce the grid load, especially at peak times and therewith reduce the necessity of a network expansion. And second, they increase the self-consumption in households and therewith help to reduce energy expenses. For the management of PV batteries charge control strategies need to be developed to reach the goals of both the distribution system operators and the local power producer. In this work optimal control strategies regarding various optimization goals are developed on the basis of the predicted household loads and PV generation profiles using the method of dynamic programming. The resulting charge curves are compared and essential differences discussed. Finally, a multi-objective optimization shows that charge control strategies can be derived that take all optimization goals into account.

1. Introduction

Incentivized by feed-in tariffs and accelerated through dramatically fallen PV module prices, an increase in decentralized renewable power generation in low voltage distribution grids can be observed worldwide. With this development, technical and stability relevant challenges arise for distribution system operators. Feed-in management and mandatory feed-in power limitation came into effect to reduce the grid load at peak times. At the same time, with falling feed-in tariffs and rising electricity prices, local power producers tend to increase their self-consumption.

Due to a lack of synchronization between solar irradiance and local loads, self-consumption of domestic PV systems is usually limited between 25% and 30% [1]. Increasing self-consumption by reducing the size of the PV installation is also not a desirable choice, as it reduces the share of renewable energy content in the energy mix of the household [2]. A solution to reach both goals is the usage of electrical energy storage systems to buffer solar energy, and therewith temporarily decouple generation and consumption. Lithium-ion batteries are well suited in this application to meet the requirements of long calendar and cycle life with a daily charge and discharge cycle and high energy throughput over the battery's lifetime.

One of the major challenges of this solution remains the smart feed-in management applied to the battery storage system. On one hand, charging and discharging processes of lithium-ion batteries need to be controlled to ensure safe applications. On the other hand, new policies were introduced, e.g. by German Renewable Energy Sources Act (EEG 2012) to avoid the overload of the electric grid in Germany. The feed-in limitation of active power is generally limited to 70% of installed peak power of photovoltaic modules, known as peak shaving. If the installed energy storage system is

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funded by the government, the limitation is further reduced to 60%. Several studies have already addressed this broader issue. In Ref. [3] demand side management (DSM) is presented to encourage the consumer to shift the energy use to solar peak times such as midday time. According to [4], an extended active DSM with model predictive control is studied to maximize the use of local PV generation. In this way, the need for investments in networks or power plants could be reduced. From the perspective of the energy storage system, Tan et al. [5] proposed a stochastic approach to optimize the battery size in distribution grids with PV plant. In Ref. [6] a rule-based optimal management algorithm is performed to maximize the utilization of renewable energy sources in distribution grids. Williams et al. [2] describe a delayed charging algorithm, which enables the battery charging between 9:00 and 14:00 in the high irradiation months to reduce the grid injection levels. However, these approaches do not take the battery internal dynamics and energy losses into consideration. Technically, the battery operating strategy is not clearly defined.

Given this gap in the literature, this paper proposes an elaborate control strategy to achieve the defined optimization goals without enlarging the battery size or using DSM. Since the power of PV panels and the household consumption could be predicted to some degree, the battery charging power can deterministically be optimized using dynamic programming (DP). Based on different mathematical formulations of the optimization problem results differ in their charging behaviors. An additional goal, extending the battery lifetime, is also considered in this paper since the algorithm takes the battery aging into account.

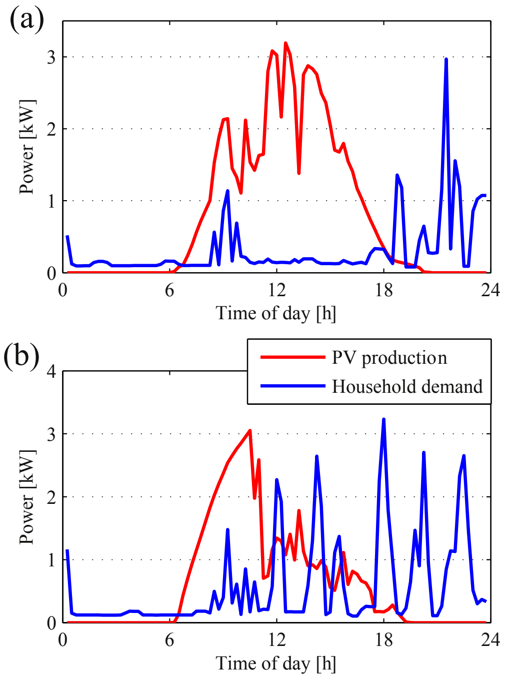

Fig. 2. PV generated power and household loads profiles of two exemplary days with a low (a) and a high (b) correlation of the power demand of the household and solar irradiation, i.e. with a low and high natural self-consumption.

2. Description of the PV battery system

Typical PV systems with integrated battery could be classified as DC coupled and AC coupled power system according to the system configurations. The corresponding DC and AC structures are illustrated in Fig. 1.

In DC coupling energy storage system and PV plants are joined together on the DC side of the system. The battery is connected in the intermediate DC circuit of the PV inverter. In comparison, AC coupled systems join the various power sources on the AC side and the battery is decoupled of the PV inverter. It is notable that in AC coupling energy storage could be retrofitted more flexibly. Batteries are easily integrated into the household independent from the solar installation. Hence AC coupled systems are studied in this work.

The main components of the AC coupled PV battery system are the PV generation, local electrical demand of consumers, distribution grid, and the battery storage system. According to the sign convention, the power balance in the system could be described as the feed-in power

$$P_F(k) = P_{PV}(k) - P_B(k) - P_L(k), \text{ when } P_{PV}(k) > P_L(k) \qquad (1)$$

and the grid supplied power

$$P_G(k) = P_L(k) - P_{PV}(k) - P_B(k), \text{ when } P_{PV}(k) < P_L(k) \qquad (2)$$

with k the discrete-time index.

2.1. PV generator and electrical loads

One of the subjects in this paper is to evaluate the self-consumption level of solar energy. It is calculated as the ratio of directly consumed energy to generated PV energy. Therefore, the PV generated profile and household loads should be defined first. These profiles differ from country to country and vary over the

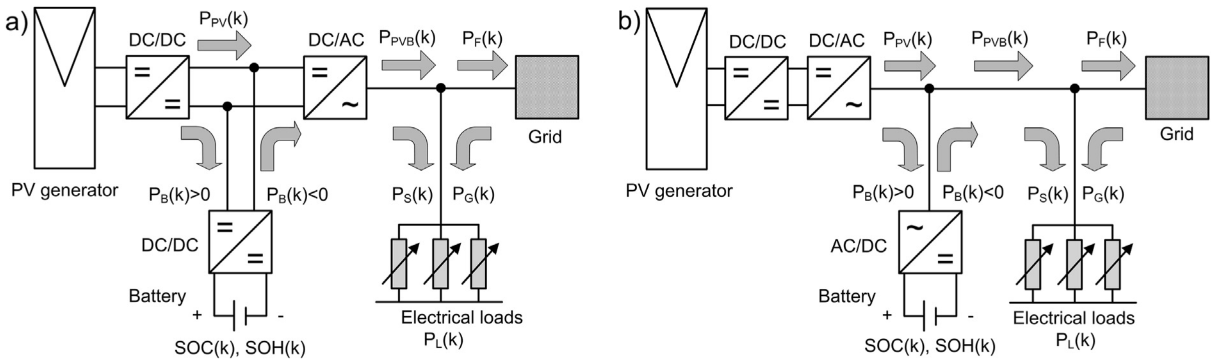

Fig. 1. Schematic illustration of the PV battery systems with power direction and sign convention of PV generated power P_{PV}, battery charge/discharge power P_B, electrical loads P_L, self-consumption P_S, feed-in power P_F, and grid power P_G. (a) Structure of a DC coupled system. (b) Structure of an AC coupled system. Charging the battery from the grid is prohibited.