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Stochastic control of smart home energy management with plug-in electric vehicle battery energy storage and photovoltaic array

Xiaohua Wu [a], Xiaosong Hu [b, *], Scott Moura [c], Xiaofeng Yin [a], Volker Pickert [d]

[a] School of Automobile and Transportation, Xihua University, Chengdu, 610039, China
[b] The State Key Laboratory of Mechanical Transmissions, Chongqing University, Chongqing, 400044, China
[c] Energy, Controls, and Applications Laboratory, University of California, Berkeley, USA
[d] School of Electrical and Electronic Engineering, Newcastle University, UK

HIGHLIGHTS

- Markov Chain model of PEV mobility is achieved.
- Conditional probability of trip length is developed.
- Predictive models of home power demand and PV power supply are achieved.
- PEV energy storage availability by SDP is modeled.
- The SDP control can bring significant cost savings for customers.

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ABSTRACT

Energy management strategies are instrumental in the performance and economy of smart homes integrating renewable energy and energy storage. This article focuses on stochastic energy management of a smart home with PEV (plug-in electric vehicle) energy storage and photovoltaic (PV) array. It is motivated by the challenges associated with sustainable energy supplies and the local energy storage opportunity provided by vehicle electrification. This paper seeks to minimize a consumer's energy charges under a time-of-use tariff, while satisfying home power demand and PEV charging requirements, and accommodating the variability of solar power. First, the random-variable models are developed, including Markov Chain model of PEV mobility, as well as predictive models of home power demand and PV power supply. Second, a stochastic optimal control problem is mathematically formulated for managing the power flow among energy sources in the smart home. Finally, based on time-varying electricity price, we systematically examine the performance of the proposed control strategy. As a result, the electric cost is 493.6% less for a Tesla Model S with optimal stochastic dynamic programming (SDP) control relative to the no optimal control case, and it is by 175.89% for a Nissan Leaf.

1. Introduction

1.1. Motivation

The present energy demand and environmental crisis have been promoting the rapid development of electric vehicles (EVs) and renewable energy including solar rooftop photovoltaic (PV) and wind power [1,2]. However, EVs charging activities and renewable energy generation are always intermittent and volatile. If uncontrolled, a significant impact on the power grid may happen, including performance degradations, overloads, and over-generation, especially when a larger scale distributed generation (DG) unit and EVs are used [3–5]. Reconciling EVs and renewable energy to ensure optimal usage of electric power is very important for the performance and economy of smart grid [6–8]. As a consequence, researchers have recently focused on developing effective management for integrating EVs and renewable energy into house loads and grid, as well as new material and structure of renewable energy considering power conversion efficiency, such as SiO_2 nanoparticles [9], iodide/triiodide-based redox mediator [10],

* Corresponding author.
E-mail address: xiaosonghu@ieee.org (X. Hu).

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and photopolymerization of Co(II)/Co(III) used for solar cells [11]. Related to recent attention paid to smart grid vision, smart homes that can optimize energy consumption and lower electricity bills have also gained specific importance. Developing a smart home energe management system (SHEMS) has become a common global priority to support the trend towards a more sustainable and reliable energy supply for smart grid [12]. Hence, this paper focuses on optimal energy management of a smart home with plug-in electric vehicle (PEV) battery energy storage and solar power supply.

1.2. Literature review

The existing literature, e.g., the forgoing work, has presented several optimization methods, such as mixed-integer linear programming (MILP) [13–17], model predictive control (MPC) approach [4,18], rolling horizon strategy [19], and game theory [20], for creating efficient operational schedules or making good consumption and production decisions to smart home energy management. The operation of a smart household that owned a PV, an energy storage system that consisted of a battery bank and also an EV with vehicle to home (V2H) option was considered through solving a MILP in Ref. [13]. A MILP model of the HEM structure was provided to perform a collaborative evaluation of a dynamic pricing based demand response (DR) strategy, a distributed small-scale renewable energy generation system, the V2H capability of an EV together with two-way energy trading of EV (using V2G option) and enenrgy storage system (ESS) in Ref. [14]. An optimal smart household appliances scheduling was established under hourly pricing and peak power-limiting (hard and soft power limitation)-based demand response strategies in Ref. [15], where thermostatically and non-thermostatically controllable loads were explicitly modeled. The optimal operation of a neighborhood of smart households in terms of minimizing the total energy procurement cost was analyzed using MILP by considering bi-directional power flow both at household and neighborhood level in Ref. [16]. A MILP model for techno-economic optimum sizing of additional PV and ESS investment for a DR-based HEM system controlled smart household was provided with the consideration of the notably changing load pattern due to DR activities in Ref. [17]. Renewable integration was considered in Ref. [4], which derived optimal EV charging schedules based on predicted PV output and electricity consumption. A nonlinear predictive energy management method for buildings with PV system and battery storage was presented in Ref. [18], which forecasted house load demand via artificial neural networks. A novel energy management system based on a rolling horizon strategy for a renewables-based microgrid was proposed and implemented, composed of PV panels, two wind turbines, a diesel generator and an energy storage system in Ref. [19]. The impacts of the response capability levels of consumers on the economic integration of distributed PV power in smart homes, and the impacts of PV capacities and battery capacities on consumers power expenses were analyzed using non-cooperation game theoretical power market complementarity model in Ref. [20].

Most of the related literature pursues a smart home technology potential evaluation objective. Few seek a real-time control system that optimizes energy management with an explicit consideration for stochastic home loads, PV generation, and EV mobility patterns. The main challenge of smart home energy management arises from multiple sources of randomness, i.e., PEV mobility, customer power demand, and renewable power generation. Liang et al. [21] provided a comprehensive literature survey on the stochastic modeling and optimization tools for microgrid and demonstrated the effectiveness of such tools.

To minimize consumer's expected power cost, the optimal scheduling algorithms for power consumption with uncertain future price had been derived under stochastic dynamic programming (SDP) [22]. Iverson et al. accounted for probabilities of vehicle departure time and trip duration to formulate a SDP algorithm to optimally charge an EV based on an inhomogeneous Markov chain model [23]. To promote user demand response through optimizing the utilization of wind power generation, the coordinated wind-PEV dispatch problem was also studied in a stochastic framework capturing the uncertainties of wind power generation and statistical PEV driving patterns [24]. A stochastic energy consumption scheduling algorithm with the objective of reducing monetary expenses was featured by modelling the random property of customer energy consumption practices [25]. However, all the foregoing articles focus on the microgrid energy management problem using stochastic optimization, given one and only one random factor: either electric price or PEV mobility, either renewable energy generation or home load. The interactions among various random variables were constantly overlooked. A probability distribution model combining household power consumption, EV home-charging and PV power production was developed using a convolution approach to merge three separate existing probability distribution models in Ref. [26]. Donadee et al. [27] used stochastic models of (i) plug-in and plug-out behavior, (ii) energy required for transportation, and (iii) electric energy prices. These stochastic models were incorporated into an infinite-horizon Markov decision process (MDP) to minimize the sum of electric energy charging costs, driving costs, and the cost of any driver inconvenience. A later study by Ref. [28] constructed a Markov Chain to model random prices and regulation signal and formulated a SDP to optimize the charging and frequency regulation capacity bids of an EV. The previous two studies, however, did not consider integrated PEV charging with building loads and renewable energy.

1.3. Contributions

To surmount the shortcomings of the foregoing studies [29,30], this paper proposes an SDP framework for the optimal energy management of a smart home with PEV energy storage and PV array, considering multiple uncertain variables. Based on real statistical data, Markov Chain models of vehicle trip time and conditional probability of trip length is achieved, as well as predictive models of home load demand and PV power supply. To the best knowledge of the authors, this is the first time study in the literature modelling PEV energy storage availability by incorporating multiple random variables into a SDP control formulation of a single smart home energy management, which is the main novelty of this paper. We can generally conclude that the smart home with PEV energy storage and PV array under such optimal control can bring significant cost savings for customers.

1.4. Outline of paper

The remainder of the paper is arranged as follows. Section 2 details the system model of a smart home. Detailed random variables are described in Section 3. The optimization problem is formulated in Section 4. The case study optimization results are discussed in Section 5, followed by conclusions presented in Section 6.

2. Smart home model development

2.1. Smart home configuration

We consider a smart home with a PEV and solar panels as shown in Fig. 1. The energy management system communicates with home