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Optimal integration of a hybrid solar-battery power source into smart home nanogrid with plug-in electric vehicle☆

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HIGHLIGHTS

- Hybrid solar-battery power source is rapidly optimized.
- Optimal energy management strategy is developed for a smart home.
- Coupling among PEV, renewable, and home battery is studied.
- Home battery is important for home economy.

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ABSTRACT

Hybrid solar-battery power source is essential in the nexus of plug-in electric vehicle (PEV), renewables, and smart building. This paper devises an optimization framework for efficient energy management and components sizing of a single smart home with home battery, PEV, and potovoltatic (PV) arrays. We seek to maximize the home economy, while satisfying home power demand and PEV driving. Based on the structure and system models of the smart home nanogrid, a convex programming (CP) problem is formulated to rapidly and efficiently optimize both the control decision and parameters of the home battery energy storage system (BESS). Considering different time horizons of optimization, home BESS prices, types and control modes of PEVs, the parameters of home BESS and electric cost are systematically investigated. Based on the developed CP control law in home to vehicle (H2V) mode and vehicle to home (V2H) mode, the home with BESS does not buy electric energy from the grid during the electric price's peak periods.

1. Introduction

1.1. Motivation

The present energy demand and environmental crisis has been promoting the rapid development of electric vehicles (EVs) and renewables [1,2]. However, EVs charging activities and some renewable energy generation, such as solar and wind power, are always intermittent and volatile. Reconciling EVs and renewables to ensure optimal usage of electric power is critical for the performance and economy of smart grid [3,4], especially when larger-scale distributed generation (DG) units and EVs are deployed [5]. As a consequence, researchers have recently focused on developing effective management and sizing techniques for integrating EVs and renewables into house loads and the grid. New material and

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Nomenclature

c_b	home battery price per kiloWatt-hour [$/kWh]
c_c	charger price per kiloWatt [$/kW]
$c_{e,k}$	electricity price [cents/kWh]
C_{ny}	*n*-year total electricity cost [$]
$E_{ev,k}$	energy of PEV battery [kWh]
$E_{ev,init}$	initial PEV battery energy [kWh]
$E_{ev}^{plug-out}$	energy of PEV battery when the vehicle plugging-out [kWh]
$E_{ev}^{plug-in}$	energy of PEV battery when the vehicle plugging-in [kWh]
E_{dr}	consumed energy for driving in a whole day [kWh]
$E_{b,k}$	energy of home battery [kWh]
$E_{b,init}$	initial home battery energy [kWh]
k	time index
N	final time step of one year
n	time horizon of optimization [year]
$P_{grid,k}$	electric power from the grid [kW]
$P_{dem,k}$	electric load demand of the house [kW]
$P_{b,k}$	electric power of home battery [kW]
$P_{evc,k}$	electric power of PEV battery [kW]
$P_{pv,k}$	power supply of PV arrays [kW]
$P_{grid}^{\max}$	maximal power from the grid [kW]
$P_{evc}^{\min}$	PEV battery's minimal power [kW]
$P_{evc}^{\max}$	PEV battery's maximal power [kW]
$P_{b}^{\max}$	home battery's maximal power [kW]
$Q_{evc,eap}$	energy capacity of the PEV battery [kWh]
$Q_{b,eap}$	energy capacity of the home battery [kWh]
S_k	PEV state at time *k*
t_d	plugging-out time
t_a	plugging-in time
$SOC_{ev}^{\min}$	PEV battery's minimal SOC
$SOC_{ev}^{\max}$	PEV battery's maximal SOC
$SOC_{b}^{\min}$	home battery's minimal SOC
$SOC_{b}^{\max}$	home battery's maximal SOC
Δt	time-step [h]
η_{evc}	lost efficiency of PEV battery
η_b	lost efficiency of home battery

structure of renewables devices were also reported. For example, a newly designed microfluidic architecture with a hyperflexible siliconic matrix is proposed in Ref. [6], as a polymeric cage in dye-sensitized solar cell (DSSC). A photocurable polymeric membrane is employed as quasi-solid electrolyte for both the electrochromic device and the DSSC in Ref. [7]. Moreover, a flexible integrated energy harvesting and storage system is devised in Ref. [8] by coupling DSSC and an electrical double layer supercapacitor.

Related to the recent attention given to smart grid vision, smart home nanogrids that can optimize energy consumption and lower electricity bills have also gained particular importance. The results in Ref. [9] have comprehensively demonstrated the second-life battery energy storage's performance in solar charging, home load following, and utility demand side management for a single family home. Developing a smart home energy management system (SHEMS) and component sizing method has become a common global priority to support the trend toward a more sustainable energy supply for smart grid. One of the key features of smart home nanogrid is the SHEMS that intelligently controls household loads through an association between smart meters, smart appliances, EVs, and home power generation and storage, etc. Besides, power source dimension is another important factor. Hence, this paper focuses on optimal energy management and sizing of a smart home nanogrid with home battery energy storage system (BESS), plug-in electric vehicle (PEV), and potovoltatic (PV) power supply.

1.2. Literature review

There is a rich literature for optimized home energy management (HEM) approaches, which can be generally categorized into mixed-integer linear programming (MILP) [10], geometric program [11], model predictive control (MPC) [12], dynamic programming (DP) [13], stochastic dynamic programming (SDP) [14]. The optimal operation of a smart household with a PV, a home battery bank, and an EV with vehicle to home (V2H) option is considered through solving a MILP in Ref. [15]. A MILP model of the HEM structure is established in Ref. [16] to investigate a joint evaluation of a dynamic pricing and peak power limiting based demand response (DR) strategy, with a bi-directional utilization of EV and energy storage system. An optimal day-ahead household appliances scheduling is developed in Ref. [17] under hourly pricing and peak power-limiting based DR strategies, where thermostatically and non-thermostatically controllable loads are explicitly modeled using MILP. In addition, the optimal operation of a smart neighborhood, in terms of minimizing the total energy procurement cost, is analyzed using MILP by considering all possible bi-directional power flows in Ref. [18]. A MILP model of home energy management system (HEMS), as well as a wavelet transform (WT)-artificial neural network (ANN) forecasting of residential loads, is described in Ref. [19] for different price signals. A MILP-based DR strategy with end-user comfort violation minimization is synthesized for residential heating, ventilation, and air conditioning (HVAC) units in Ref. [20]. Considering DR, sizing of PV and energy storage system applied in smart households is assessed with HEM modeling in a MILP framework in Ref. [21]. It is clear that MILP has been widely adopted for either creating efficient operational schedules for HEM or sizing of component. However, few studies exploring HEM MILP models considered optimal component size and control strategy simultaneously. A new effective tool, convex programming (CP), which can rapidly and efficiently optimize both management strategy and parameters, has also been applied by some researchers in the energy management field.

Due to the significant advantage of CP in computational efficiency, CP is gaining growing popularity in energy management of energy systems. The problem of integrating residential PV power generation and storage systems into the smart grid is addressed in Ref. [22] for simultaneous peak power shaving and total electricity cost minimization over a billing period, where a convex optimization problem is formulated and solved. A renewable energy buying-back scheme with dynamic pricing to achieve the goal of energy efficiency for smart grids is modeled as a convex problem in Ref. [23], which can significantly reduce peak time loading and efficiently balance system energy distribution. Based on convex objectives and constraints of a grid-tied PV storage system, an optimization problem to obtain a control schedule for storage units is solved by CVX in Ref. [24]. Based on the objective of reduction of the substation transformer losses, cost saving of energy delivered from the grid, and reduction of the impact on the life-cycle cost of the BESS, a convex optimization approach to schedule charging and discharging of the lithium-ion-based BESS in a distribution feeder