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A Markov Decision Process for managing a Hybrid Energy Storage System

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ABSTRACT

The high penetration of photovoltaic installations in the domestic sector and the clear reduction of the feed-in-tariffs have made the need for storage systems more and more imminent when greater amounts of energy ought to be daily allocated and assigned. Hybrid Energy Storage Systems (HESS) are a nascent technology which can contribute towards maximization of self-energy consumption and grid stability by smoothing out peaks. In the frame of this paper it is attempted to delimitate the capability of a HESS so as to support the domestic load demand of a single family house in a central north area in Germany, accumulated from the load demand of an E-vehicle which is used for commute reasons of the family and always charges at home. The designed HESS is composed of two storage devices, namely a lead acid battery system (LAB) and a Vanadium Redox Flow Battery (VRB), and supported also from a photovoltaic installation. So as to succeed an optimized utilization of the dual storage system a novel algorithm is developed based on the Markov Decision Process, according to which the priority for charging and discharging process is assigned to the storage facility which depicts a favorable performance under the respective given conditions. The performance of this algorithm is compared to a naive policy—a control strategy based on the constant prioritization of the LAB over the VRB due to LAB's efficiency overperformance. Results demonstrate that with the proposed markov algorithm the system consumes annually almost 5% more from the on-site renewable production whereas less load peaks are noticed during grid exchange, compared to those extracted from the naïve method. Furthermore, it is shown that during sunnier months results are more distinct in comparison to the naïve policy (up to 9% increase in self-energy consumption and 3% reduction in grid fluctuations), due to higher power rating setting thus the designed algorithm as more suitable to coordinate the operation of the two storage devices.

1. Introduction

Load and renewable generation profiles do not coincide, setting thus the integration of ancillary devices in the domestic field as imminent in order to increase the self-consumption which amounts to 20–40% of the onsite-generation, when no storage facilities are available [1]. To this respect, the last three years more than 34,000 decentralized solar energy storage systems were installed in Germany, proving that these applications are considered already a routine by installation of new photovoltaic plants in the domestic field [2]. Although a wide range of those systems is marketable and commercially viable during the last years, it is also common knowledge that none of the existing storage systems regardless of their type (batteries, chemical-hydrogen storage, supercapacitors, etc.) is attributed with the ensemble of assets that such devices are featured. According to Daniel et al. since no system is able to meet all the needs of the customer or of the respective application, the final decision for the appropriate system choice is often a compromise [3]. In particular, there are residential storage systems that are characterized from high energy density and other which belong to high power systems. It would be thus of great interest to combine two or more different battery systems in order to aggregate the complementary attributes and benefit from their coupling. In such a case consequently is more substantial to design a management system that would apply the devices at an overall higher efficiency. The optimal allocation of the self-produced energy is the crucial element, since an inappropriate energy management would eventually end up to a misuse of the available facilities and energy. The potential of such a coupling of storage systems in the building sector is actually the motivation of this research and the optimal operational mode of these facilities is regarded its core part.

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The pairing of two different storage devices is regarded as a Hybrid Energy Storage System (HESS) and their employment in swap mode stands in the focus of this study. HESSs are optimally featured with complementary characteristics and the target of coupling them is to benefit from the strengths of each one. The hybrid system avails itself of the combination of the different storage systems by operating them interchangeably so as to benefit in each case from the respective facility with the most efficient characteristics.

In particular, the present paper is actually addressing a HESS which is composed of a Solar Lead Acid Battery, a vanadium redox flow battery and the peripheral components which are a photovoltaic installation, domestic loads of a dwelling and the load demand of an E-Car. A combination of a market-mature technology as the Solar Lead Acid Battery with a relatively new system as the vanadium redox flow battery and their integration in a residence which produces its own decentralized energy via a PV installation and whose load demand is also aggregated from the power needed to charge an E-Vehicle every day at the house premises are explored. The upper target is to operate the two storage systems at a rational sequence which succeeds a higher rate of self-energy consumption and a lower grid interaction, which is interpreted as lower fluctuations.

Having a closer look to the battery characteristics, lead acid battery systems are characterized from short cycle life, especially when high currents occur, and intolerance at deep discharges. Though this is not the case for the VRB, since such types of batteries are attributed from cycle durability, being possible to deeply discharge it without damaging the system and they can be easily dimensioned since the capacity and power are independent sizes. Simply, by enlarging the storage tanks the capacity may increase while if the stack of the battery is replaced with a more powerful one, the battery will be able to operate in higher power ranges. On the contrary lead acid battery systems are financially favorable, have a short reaction time, medium energy density and a sufficient efficiency rate, while VRB are considered an immature technology in comparison to the lead acid battery systems, their price remains high and the efficiency is proven to be lower than the theoretical values referred in the literature [4].

A variety of techniques that are applied to control a HESS is identified in the literature. The criteria which are considered each time in order to design the optimal control method may differ among various applications. After a thorough and extensive review of the existing studies the most common cited techniques to control HESSs are clustered in the following five categories:

- Low and High Pass Filters;
- Rule-based Algorithms;
- Linear Programming Methods;
- Reinforcement Learning Techniques;
- Hybrid Approaches.

The nature of the considered attributes of the storage systems as well as the type of evaluation criteria influence the selection of the suitable applied control method. If the reaction time is the critical decision characteristic then methods based on low- or high-pass filters are favored [5,6]. When specific operation boundaries ought to be kept rule based algorithms are preferred [6–8] and when these boundaries and the expected requirements are represented by linear relationships linear programming methods are applied [9]. If the environment of the controller is deterministic, i.e. the employed models do not learn from the action evolution, and the degree of freedom during parametrization is also significant for the developed optimization technique, while a sequential decision-making problem is to be solved, a decision making algorithm which does not factor in the preceding states is ideal [10]. Finally hybrid methods are employed when a combination of characteristics should be taken into account [11,12].

Delving into the already reported control systems for HESSs, it is accrued that the already employed methods are not ideal for optimizing the current studied system. In particular, in Zhang et al. [7] rule-based algorithms are applied so as to manage the energy flow between a supercapacitor and a conventional battery. Parameters such as load demand and battery output current are compared with threshold values and the respective rule is applied. Takeda et al. in [6] compare the results extracted from applying two of the above-mentioned methods so as to control a HESS which is constituted from a LAB and a Lithium ion battery. The amplitude sharing algorithm, which is a rule-based approach, delivers better results in comparison to the first order filtering. Moreover, Ise et al. in [8] and Natsheh et al. in [13] have applied a fuzzy logic controller so as to manage the power allocation between two storage systems, namely a superconducting magnet and a battery, and a fuel cell and a battery respectively. This control technique, which belongs to the rule-based algorithms, has the benefit that it is based on a set of rules which are designed from experts and the most appropriate alternative is selected without requiring complicated mathematical knowledge. However, the configuration becomes extremely difficult if the system is quite complex [14]. Moreover, in Natsheh et al. [13] emphasis is placed on the smooth operation of the fuel cell and not on the exploitation of the high efficiency operation ranges of the storage systems, as it is planned to be implemented in the current method. The attribution and setting of a group of rules in advance during the design of the management method for the examined HESS weakens the generalization aspect of the method, thereby it is not preferred in the frame of this paper.

In the literature, the most widely used technique to manage HESSs is the first-order filtering method. According to it, the high power fluctuations are allocated to one storage system, often a supercapacitor, and the rest is undertaken from a conventional battery system [5,11]. This linear filtering is actually designed based on the response time of the two storage technologies; nonetheless various other parameters are not being considered. Filtering methods as the ones applied from Li et al. and Takeda et al. [5,6] are regarded also unsuitable for system cases as the one described in the current study, since the response time of the storage systems is not the determinant factor for designing the present management system.

Another HESS is also studied from Nikolai et al. [9], referring to the project on the island Pellworm of the North Sea. By exploiting all the renewable energy sources installed on it (a PV park of 700kWp and a wind farm of 300kWp) and with the support of several storage systems (mainly lithium-ion batteries and redox flow batteries) a stable and cost-effective energy supply is pursued. In this case a mixed integer linear programming method is applied for the optimization approach. While linear programming algorithms are easily comprehensive and simply applicable, though they lack in the generalization part, and therefore avoided if global solutions are claimed.

Hybrid methods are recommended because they combine different techniques and they are often preferred in the literature. For instance, Abbey et al. in [12] apply a low-pass filter combined with two neural networks and the percentage of the reference power which should be allocated to each facility is decided. Such a technique is though unfavourable because the partitioning of the demanded energy or the surplus of the on-site generation between the existing two storage devices which constitute the examined HESS could worsen their efficiency behavior. Moreover, as already explained earlier, low pass filters do not apply in a case as the one designed here. For this reason, the combination of a rule based algorithm with a filtering technique, as the one conceptualized from Li et al. in [11], still cannot fulfill the needs addressed from this topic.

Conclusively, as it is argued in [12], there is not an ideal energy management system which can be applied in any case, since every application of Hybrid Energy Storage Systems is attributed from varying characteristics, which must be taken into account during the design of the control process and the optimization goal or parameter can be different in each case. However, advanced control algorithms which are optimized-based are considered as more efficient in acquiring