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Network security-aware charging of electric vehicles

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ABSTRACT

Large-scale integration of electric vehicles (EV) and wind power could have significantly negative impacts on power systems security. So, it is becoming an increasingly important issue to develop an effective network security-aware charging strategy of EVs. This paper proposes a multi-objective formulation for the optimal charging schedule of EVs while considering N − 1 security constraints. An EV aggregator representing a cluster of controllable EVs is modeled for determining the optimal charging schedule based on a trilevel hierarchy. On the top level, the grid control center determines the EV charging strategy from the proposed formulation, where bus voltage fluctuations, network power losses, and EV charging adjustments are considered as multi-objective functions. To reduce the computational burden, Lagrangian Relaxation (LR) is introduced to handle time coupled constraints and Benders Decomposition is introduced to handle contingencies. Case studies have been conducted on the New England 39-bus system, and the results verify the necessity of considering N − 1 security constraints and the effectiveness of the proposed formulation and solution approach.

1. Introduction

Electric vehicles (EVs) have been receiving considerable attentions worldwide as they are clean and green. However, the large-scale integration of EVs, without coordination, may bring negative impacts on power systems operation, such as lower voltage quality, larger power losses, and more harmonics [1]. Therefore, effective strategies should be developed to schedule the charging of EVs to mitigate the negative impacts and even benefit the grid [2].

In the literatures, studies about EV charging schedule are concentrated on distribution network. Up to now, only a few literatures discussed the charging issues of EVs from the transmission network viewpoint. Ref. [3] presented a bi-level model for coordinating the charging/discharging schedules of EVs. The upper-level model minimizes the system load variance to implement peak load shifting by dispatching each aggregator, and the lower one traces the dispatching scheme determined by the upper-level decision-maker by figuring out an appropriate charging/discharging schedules throughout a specific day. Ref. [4] proposed a multi-objective non-linear mixed integer optimization model for EV charging scheduling considering the uncertainties of photovoltaic and wind power in regional power grids. The fuzzy theory was used to change the multi-objective optimization model into a single-objective non-linear optimization problem.

EV charging schedule problems are mostly formulated as optimization issues aiming at improving voltage profile [5–7], flattening load profile [6–10], reducing power losses [7–11], offering ancillary services [12], minimizing the charging cost [13–15], or increasing user satisfaction level [16,17]. Ref. [5] presented a decentralized optimization methodology to coordinate EV charging to facilitate the voltage control on a residential distribution feeder. Ref. [10] presented a methodology to optimize power system demand due to EV charging load, and it was demonstrated that EV charging load has significant potential to flatten the national demand profile in the U.K. Ref. [11] proposed an optimization model considering EV charging demand and voltage constraints to minimize the power losses of distribution systems. Ref. [12] presented a stochastic method for optimal coordination of charging and frequency regulation for an EV aggregator using the Least Square Monte-Carlo technique while modeling electricity price uncertainty. Ref. [15] proposed an intelligent method to control EV charging loads in response to time-of-use price in a regulated market. Ref. [16] proposed a new metric to represent the EV user satisfaction fairness to achieve a tradeoff between the user satisfaction fairness and the total charging cost of electricity.

The existing EV charging scheduling methods did not take the $N-1$ security constraints into account. However, the secure operation of the system under $N-1$ contingency is an essential requirement [18]. This paper proposes a multi-objective optimization model for EV charging schedule considering $N-1$ security constraints. The main

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Nomenclature

Indices and sets

b	index for lines
i	index for EV aggregators
j,m	index for buses
k	index for generators
l	index for iterations
s	index for system operation scenarios: 0 denotes normal condition, and others represent contingencies
t	index for hours

Constants

T	scheduling duration (24 h in this paper)
n	number of EV aggregators
S	number of slave problems
N	number of buses
L	number of lines
Δt	time interval, 1 h in this paper
w_1,w_2,w_3	weighting factors of the three objectives
$d_{i,t}$	charging duration of EV aggregator i at time t
E_{ev}	total energy demands of EVs during one day
$P_b^{\max}$	upper limit of power flow through line b
$Pch_{i,t}^{\min}$	lower limit of charging power of EV aggregator i at time t
$Pch_{i,t}^{\max}$	upper limit of charging power of EV aggregator i at time t
$P_{\mathrm{Gk}}^{\min}$	lower limit of active power of generator k
$P_{\mathrm{Gk}}^{\max}$	upper limit of active power of generator k
$Q_{\mathrm{Gk}}^{\min}$	lower limit of reactive power of generator k
$Q_{\mathrm{Gk}}^{\max}$	upper limit of reactive power of generator k
$U_j^{\min}$	lower limit of voltage at bus j
$U_j^{\max}$	upper limit of voltage at bus j
U_j^d	desired voltage at bus j (per unit)
$\Delta U_j^{\max}$	maximum permissible voltage deviation at bus j
$Pch_{i,t}^{pre}$	predicted charging power of EV aggregator i at time t

Variables

f_1,f_2,f_3	three objective functions
$P_{\mathrm{loss},t}$	power loss at time t
$R_{b,t}$	line resistance of line b at time t
$I_{b,t}^f + jI_{b,t}^e$	current thought line b at time t
$P_{ll,t}$	total load at time t
Pch_i	total charging power of EV aggregator i
$Pch_{i,t}$	optimal charging power of EV aggregator i at time t
$P_{j,t}^s$	active power injection at bus j at time t
$P_{\mathrm{Gk},t}^s$	active power of generator k at time t
$Q_{\mathrm{Gk},t}^s$	reactive power of generator k at time t
$Q_{j,t}^s$	reactive power injection at bus j at time t
$U_{j,t}^s$	voltage at bus j at time t (per unit)
$G_{jm,t}^s$	the element in j^{th} row and m^{th} column of the conductance matrix at time t
$B_{jm,t}^s$	The element in j^{th} row and m^{th} column of the susceptance matrix at time t
$\theta_{jm,t}^s$	voltage angle difference between buses j and m at time t
λ	Lagrangian multiplier for the time coupled constraint
$Pch_{i,t}^*$	trial charging strategy of EV aggregator i at time t
$I_{b,t}^s$	Current through line b at time t
x	state vector (bus voltage in this paper)
u	control vector (charging power of EV aggregators)
u_0	EV charging strategy vector in normal condition
u_0^*	trial EV charging strategy vector
u_s	EV charging strategy vector in contingency s
δ_b,δ_c	vectors of slack variables for $u_s = u_0^*$
Λ	dual variable vector for $u_s + \delta_c - \delta_b = u_0^*$

contributions of this paper include: (1) the day-ahead optimal EVs charging model, aiming at improving voltage profile, reducing network power loss, and improving user satisfaction, from the transmission network viewpoint is proposed; (2) the $N-1$ contingencies are taken into consideration to guarantees the secure operation of the system under $N-1$ contingencies, which is important for transmission systems. For better implementation, we introduce Lagrangian Relaxation (LR) [19] and Benders Decomposition (BD) methods to solve the proposed formulation. The former is to handle the time coupled constraint and the latter is to handle contingencies in the optimal EV charging scheduling model.

The rest of the paper is organized as follows. Section 2 presents the problem formulation. Section 3 proposes the solution methodology based on LR and BD. The proposed model and solution approach is tested with the IEEE 39-bus systems in Section 4. Conclusions and future work are discussed finally.

2. Problem formulation

2.1. Conceptual framework

Since the capacity of a single EV is too small to have a measurable influence on a transmission grid, an equivalent model (EV aggregator) that represents a cluster of controllable EVs is introduced here to describe their aggregated effects. Using these EV aggregators, a conceptual framework for optimal EV charging schedule based on a trilevel hierarchy is developed and shown in Fig. 1.

At the top level, the optimal dispatch is determined by the control center, and the objective is to determine the charging power of individual EV aggregators based on the predicted wind, solar, and load power. At the middle level, each EV aggregator receives the optimal schedule from the control center and decomposes them into charging strategies for individual EVs. At the bottom level, individual EV communicates with the aggregator, and follows the schedule it receives [20].

This paper focuses on the top transmission level to obtain a day-ahead schedule of EV aggregators for improving the system voltage profile, reducing the power loss, and improving user satisfaction. The main assumptions are as follows:

- The base case is formulated with unit commitment calculated in advance according to daily load curve, daily wind power curve, and predicted EV charging demand/ profile curves.
- The power outputs of conventional generators are adjusted according to the total load change during the optimization.

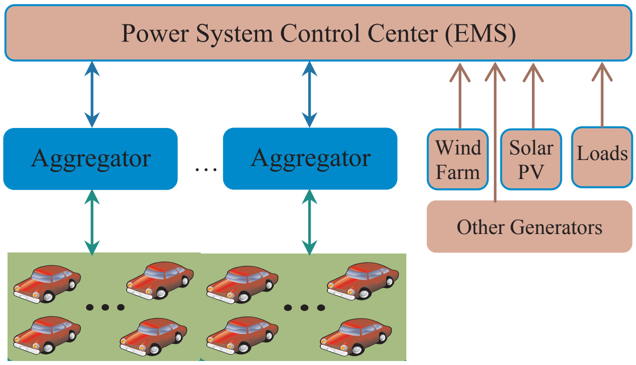

Fig. 1. Trilevel hierarchy for EV charging schedule.