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A linear programming based heuristic algorithm for charge and discharge scheduling of electric vehicles in a building energy management system ☆

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ABSTRACT

Electric vehicles (EVs) are becoming an attractive alternative to gasoline vehicles owing to the increase of greenhouse gas emissions and gasoline prices. EVs are also expected to function as battery storages for stabilizing large fluctuations in the power grid through the vehicle-to-grid power system, which requires smart charge and discharge scheduling algorithms. In this paper, we develop a linear programming based heuristic algorithm on a time–space network model for charge and discharge scheduling of EVs. We also develop an improved two-stage heuristic algorithm to cope with uncertain demands and departure times of EVs, and evaluate the effect of the smart charge and discharge scheduling of EVs on a peak load reduction in a building energy management system.

1. Introduction

With rising greenhouse gas emission and gasoline prices, electric vehicles (EVs) are becoming an attractive alternative to gasoline vehicles. However, the rapid growth in electricity demand may cause large and undesirable peak loads in the power grid. Fortunately, EVs can flexibly coordinate charge schedules, and most owners will not be inconvenienced, providing that the EV batteries are full before departure. A wide variety of models and algorithms has been proposed for charge scheduling of EVs. Clement et al. [2] proposed a quadratic programming model to minimize power losses and voltage deviations. Deilami et al. [4] reported a fast heuristic algorithm, called the maximum sensitivities selection algorithm, to minimize the total cost involved with the additional electricity demands of EVs and power losses. Sortomme et al. [22] described and compared three optimization models; minimizing power losses, minimizing load variance, and maximizing load factor. Soares et al. [21] proposed a linear programming (LP) model that minimizes deviations between expected and actual demands, which was suitable for quasi-real time applications because of its low computational cost. Hernánedz-Arauzo et al. [11] formulated the scheduling problem as a sequence of constraint satisfaction problems (CSPs) over time called the dynamic CSP, and decomposed each CSP into three instances of a one-machine scheduling problem. Kim et al. [17] analyzed performance measures of two typical charge scheduling methods: the first-in-first-out and the processor sharing under a realistic stochastic model for EV battery charging stations.

EVs can offer further benefits to the power grid by discharging electricity from their batteries, which is called vehicle-to-grid power [15,16]. The rapid growth of intermittent renewable energy sources, such as photovoltaic and wind power generation, requires huge number of battery storages for stabilizing the large fluctuations in the power grid. EV batteries are expected to provide an alternative to expensive stationary battery storages and to play an important role in the emerging power grid that has a large number of renewable energy sources.

Several optimization models and algorithms have been proposed for charge and discharge scheduling of EVs. Han et al. [8] reported a dynamic programming algorithm to optimize frequency regulation, in which charge and discharge scheduling of individual EVs was considered rather than that of multiple EVs. Clement et al. [3] proposed an LP model and He et al. [10] proposed a quadratic programming model to minimize the total charge cost. Zakariazadeh et al. [26] formulated a multi-objective model to minimize operational costs and emissions as a mixed integer nonlinear programming (MINLP) model and it solved with Bender's decomposition technique. Kawashima et al. [14] reported a mixed integer linear programming (MILP) model to minimize a total

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charge cost, and García-Villalobos et al. [7] presented a comprehensive review of models and algorithms for charge and discharge scheduling of EVs.

We have considered an optimal electric power management in a home energy management system (HEMS) using photovoltaics (PVs) and stationary battery storages, and developed an MILP formulation to minimize electricity costs on a time–space network model [5]. In this paper, we investigate peak load reduction in a building energy management system (BEMS), and develop an LP based heuristic algorithm on a time–space network model for charge and discharge scheduling of EVs. Japanese electric utilities use the net feed-in tariff system; they are obliged to purchase surplus electricity generated by renewable energy sources immediately, and are not allowed to purchase electricity from battery storages. Therefore, the electricity in EV batteries is available for only onsite demand. Conventional studies of BEMS have mainly focused on managing appliance demand, such as air conditioning, lighting, and elevators [23,12,6]. Therefore, peak load reduction in a BEMS may encourage individual enterprises to introduce EVs under the current Japanese electricity tariff system.

The proposed algorithm is aimed at working as a sub-routine of various types of BEMS, in which demands and departure times of EVs are given by some prediction algorithms [13] and updated frequently. This approach has been often referred as the rolling horizon in logistics and production planning [24,20]. Exact optimization algorithms, which are time-consuming, are not suitable for charge and discharge scheduling of EVs, because the schedules must be updated whenever demands and departure times of EVs are updated. Thus, we develop a fast LP based heuristic algorithm for computational efficiency and a two-stage heuristic algorithm to cope with uncertain demands and departure times of EVs.

The rest of the paper is organized as follows. In Section 2, we illustrate the considerations for a BEMS with EVs and a time–space network model to describe the charge and discharge schedules of EVs. In Section 3, we formulate an optimization problem for charge and discharge scheduling of EVs in the time–space network model. We present an LP based heuristic algorithm in Section 4 and a two-stage heuristic algorithm to cope with uncertain demands and departure times of EVs in Section 5. We report the computational results in Section 6 and make concluding remarks in Section 7.

2. Building energy management system with electric vehicles

We focus on a local electric power network of a BEMS that includes a number of EVs, in which every EV is used not only as a means of transportation but also as a battery storage. EVs repeatedly charge and discharge their batteries with supplementary electricity to satisfy the demand for appliances in the building. Fig. 1 illustrates the local electric power network of the BEMS. The local electric power network has an alternating current (AC) and a direct current (DC) electric transmission system. Several electric devices are connected with each other through converters and inverters resulting in electric decay.

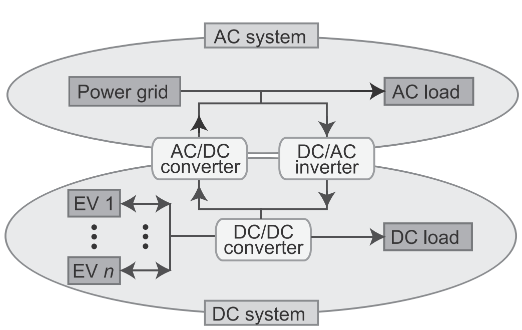

Fig. 1. Local electric power network of the BEMS.

The main functions of EVs are travel and charging and discharging their batteries. We consider the charge and discharge scheduling of EVs supposing that the travel schedules of all EVs are given. EVs are usually disconnected from the local electric power network while they are away from their parking lots. We accordingly use a time–space network model to describe the dynamic changes in the local electric power network over the time horizon. The time–space network model is an expansion of the standard network model, which illustrates a dynamic network varying over time, and the model has a wide variety of applications, such as airline scheduling [9], forest management [1], vehicle scheduling [19], and evacuation routing [25]. A time–space network contains a copy of the node set of the underlying network for every time period, in which each pair of nodes in consecutive time periods is connected by a forward directed arc.

Fig. 2 shows a time–space network model for the local electric power network, in which copies of a node of the underlying network are arranged in a row. The possible charge and discharge operations of EVs are represented by forward directed arcs. We introduce internal nodes, called AC and DC systems, to aggregate the electricity supply through AC and DC converters, respectively. The time–space network model makes it easy to describe the structural changes in the local electric power network; we can describe the absence of EVs from their parking lots by removing the corresponding nodes from the time–space network.

3. Mixed integer linear programming formulation

We consider an optimization problem to achieve peak load reduction in the BEMS. We formulate the problem as an MILP model on the time–space network model. The switching operations between charging and discharging EV batteries are described with binary variables, in order to control the frequency of switching operations appropriately while satisfying AC and DC loads that change significantly in a short time. The inflow and outflow at each node represents the total electricity supply and demand, respectively. We set the lower and upper bounds of the amount of inflow and outflow at each node, which represents the demands and limits of the electric equipment in the local electric power network, e.g., the electricity demands of AC and DC loads and EVs, the maximum electricity supply from the power grid, and the maximum charge and discharge of EV batteries per unit time period. We also set the departure and arrival times of EVs supposing that all EVs depart their parking lots once or twice in the scheduling period. The sets, parameters and variables in the MILP formulation are defined as follows.

Sets

- N set of EVs.
- J_i set of trips of EV i.
- T set of time periods.
- T_i set of time periods when EV i stays in the parking lot.
- T_{peak} set of time periods on peak hours.

Parameters

- c_i battery capacity of EV i.
- f_i maximum electricity charge per unit time of EV i.
- g_i maximum electricity discharge per unit time of EV i.
- $a_{i,j}$ departure time of the jth trip of EV i.
- $b_{i,j}$ arrival time of the jth trip of EV i.

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