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Optimal spatio-temporal scheduling for Electric Vehicles and Load Aggregators considering response reliability

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ABSTRACT

The increasing power in the demand side, the large-scale Electric Vehicles' (EVs) randomness in charging/discharging modes and uncertainty in demand response are posing a threat to the stable operation and security of power systems. A spatio-temporal bi-layers scheduling model for EVs and Load Aggregators (LAs) considering response reliability is proposed in the paper. In the upper layer, the indices of charging urgency and discharging adequacy are established to describe the controllability of EVs. Further, the EVs are sequenced, and the upper and lower boundaries of controllable power domain are determined. Then, the optimal nodal schedulable load is obtained through an improved optimal power flow model considering the spatial characteristics. In the lower layer, pricing strategies for charging/discharging considering the response reliability of LAs and EVs are developed, and the optimal scheduling strategies are built. Finally, the effectiveness of the proposed model is verified through a modified IEEE 33 system, in addition, impacts of response reliability on the energy allocation and economic benefits are analyzed in the case study.

1. Introduction

Due to the growing concern in the society about energy and environmental issues and drastic development of battery technology in recent years, there comes new opportunities for the large-scale application of Electric Vehicles (EVs). The access of EVs has an important influence on the operation and investment of the power system [1–4]. In the meantime, the concept of Load Aggregator (LA) is proposed [5]. Both LAs and EVs can be regarded as schedulable resources with flexibility on the demand side, which are the key to optimal scheduling of the grid. If the EVs and LAs can be reasonably guided to participate in scheduling, the construction of the distribution network may be decelerated under the premise of meeting the fast-growing charging loads; ulteriorly, investment costs will be saved; moreover, the load curves can be flattered, as well as the effect of EV charging will be mitigated in the distribution network.

At present, there have been many researches on the participation of EVs in grid scheduling. An optimal scheduling strategy that aims to save the costs of EV clusters is proposed in Ref. [6], and the feasibility is verified through simulation. Considering the constraints of EV users' charging demands and voltage amplitude, a charging optimization model of EV is established, aiming at minimizing the power loss of distribution network, and reducing the impact of large-scale EV clusters integration [7]. In general, the charging time of the grid-connected EVs is during the valley of load profiles in the grid, thus contributing to the peak shaving [8]. In order to minimize the active power loss, the internal point method is applied to solve the optimal charging problem of the grid-connect EVs [9]. A multi-agent system is established to coordinate the charging and discharging time of EVs [10].

The studies above neither consider the charging and discharging urgency of EVs, nor the impact of EV charging and discharging orders on the optimal scheduling of the grids. In fact, the schedulable time and capacity of EVs are different. If no appropriate control strategy is adopted, occasions may happen that part of EVs are not involved in the scheduling during the schedulable period, or EVs are centrally dispatched during certain periods of time, while supply shortages occur during other periods. Therefore, further studies should be conducted to evaluate the charging and discharging priority of EVs, determine the optimal charging and discharging time of EVs. Only by making the available capacity of EVs utilized more fully and rationally, the V2G

Abbreviations: AMI, advanced metering infrastructure; LAs, Load Aggregators; EVs, Electric Vehicles; DR, demand response; PSO, particle swarm optimization

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Nomenclature

Parameters and variables

$\Gamma_{ch,n}$	Degree of the *n*th EV's charging urgency
$\Gamma_{dis,n}$	Degree of the *n*th EV's discharging adequacy
$t_{in,n}$, $t_{out,n}$	The time when the *n*th EV plugs in and plugs out
$t_{ch,n}$, $t_{dis,n}$	The charging and discharging time of the *n*th EV
SOC	State of charge
$SOC_{in,n}$	The initial SOC of the *n*th EV
$SOC_{ex,n}$	The expected SOC of the *n*th EV
η_{ch}, η_{dis}	The charging and discharging efficiency of EV
$P_{ch,n}$	The rated charging power of the *n*th EV
$P_{dis,n}$	The rated discharging power of the *n*th EV
$B_{c,n}$	The battery capacity of the *n*th EV
$P_{EV,max}(t)$	The upper limit of the power controllable domain
$P_{EV,min}(t)$	The lower limit of the power controllable domain
C	The total operation cost in the grid
T	The scheduling period
$C_{GEN,t}$	The total fuel cost of all generator units during time t
$C_{S,t}$	The total start-up/shut-down cost of all generator units during time t
$P_{gen,i}(t)$	The active power output of the *i*th generator unit
H	The number of generator units
$a_i b_i$ c_i	The consumption parameters of the *i*th generator unit
$S_{gen,t}$	The start-up/shut-down cost of the *i*th generator unit
$u_i(t)$	The state of the *i*th generator unit, where "1" means on and "0" means off
V_i	Voltage amplitude of the *i*th node
$V_{\min}$, $V_{\max}$	The minimum and maximum of node voltage amplitude
$P_{G,i}(t)$	The active power output at time t of node i
$Q_{G,i}(t)$	The reactive power output at time t of node i
$P_{L,i}(t)$	The active load of node i at time t
$Q_{L,i}(t)$	The reactive load of node i at time t
$V_i(t)$	The voltage amplitude of node i during time t
$V_j(t)$	The voltage amplitude of node j during time t
G_{ij}	The conductance of branch *i–j* in system admittance matrix
B_{ij}	The susceptance of branch *i–j* in system admittance matrix
$\theta_{ij}(t)$	The node voltage phase difference
$P_{EV,i}(t)$	The total load of EVs at node i during time t
$P_{LA,i}(t)$	The total interruptible load of LAs at node i during time t
$P_{LA,Max}$	The upper limit of the interruptible load of LAs
$P_{LA,min}$	The lower limit of the interruptible load of LAs
$W_{E,i,t}$	The electrical energy of node i during time t
$state_{ch,n}(t)$	The charging state of the *n*th EV
$state_{dis,n}(t)$	The discharging state of the *n*th EV
SOC_{min}	The minimum SOC of EV
SOC_{max}	The maximumSOC of EV
$N_i(t)$	The number of EVs at node i during time t
N	The total number of EVs in the system
η_{self}	The coefficient of EV self-discharging
$t^*_{dis,n}$	The modified discharging time
$\rho_{price,t}$	The node price (i.e. the charging price)
$\rho_{ch,t}$	The charging price (i.e. the node price)
$W_{dis,n}$	The discharging energy of the *n*th EV
$\phi(\delta)$	The probability density function of the normal distribution
$\Phi(\delta)$	The cumulative distribution function
$\gamma_{EV,n}$	The response reliability of the *n*th EV user
γ_{LA}	The response reliability of LA
$\gamma_E(t)$	The integrated response reliability of the scheduling strategy implemented by all users during interval t
N^*_{EV}	The number of EVs response to discharging price after optimization
P_{LA1}, P_{LA0}	The load of LAs before and after the scheduling
$\Delta W_{E,t}$	The variation of electrical energy
β	The response rate of EV users to discharge price
$\beta_{E,\max}$	The saturation value of the percentage of EV users who response to scheduling
k_E	The slope of response curve of EV user in linear region
$\rho_{EV\_dis,t}$	The acceptable lower boundary of discharging price of EV
$\rho_{Gr\_dis,t}$	The upper boundary of discharging price of EV accepted by power company
$C_{EV\_Loss,t}$	The loss cost of EV
$C_{EV\_dis,t}$	The loss cost caused by discharging process
$C_{EV\_L,t}$	The equivalent cost of battery life loss
$W_{EV,t}$	The released electrical energy of EV
φ_{EV_t}	The coefficient of loss cost due to cyclic charging
$C_{EV\_S,t}$	The discharging benefit of EV
$\rho_{dis,t}$	The discharging price of EV
$C_{Grid,t}$	The increased cost of power supply company
$C^*_{GEN,i}$	The new generation cost of power company
$C_{GEN,i}$	The original generation cost of power company
$C_{G\_S,t}$	The benefit function of power supply company
K	The number of LA
$C_{EV,t}$	Economic benefit of EVs
$C_{LA,t}$	Economic benefit of LAs
$\rho_{LA\_price,k}(t)$	The interruption compensation price of the *k*th LA
$h_k(\cdot)$	The high-compensation multiple transfer function
$\rho_{price,k}(t)$	The real-time price of the *k*th LA

scheduling can be implemented effectively.

As a daily transportation for the residents, the EVs must meet the daily routine and lifestyle at the first place. In other words, on the premise of meeting the driving requirements, only by the consent of the owner can they participate in the scheduling of power system. Hence, it is very important to formulate a reasonable electricity price mechanism to stimulate the participation of the EV owners. Massive efforts have been made to explore the electricity price mechanism and existing work can be classified into two classes both at home and abroad currently: (1) the charging and discharging price is formulated by using the method of allocating optimal time-of-use (TOU) electricity price, and (2) the game theoretic approach between EV aggregators and the grid are also employed in mechanism formulation. A method of reasonable TOU electricity price to guide the EVs' charging and discharging behaviors are proposed in Refs. [11–14]. The results indicate that the optimal TOU electricity price can direct EV owners to minimize their fueling costs and concurrently minimize the electric system impact of EVs. In Ref. [15], the simulation results under TOU electricity price and that of under fixed electricity price as well as the influences of different TOU price on scheduling strategy are contrasted and analyzed. Ref. [16] studies the efficacy of TOU rates in guiding EVs' charging behaviors. Refs. [17,18] put forward the idea of using game theory to find out the Nash equilibrium solution of the grid and consumers, then finally obtain reasonable charging and discharging price. A bi-level planning is presented for the maximum corporate gains and the minimum consumer costs in Ref. [17]. Based on the game theory, Ref. [19] constructs a multi-agent system based on micro-network and expounds its application. Ref. [20] obtains the relationship between the optimal discharging price of the electricity grid and the corresponding proportion of the EVs through the chaos algorithm, and provides the reference for the electricity grid to get the discharging price. As reviewed above, there are still deficiencies in mechanism formulation of electricity price mainly reflected in the following points: (1) consider too much on the benefits of EVs while ignore the revenue of the electricity grid, (2) the charging price is taken into account only, (3) the uncertainty of the response of EVs and LAs is not considered.