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Power-traffic coordinated operation for bi-peak shaving and bi-ramp smoothing – A hierarchical data-driven approach☆

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HIGHLIGHTS

- It is unique to use the flexibility provided by electrical vehicle to optimize power-traffic system operation.
- A hierarchical operation approach is designed to shave the peak and smooth the ramp for both systems.
- The electrical vehicles and charging/discharging stations are used to couple the power-traffic system.
- The distributed algorithm is designed to reduce the computation time.

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ABSTRACT

The power distribution system and urban transportation system are two networked system bare their own operation constraints, such peak load in power systems and traffic congestion in transportation system. With the increasing number of electrical vehicles and charging/discharging stations, two systems are become tightly coupled. However, to optimize the two systems target using electrical vehicles as decision control variables cannot be easily solved using a uniformed optimization frame work. Thus we propose a hierarchical optimization approach to address this problem, which consists of a higher and a lower level. In the higher level, the power distribution system and urban transportation system are treated together to minimize the social cost. Meanwhile, the electrical vehicles and the charging/discharging stations are treated as customers to minimize their own expenditures. Then, an equilibrium is designed to determine the optimal charging/discharging price. In the lower level, the models of power distribution system and urban transportation system are developed to provide a detailed analysis. Specifically, in power distribution system, the three-phase unbalanced optimal power flow problem is relaxed with the semidefinite relaxation programming, and solved with alternating direction method of multiplier. A dynamic user equilibrium problem is formulated for the urban transportation system. For electrical vehicles, the state of charge is considered to optimize the charging/discharging schedule and reduce the impacts of power distribution systems. We conducted the simulation and numerical analysis using the IEEE 8500-bus distribution system and the Sioux Falls system with about 10,000 cars. The results demonstrate the feasibility and effectiveness of the proposed approach.

1. Introduction

Rooftop photovaltaic (PV) gained a foothold in many power systems because of its continuously declining cost [1–7]; however, it also presents unprecedented challenges to power systems operation and control. For example, the “duck curve” has been recorded in some high-distribution PV regions such as California [8–13].The peak solar generation in the middle of the day sinks netload to lower valley and then when peak load occurs right after sunset, a huge volume of energy demand ramps up in a short time frame. This creates the artificial peak and ramping that are costly to balance using the current power system assets. Similarly, transportation system also has high peaks and steep

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Nomenclature

PDS, UTS, CDS	power distribution system, urban transportation system, charging/discharging station
SUE, DUE	static user equilibrium, dynamic user equilibrium
OPF, SDP, ADMM	optimal power flow, semidefinite relaxation programming, alternating direction method of multiplier
EV, SOC	electrical vehicle, state of charge
F^t_{UTY}, F^t_{CSO}	the objective function of the utility and customer in time interval t, $t \in D_t$
$Q^t_{PDS}, Q^t_{DPDS}, Q^t_{DUTS}$	the netload of PDS, the total charging/discharging power of all CDS, total EVs for charging/discharging
π^{*t}	the optimal charging/discharging price in time interval t
$f^t_{PS}, f^t_{UTS}, f^t_{WT}$	the cost function of PDS, UTS, and charging/discharging time
$\mathscr{G}^{UTS}$	the graph for UTS with a node set and a link set: $\mathscr{G}^{UTS} = [\mathscr{V}^{UTS}, \mathscr{E}^{UTS}]$, where $\mathscr{V}^{UTS} = \{1, 2, ..., n_{\mathscr{V}^{UTS}}\}$, and $\mathscr{E}^{UTS} = \{1, 2, ..., m_{\mathscr{E}^{UTS}}\}$
$\theta^t_{k_a}, C_{k_a}$	the traffic flow on link k_a and the traffic flow capacity on link k_a
$P_{r_u s_u}$	a set of path used to connect the OD pair, which is defined as $r_u \in \mathscr{V}^{UTS}_{r_u}$ and $s_u \in \mathscr{V}^{UTS}_{s_u}$, $\mathscr{V}^{UTS}_{r_u}$ and $s_u \in \mathscr{V}^{UTS}_{s_u}$ are the original node set and destination node set, respectively
$q^{dt}_{r_u s_u}$	number of vehicles from r_u to s_u departing in time interval d via any path, $d \in D_t$, D_t is the time interval set
$h^{d_1}_{p_{r_u s_u}}$	number of vehicles assigned to path $p_{r_u s_u}$ with departing time interval d_1
$f_{k_a}(x^t_{k_a})$	the travel time on link k_a in time interval t, where traffic flow is $x^t_{k_a}$
$\delta^{d_1 t}_{p_{r_u s_u k_a}}$	a 0–1 variable to indicate in time interval t, whether the trip from r_u to s_u assigned to path $p_{r_u s_u k_a}$ via link k_a departing in time interval d_1
$\mathscr{G}^{PDS}$	the graph for PDS with a node set and a link set: $\mathscr{G}^{PDS} = [\mathscr{V}^{PDS}, \mathscr{E}^{PDS}]$, where $\mathscr{V}^{PDS} = \{1, 2, ..., n_{\mathscr{V}^{PDS}}\}$, and $\mathscr{E}^{PDS} = \{1, 2, ..., m_{\mathscr{E}^{PDS}}\}$
F^t_{PDS}	the objective function of OPF in PDS
$V^{\phi t}_i, I^{\phi t}_i$	the complex voltage and current on bus i with phase ϕ, $\phi \subseteq \{a, b, c\}$
$s^{\phi t}_i$	power injection on bus i, where $s^{\phi t}_i = p^{\phi t}_i + \mathbf{i} q^{\phi t}_i$
z^{ϕ}_i	the complex impedance matrix $z^{\phi}_i = r^{\phi}_i + \mathbf{i} x^{\phi}_i$
$S^{\phi t}_i$	the complex power from bus i to bus i^1, where bus i^1 is the ancestor of bus i, $S^{\phi t}_i = V^{\phi t}_i (I^{\phi t}_i)^H$, H indicates the hermitian transpose
$v^{\phi t}_i, i^{\phi t}_i$	$v^{\phi t}_i = V^{\phi t}_i (V^{\phi t}_i)^H$, $l^{\phi t}_i = I^{\phi t}_i (I^{\phi t}_i)^H$
$x^{t,k+1}, y^{t,k+1}, \lambda^{t,k+1}$	the iterative variables of ADMM for distributed OPF computation
F^t_{CDS}	the objective function of smart charging/discharging in a CDS
$C^{t_1}_{ev,i_3}$	the discharging (positive) and charging (negative) speed of EV i_3 at time t_1.

ramps due to fairly constrained traffic patterns at the rush hours in urban areas [14–20]. With the increasing amount of EVs and charging stations, the peak and ramp problem in both power distribution system (PDS) and urban transportation system (UTS) are attracting more attention in recently researches [21–30].

Specifically, the power-traffic topic has be widely researched in different aspects. From the transpiration side in [31], based on locational marginal price (LMP), an useful optimal deployment of charging stations is proposed for EVs, which formulates the allocation model as a mathematical optimization problem, and solves it with the active-set algorithm. Unfortunately, this method doesn't consider the impact of EV charging behaviors to power distribution systems. Similarly, in [32], the optimal placement of the charging stations is studied with geographical information and transportation information, which also ignores the impacts to PDSs. Based on the studies in [33], the optimal prices is computed for public charging stations, while, these researches do not consider the discharging of EVs and three-phase unbalanced situation of an actual distributed system. From EVs side in [34], a promising optimal charge control is proposed for plug-in EVs with considering the deregulated electricity markets, but the urban transportation system (UTS) doesn't be taken into consideration. In [35], a novel EV battery charging/swap station planning strategy is proposed to reduce the cost, which also doesn't consider the interactions of PDSs and UTS. Based on these researches, a centralized charging strategy and scheduling algorithm is designed for EVs in electrical markets in [36], which is lack of considering the UTS part. From power system side in [37], a framework of EVs charging is designed to integrate the EVs into PDSs with electricity markets, but less concentrates on the impacts of UTS. In [38], an interesting optimal traffic-power flow is proposed with the wireless charging technology and congestion toll manipulation. The state of charge (SOC) [39,40] of EVs charging is ignored in this research, and the proposed Second-Order Cone approach only focuses on three-phase balanced power flow, which is not the actual status of a three-phase unbalanced PDS. Based on the studies above, it is clear that PDSs, UTS, and EVs are indispensable roles for the comprehensive research on the power-traffic system.

Recently, the charging/discharging stations (CDSs) provide a bi-directional way for EVs to further benefit the PDSs [41,42,23,43–49]. In the proposed approach, a large number of EVs and widely located CDSs are employed as reserves to couple PDSs and UTS. The power flow of the PDSs and traffic flow of the UTS can be manipulated in a convenient manner to shave bi-peak and smooth bi-ramp problem.

To summarize, there are many ongoing works to use the EVs to optimize optimal power flow in PDS or to optimize dynamic user equilibrium in UTS. However, if one to optimize the peaking shaving and ramp smoothing problem for both systems at the same time, it becomes a multi-target and multi-scale optimization problem and cannot be solved with existed approaches in a simple way. To solve this problem, it is imperatively to design a hierarchical approach. The approach firstly identify the equilibrium point of both PDS and UTS to achieve the targets and quantify the EVs capacity as reserves for both systems. Then in the lower level, the detailed model of PDS, UTS and CDSs are composed and the optimal solutions are achieved for bi-peak shaving and bi-ramp smoothing.

Therefore, a hierarchical power-traffic coordinated operation approach is designed as following and the **main technical contributions** of this paper are:

1. A hierarchical coordinate approach is firstly designed from the higher level to lower level to operate the power-traffic system. In the higher level, both PDS and UTS are regulated and treated as an utility to minimize the social cost. The EVs and CDSs are treated as customers to minimize their expenditure. Then, an equilibrium exists between utility and customers to determine the operation variables. Considering the computation load, the equilibrium computation is designed in a distributed way. In the lower level, the detailed models of PDS, UTS, EVs & CDSs are considered to specifically determine these variables.
2. In the lower level, PDS is built with branch flow model, which is equivalent to classic bus-injection model and more suitable for PDS with radial topology. Considering three-phase unbalanced power flow in distribution systems, the optimal power flow (OPF) problem is relaxed with semidefinite programming (SDP). Then, the alternating direction method of multipliers (ADMM) is implemented to

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