Joint Deployment of Charging Stations and Photovoltaic Power Plants for Electric Vehicles

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1. INTRODUCTION

Electric vehicles (EVs) are gaining increasing attention worldwide as a potential approach to reducing carbon emissions from transportation systems (Yu et al., 2018). From some well-to-wheel emission analyses, it is recognized that the popularization of EVs should be synchronized with the deployment of renewable energy generation (Elgowainy et al., 2009; Zhang et al., 2018). Among the existing types of renewable energy, solar has a higher potential for supporting the daily movements of EVs, because of demand matching (Denholm et al., 2013) and local consumption (Zhang et al., 2018).However, even with the advantages presented above, jointly considering the planning of charging stations and PV power plants remains a significant challenge. i.e., complex driver behavior, high variance of travel demand as well as solar energy.

The methodologies to deploy public charging stations on transportation networks can be roughly classified into the following five approaches: clustering (Ip et al., 2010; Momtazpour et al., 2014), flow-capturing (Hodgson and Berman, 1997; Wu and Sioshansi, 2017), simulation-based (Dong et al., 2014; Andrews et al., 2013; Li et al., 2017), activity-based (Recker and Kang, 2010; Kang and Recker, 2014), and equilibrium-based (He et al., 2013, 2014, 2015; Wang et al., 2019). But they all neglect the renewable generations. The

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methodologies on power system if based on optimal power flow (OPF) equation (Dommel and Tinney 1968; Gan et al. 2015). Some researches studies the combination of EV charging and photovoltaics generators, but they mainly oversimplify the transportation system (Munkhammar et al., 2015; Salpakari et al., 2017; Tulpule et al., 2013) or neglect the complex driver behavior (Zhang et al. 2017, 2018).

This research aims to fill this gap by investigating the joint deployment of charging stations and PV plants with a comprehensive capture of the interplay between the coupled transportation and power networks under time-variant traffic demands and energy supplies. Then it proposes a time-dependent charging fee for better managing the coupled networks.

2. MOTHODOLOGY

2.1 Basic consideration

We consider a system with EV drivers, transportation agency, power agency, and city manager (see Figure 1). The object is to minimize the costs associated with this system.

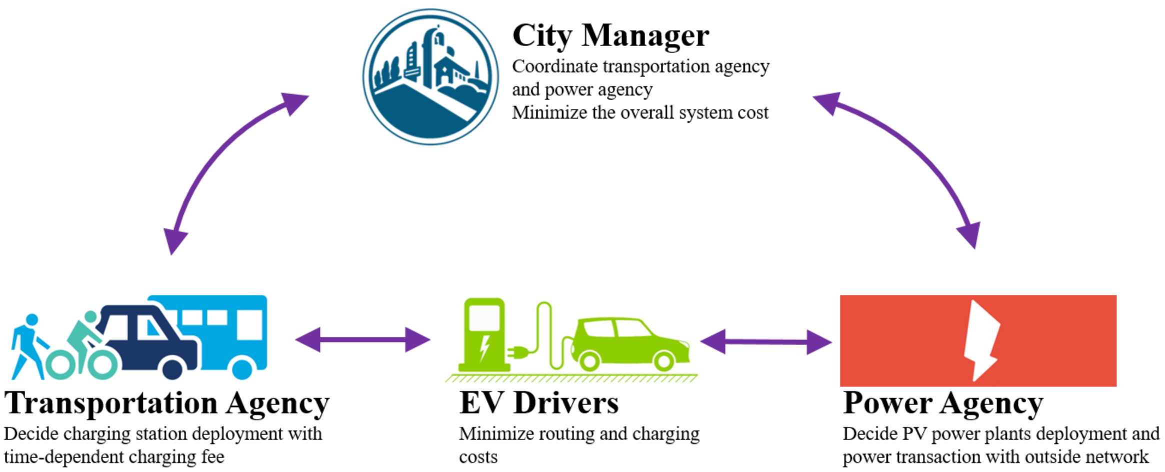

Figure 1. Relationship between stakeholders in this research

2.2 Joint routing and charging problem of EV drivers

A novel extended label-setting algorithm to solve the joint routing and charging problem (JRCP) for EV drivers considering driving time, recharging time, recharging price, and queuing time at charging stations is developed. Specifically, the algorithm can simultaneously optimize the route and recharging amount choices. Moreover, it can capture the possible loops in drivers' route choice, which are basically ignored in previous research.

2.3 Equilibrium on transportation network

A variational inequality (VI) formulation is proposed to model the equilibration of EV drivers' routing choices on transportation networks considering both traffic congestions on roads and queuing delays at charging stations due to high charging demands. Specially, the queuing is modeled as a M/G/K system (Kimura, 1996). We then turn the VI as a NLP problem (Aghassi et al., 2006).

NLP:

$$\min_{f,\zeta,c} z = \sum_{w\in\mathcal{W}} \sum_{p\in\mathcal{P}_w} c_p^w f_p^w - \sum_{w\in\mathcal{W}} \zeta_w D_w$$

$$s.t. \quad \sum_{p\in\mathcal{P}_w} f_p^w = D_w \qquad \forall w \in \mathcal{W} \qquad (1)$$

$$f_p^w \geq 0 \qquad \forall w \in \mathcal{W}, p \in \mathcal{P}_w \qquad (2)$$

$$\zeta_w \leq c_p^w \qquad \forall w \in \mathcal{W}, p \in \mathcal{P}_w \qquad (3)$$

where c_p^w is the cost for choosing routing and charging choice p, which is a nonlinear function of f_p^w. A column-generation approach, coupled with the proposed routing model, is developed accordingly to solve the equilibrium model.

2.4 Optimal power flow

An MISOCP model is constructed to model the OPF with an AC power network. Power selling and purchasing are incorporated into the model. The input is electricity loads and the output is the deployment of PV power plants as well as power transaction and network power flow.

2.5 Joint optimization model

A joint optimization model for the design of charging stations, PV power plants, and time-dependent charging fee is formulated with the above equilibrium model and OPF model. Such optimization model is difficult to solve by conventional optimization techniques; thus, a parallel surrogate-based optimization (SBO) algorithm (Chen et al., 2014) is incorporated to find high-quality solutions within an acceptable computational time.

3. NUMERICAL EXAMPLES

We conduct this numerical test on the coupled Sioux-Falls and a power network (Zhang et al., 2018), the deployment result is shown in Figure 2. The lower bound analysis and comparison with genetic algorithm shows the efficiency of our algorithm (see Figure 3). Further analysis on queuing time at charging station with or without time-dependent charging fee shows the benefits of time-dependent economical strategy.

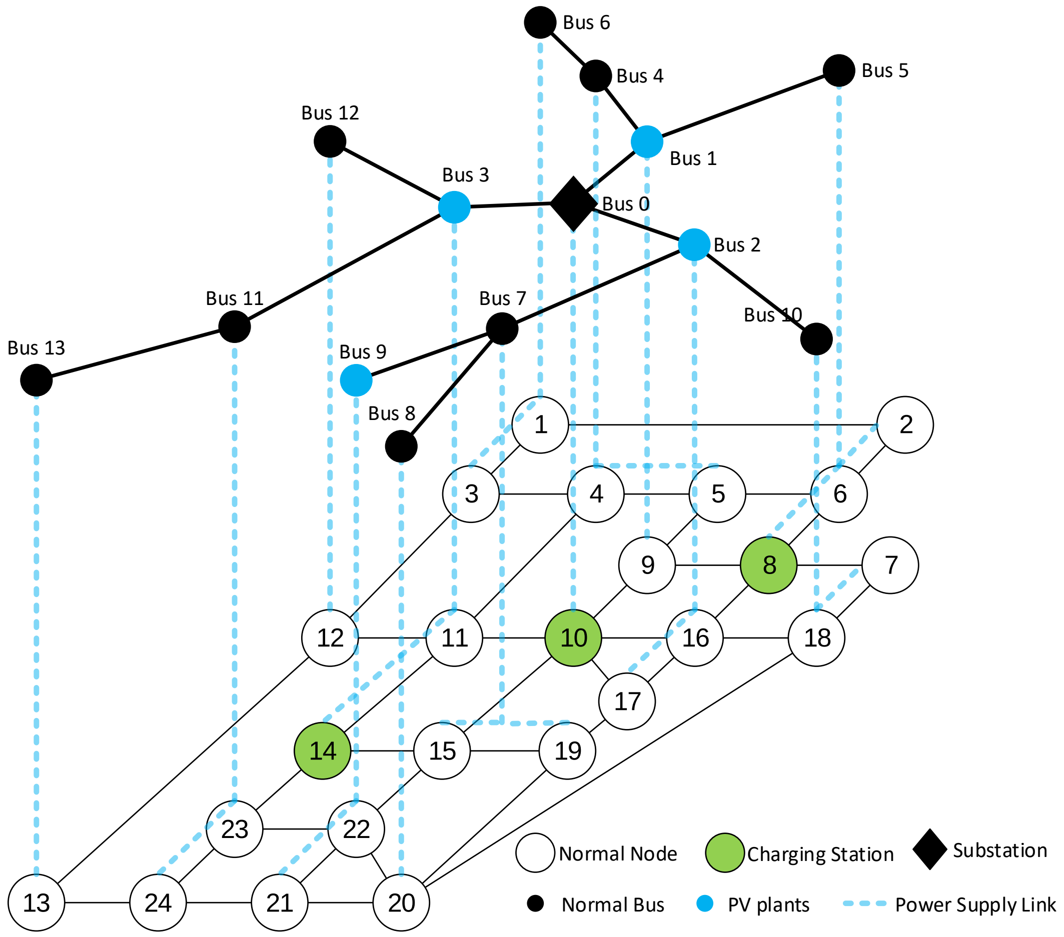

Figure 2. Planning results of charging stations and PV plants

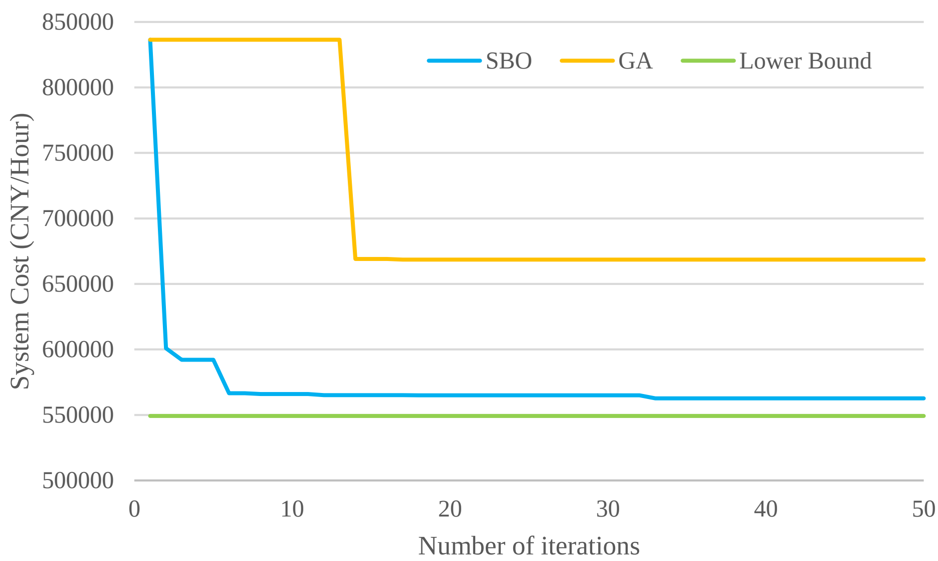

Figure 3. Convergence curve and lower bound

4. CONCLUDING REMARK

This paper is primarily concerned about the joint optimization on the planning of charging stations and PV plants with time-dependent charging fee to better manage coupled transportation and power networks. Future research will focus on more flexible and heterogeneous charging choice.

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