Optimal Scheduling of an EV Aggregator for Demand Response Considering Triple Level Benefits of Three-Parties

Hui Ren[1], Aiwei Zhang[1], Fei Wang[1,2,3,*], Xihui Yan[1], Yu Li[4], Neven Duić[5], Miadreza Shafie-khah[6], João P. S. Catalão[7]

1. Department of Electrical Engineering, North China Electric Power University, Baoding 071003, China
2. State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources (North China Electric Power University), Beijing 102206, China
3. Hebei Key Laboratory of Distributed Energy Storage and Micro-grid, North China Electric Power University, Baoding 071003, China
4. State Grid Xinjiang Electric Power Co., Ltd, Urumqi 830018, China
5. Department of Energy, Power and Environmental Engineering, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, HR-10000 Zagreb, Croatia
6. School of Technology and Innovations, University of Vaasa, 65200 Vaasa, Finland
7. Faculty of Engineering of the University of Porto and INESC TEC, 4200-465 Porto, Portugal

*Corresponding author at: Department of Electrical Engineering, North China Electric Power University, Baoding 071003, China
E-mail address: feiwang@ncepu.edu.cn (F. Wang)

Abstract—The electric vehicle (EV), when aggregated by an agent (Aggregator), is a suitable candidate for participating in demand response in power system operation. As the interface between distribution network and EV users, as well as an independent party at the same time, an optimal scheduling algorithm is necessary with consideration of benefits of three parties, which in return will affect aggregators' sustainable development. The benefits of distribution system from demand response, aggregator and EV users are defined in this paper. EV users' benefit is described by their satisfaction on SOCs reached after a given period of time and overall costs/revenues for charging/discharging and policy award/penalty, while the benefit of distribution network for the integration of large amount EV loads through aggregator is evaluated by aggregator's load shifting capability through a price-based demand response (DR) program under real time electricity price. The optimal scheduling of the aggregator is with an objective of maximizing its own benefit under constraints of EV users' minimum satisfaction and minimum load-shifting capability required by distribution network. The optimization scheduling is tested by a test system, and further analysis is given on the effect of aggregator's facility level and technology (Vehicle to Vehicle) and the operation mode of aggregator group on the benefits of three parties.

Index Terms—Aggregator; Demand response; Electric vehicle; Users' satisfaction; Load shifting; Vehicle to Vehicle

Nomenclature

Acronyms

DGs	Distributed Generations
DR	Demand Response
EV	Electric Vehicle
V2G	Vehicle to Grid
V2V	Vehicle to Vehicle
SOC	State of Charge
SOH	State of Health
DSO	Distribution System Operator
TOU	Time-of-Use

Indices

t	Index of time slot.
i	Index of EV.

Parameters and Variables

$M_{day}\%$	Evaluation function of aggregator's demand response (DR) capability.
M_a, M_e	Variance of the latest 24-hour load curve with DR and base-line load curve, respectively.
L_t	Base load of the system at time t (kW).
$\bar{L}$	Average load of base-line load curve of the latest 24 hours (kW).

$P_{DR,t-1}, P_{DR,t}$	DR power of the aggregator at the $(t\text{-}1)^{\text{th}}$ and t^{th} scheduling moment (kW), respectively. $P_{DR,t} < 0$ means the aggregator sends power to the network.
$\overline{P_{DR}}$	Average power of the aggregator of the latest 24 hours (kW).
$P_{DR,t}^{min}, P_{DR,t}^{max}$	Maximum and minimum of load of the aggregator of time slot t (kW).
$P_{c,t}'$	Charging price for the tth slot by the aggregator without considering the penalty during high load period (CNY/kWh).
$P_{d,t}'$	The purchasing price (V2G price) given by aggregator without considering the policy award for time slot t (CNY/kWh).
$P_{c,t}$	Forecasted real-time electricity price given by distribution system for time slot t (CNY/kWh).
$P_{add,t}$	Service fee for charging service collected by the aggregator (CNY/kWh).
$P_{m,t}$	Whole V2V power available at time slot t (kW).
$E_{c,i}$	Charging cost of the ith EV (CNY).
$R_{c,i}, R_{d,i}$	Policy penalty paid and award gained of the ith EV(CNY).
$I_{d,i}$	The ith EV's V2G revenue paid by the aggregator (CNY).
$R_{c,t}, R_{d,t}$	Policy penalty for charging service and award for V2G service at time t (CNY/kWh).
R_{dmax}	Maximum policy award an EV could obtain (CNY).
θ	Purchasing price of V2G given by distribution network (CNY/kWh).
$C_{B,i}$	Rated capacity of battery of the ith EV(kWh).
$w_{1,i}, w_{2,i}$	Weights of the ith EV's SOC and economic satisfaction.
μ	Economic benefit of aggregator's DR capability.
r_i	Maximum change rate of DR per unit time in Aggregator.
M	The minimum DR capability required by distribution network.
N	Number of piles.
m	Number of EVs that charge from distribution network.
n	Number of EVs that discharge to distribution network.
$t_{c,begin}, t_{c,end}$	Charging beginning and ending time.
$t_{d,begin}, t_{d,end}$	Discharging being and ending time.
$\Delta SOC_{i,t}^-$	SOC increment of the ith EV within time slot t. Superscript (-) means discharging.
$\Delta SOC_{i,t}^+$	SOC increment of the ith EV within time slot t. Superscript (+) indicates charging.
SOC_i''	SOC of the ith EV at the leaving time.
$SOC_{0,i}$	SOC of the ith EV at the arriving time.
SOC_i'	Target SOC of the ith EV.
SOH_i	SOH of the ith EV.
$SOC_{t,i}$	SOC of the ith EV at time t.
$G_{1,i}\%$	The ith EVs' SOC satisfaction.
$G_{c2,i}\%$	The ith EVs' economic satisfaction for charging service.
$G_{d2,i}\%$	The ith EVs' economic satisfaction for discharging service.
$G_{c,i}\%, G_{d,i}\%$	Satisfaction of the ith EV for charging service and discharging service, respectively.
$G\%$	Satisfaction of the whole user group.
$G_{min}\%$	Minimum users' satisfaction of the whole EV group.
F	The aggregator's profit during the latest 24 hours (CNY).
$F_{c,t,i}, F_{d,t,i}$	Service fees for charging and V2G service collected from the ith EV at time slot t, respectively (CNY).
$F_{V2V,t}$	Equivalent savings from serving EVs through V2V at time slot t (CNY).
F_{DR}	Aggregator's revenue of its DR capability of the latest 24 hours (CNY).
$N_{t,i}^c, N_{t,i}^d$	Priority of the ith EV for charging and V2G service, respectively.
$CR_{t,i}$	Charging and discharging rate of the ith EV, respectively.

I. INTRODUCTION

Under the pressure of energy crisis and environmental pollution, the effective application of renewable energy has become the theme of current era. Distributed generations (DGs), especially the renewable generations, provide a solution for higher efficiency and greener electricity. However, the randomness and fluctuation of renewable DGs' output brings new challenges to the operation of distribution system. Demand response (DR) provides more flexibility for maintaining the balance between supply and demand sides and improving system reliability [1-3].

As one of the most popular participants in DR, electric vehicles (EVs) play an important role on reducing $CO2$ emission under the government promotion policy in recent years. Due to the capacity limit of a single EV battery, the aggregators are necessary as market agents for EVs to actively participate in DR and other proper balancing services [4, 5]. Aggregators act as interfaces between the distribution system and multiple EV users. Due to the owners' behaviors' uncertainty, the EV aggregation agent will confront numerous challenges in order to participate in DR and other market services [6, 7]. Their performance affects EV users'

benefits as well as the market efficiency and system reliability. In return, the sustainable development of aggregators will finally be shaped by the synergic operation of distribution system and EVs. Aggregator, when being considered as a private entity, always wants to maximize its own profit by using various means including additional services [8] and selling secondary reserve in electricity market.

Cooperation among multiple aggregators could provide better service to customers with relatively low infrastructure configuration in each station and better DR flexibility. Multiple aggregators and distribution operator could coordinate between each other, for example, a centralized hierarchical framework was proposed that Distribution System Operator (DSO) seeks to coordinate the charging of all aggregators to minimize energy purchase costs under Time-of-Use (TOU) tariffs and achieve peak load controlling [9, 10]. However, it brings data privacy issues and individual economic concerns. When there is no central controller of multiple aggregators, coordination could be achieved through incentive-based mechanism between aggregators or distributed optimization algorithm [11-13].

Aggregator, as the interface between distribution system and EV users, its benefit is closely related to the other two parties. Part of the benefit of an aggregator is from the price differences between buying energy from the system and selling energy to the system [13]. Participating in different market services could enlarge its profit room. However, the EV aggregators need to secure a certain amount of EV users to make its real energy consumption as close as the energy bided by aggregators in the market, the difference of which will lead to punishment to aggregators.

Although aggregators can protect their users by signing contracts [14], a more sustainable and long-term solution is to improve users' satisfaction. Then, most studies define the optimal scheduling goal of aggregators as the maximization of user satisfaction or/and the minimization of purchasing energy cost [15][16]. The users' satisfaction is modeled through charging time, state of charge (SOC), charging cost and the combination of the above factors. For example, in Ref. [11], the users' convenience is modeled by the available charging time and the users' initial SOC. Ref. [15] defines users' satisfaction as the average value of the ratio of energy to demand provided by plug-in electric vehicles within 24 hours. Ref. [17] expresses users' satisfaction by the shortest time required to meet the charging need, and users' satisfaction can be expressed by user waiting time (including queuing time and charging time) [18-20]. In [21]and [22], users' satisfaction is measured by user charging and discharging cost under TOU electricity price. This paper models the users' satisfaction of charging service provided by the aggregator as well as discharging service. The proposed satisfaction model in our study has two parts: user's satisfaction for charging service and user's satisfaction for discharging service. Each of them is decided by SOC satisfaction and economic satisfaction. The SOC satisfaction is defined similar to that of other references, while the economic satisfaction is decided by the cost/income EV user has to pay or obtain. If the cost cannot be minimized by aggregator through avoiding charging from the grid during peak load hour, or the income cannot be maximized by aggregator through discharging to the grid during the peak load hour, EV user's economic satisfaction drops.

Through aggregator, EVs could be accumulated and participate in DR program and other market services and gain more benefit [23]. When aggregators are as sources of DR, from the perspective of distribution network, a better load profile with low peak-to-average ratio through charging/discharging behaviors of aggregators is expected [10]. The difficulties in aggregator scheduling scheme and the uncertainty in its DR capacity are caused by the randomness in EVs' behaviors. Measures are taken to minimize them in references. For example, in [24], EV users are required to book services in advance. In [4], users that cannot buy services in aggregator as booked will be punished. These measures are feasible, but they omit the fact that charging needs of EV users are rigid, and Vehicle to Grid (V2G) behavior is benefit-responsive. Under the market environment, EV users' behaviors should not be "planned". In some cases, the daily price also might be one impact factors affecting the EV users' behaviors [25].

V2V（Vehicle-to-Vehicle）is performed among multiple EVs within a local grid, and energy exchange with distribution network is not needed. Through V2V, EVs can transfer their energy by bidirectional chargers through a local grid, and then distribute the energy among other EVs by aggregator [26]. Technology to conventional charging /discharging devices with the increasing market volume of EV. As indicated in [26], V2V has multiple features, such as uncomplicated infrastructure requirements and small transmission losses, operation in community-grid, etc. At present, research on V2V technology mainly focuses on the charging and discharging strategies, the cooperation between users and system, etc. An online V2V charging / discharging strategy for switching stations based on price control is proposed in [27]. The optimal V2V charging and discharging strategy is formulated by using game theory and Lagrange dual optimization technology. Based on the concept of V2V for collaborative charging, a flexible energy management protocol with different V2V matching algorithm is proposed in [28], which helps electric vehicles to achieve more flexible and intelligent charging/discharging behaviors. Ref. [29] proposes a mobile PEVs smart grid structure with enhanced communication capability by strengthening smart grid through heterogeneous wireless network. Differently, in our research, we mainly study the impact of V2V technology in the aggregator on EV user satisfaction, aggregator's benefit, and aggregator's DR capability. Also, the condition, under which V2V effect, is also studied.

In this paper, the interaction of benefits of distribution network, aggregator and EV users were firstly analyzed and quantified. The model of EV user's satisfaction for services they seek in aggregators is improved by considering the nonlinear relationship between the changes of State of Charge (SOC) and satisfaction. Based on the analysis, an optimal scheduling algorithm for aggregator's operation is proposed. Through the optimal scheduling algorithm and necessary facility and technology, the aggregator maximizes its own profit, meantime satisfies the minimum requirements of DR capability set by distribution network and satisfaction required by EV users.

Considering the range of EV batteries and the correlation of charging and discharging behaviors among different stations due to the temporal-spatial statistics of behaviors of EVs, in this study we focus on the service quality, DR performance and the benefit of two aggregators in residential and commercial areas respectively. Due to the rigid requirement of EV users' charging needs, EV users' economic motivation for DR program, the services they order and profit of two aggregators are correlated. The benefit of each aggregator and aggregator group of 2 aggregators under different facility and technology (V2V) level is further analyzed. Useful implications for the configuration and operation of aggregators are given.

The paper is organized as follows. In section II, the benefit that distribution network obtains from the management of large amount of EV loads through aggregators, satisfaction of EV users and benefit of an aggregator as the interface between EVs and distribution system are defined. Based on them, an optimal scheduling algorithm and key issues in the scheduling are provided in section III. In section IV, models and the optimal algorithm are tested through a test system under a simulation of 5 simulated years with a resolution of 15 minutes. Effects of facility and technological level of aggregators in different areas on the benefits of three parties are further analyzed. In section V, comprehensive conclusions are provided.

II. BENEFITS OF THREE PARTIES

In this study, we propose an optimal scheduling model with consideration of the benefits of multiple parties involved. Fig.1 gives the interaction of benefits among aggregators, EV users, and distribution network, where supplement by optimization refers to the increase of income because of serving more customers by technology introduced in section III-B and potential profit brought in the future by the increase of customers' satisfaction due to the aggregator's optimal scheduling technique.
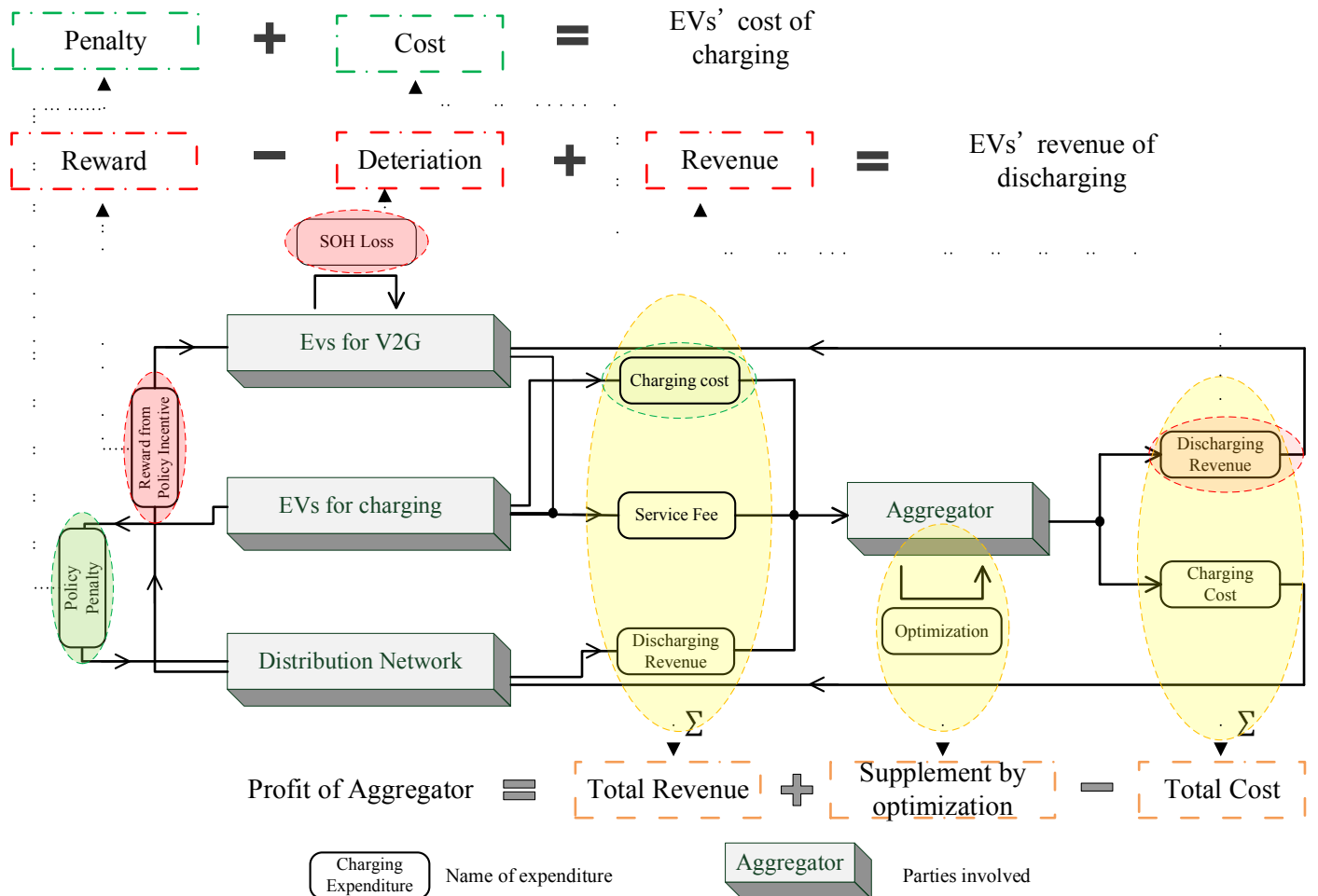

Fig. 1. The interaction of benefits among aggregators, EV users and distribution network

In this section, we define an "evaluation function", users' satisfaction, and aggregators' profit to represent the benefit of distribution system, EV users, and aggregators, respectively. Charging/V2G prices affects the profile of EV loads. In this study, real time pricing scheme is considered for a price-based demand response scheme, i.e. a real-time pricing scheme. Under the real time pricing scheme, higher tariff is charged for peak load period during the day, while lower tariff is charged for valley load

period during the night. On top of that, another incentive-based DR program is defined as follows: the DR program is on when the load level of the system is above 80% of the system's peak load. During this period of time, EV users for charging will be charged an extra penalty on top of the real time electricity price, while EV users for discharging will be paid a reward on top of the purchasing price given by the local distribution network. Since the peak load is shifted under these two DR programs, aggregator's load-shifting capability also refers to its DR capability in the following.

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A. Evaluation function for aggregator's DR capability

Fig. 2 gives the schematic diagram of the influence of EVs charging and discharging load through aggregator on the daily load curve of the distribution network. In Fig. 2, the grey area between the red and blue dot dash lines represents the energy consumed by EVs.
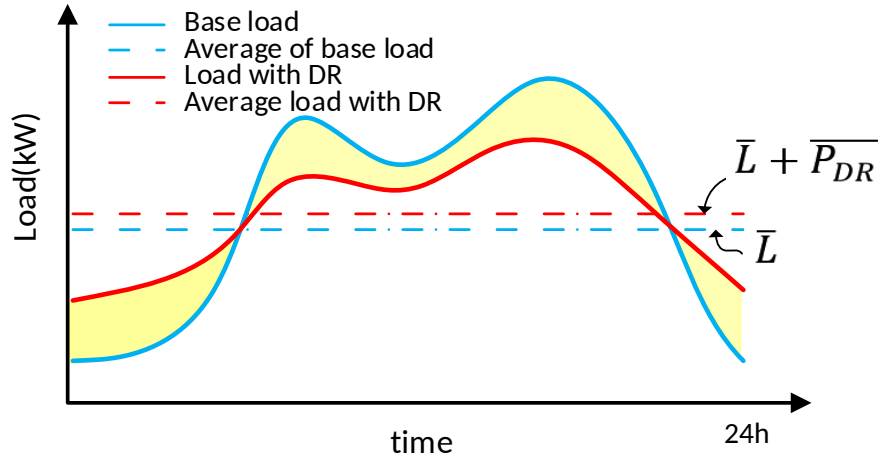

Fig. 2. Illustration of daily load without DR and daily load with DR

The red curve (the load curve with EVs' participating in DR through aggregator under optimal scheduling) fluctuates less than the blue curve (the load curve without EVs load). Peak-shifting effect is gained. Theoretically, an evaluation on aggregator's DR capability from the distribution side needs load curves of the system with EVs' participating in DR through aggregators and without EVs participating in DR programs. However, without real-time price scheme and V2G through aggregators, EV users charging load is affected not only by EV users' driving behavior, but also their charging habits, for example, charging every day or charging every two days. Therefore, more assumptions need to be made in order to obtain the load curve without EVs' participating in DR. Since a better load profile with low peak-to-average ratio is expected by the distribution system, in this study, as a replacement, we use the difference in the variation of loads with DR and base load (no EV loads and V2Gs) to reflect aggregator's DR capability. Under real-time tariff system, EV users tend to charge at low price period (normally during night time), while discharge at high price period (normally during day time). Under the proposed DR program, if EVs discharge more and charge less when policy award is available (which is also during high price period), better load-shifting is obtained, and the load curve will be flatter, and area filled in yellow will be greater.

Therefore, we define $M_{day}\%$, which is calculated by (1)-(5), to evaluate the performance of an aggregator as a provider of DR capacity for the latest 24 hours.

$$M_{day}\% = \frac{M_e - M_a}{M_e} \times 100\% \tag{1}$$

$$M_a = \sqrt{\frac{1}{T}\Sigma_{t=0}^{T}[\frac{L_t - \bar{L} + P_{DR,t} - \overline{P_{DR}}}{\bar{L} + \overline{P_{DR}}}]^2} \tag{2}$$

$$M_e = \sqrt{\frac{1}{T}\Sigma_{t=0}^{T}[\frac{L_t - \bar{L}}{\bar{L}}]^2} \tag{3}$$

$$\bar{L} = \frac{1}{T+1}\Sigma_{t=0}^{T}L_t \tag{4}$$

$$\overline{P_{DR}} = \frac{1}{T+1}\sum_{t=0}^{T}P_{DR,t} \tag{5}$$

where M_a and M_e are the standard deviation of the latest 24-hour load curve with DR and base-line load curve respectively; $P_{DR,t}$ is the power of the aggregator at the tth scheduling moment; $\overline{L}$ is the average load of base-line load curve of the latest 24 hours，where L_t is the load of the system at time t; $\overline{P_{DR}}$ is the average load of the aggregator of the latest 24 hours. The operation of aggregator of 24 hours is divided into multiple time slots, which is represented by $(T+1)$ in (2)-(5). For example, if each time slot is 15 minutes, and $t = 0,1,2,\cdots,95$, then there are 96 time slots in total for a day. Therefore, $M_{day}\%$ is the relative difference between the standard deviations of two time series $\{L_t\}$ and $\{L_t + P_{DR,t}\}$.

The distribution system evaluates aggregator's performance by $M_{day}\%$ and delivers correspondent service fee to the aggregator for the DR capacity it provides.

B. EV users' satisfaction

Under market environment, the EV user's satisfaction is one of the key factors that affect the aggregator's market volume and development. Charging time, state-of-charge (SOC) or variation of these two factors, as well as the cost of buying energy from distribution network are main factors deciding EV users' satisfaction [11, 13, 17-22].

EV user's charging time or discharging time is mainly decided by aggregator's facility level (the number of charging/discharging piles, the charging/discharging power), the number of EV users arrives at the aggregator within the same time slot, which cannot be controlled, and the order that EVs are served, which could be adjusted by the scheduling strategy of the aggregator. When the EV user could decide its leaving time in advance, the abovementioned factors will affect EV's SOC reached at the predefined leaving time. Therefore, we define EV user's satisfaction to the aggregator's service to be a weighted summation of SOC satisfaction and economic satisfaction.

We assume that EV could provide the following information to the aggregator when calling for charging or V2G service in the aggregator: current SOC, State of Health (SOH) of the battery, arriving time, charging/discharging power, the target SOC, and leaving time. We assume that EV user's intelligent device, for example, trip computer or Apps on EV driver's smart phone, can provide an optimal target SOC for charging and V2G to aggregator at arriving. For example, EV users' willingness to charge and target SOCs could be decided by its current SOC and the cost they will pay to charge, while their willingness to V2G and target SOCs are decided by forecasted purchasing prices of electricity during discharging period, cost of extra cycling of the battery (related to the SOH of the battery), and the cost of previous charging [30].

a) EVs' SOC satisfaction

SOC satisfaction is defined as the percentage that EV user's charging/discharging plan is fulfilled at the aggregator. When EV users participate in the service, there may be a difference between the expected and actual charging / discharging SOC due to the facility limitation or constraints of operation conditions, which will have an impact on the user experience. Therefore, we define an index, denoted by $G_{1,i}\%$, to reflect the ith EVs' satisfaction with SOC when leaving the aggregator.

$$G_{1,i}\% = \frac{SOC_i'' - SOC_{0,i}}{SOC_i' - SOC_{0,i}} \tag{6}$$

where $SOC_{0,i}$, SOC_i', and SOC_i'' are the SOC at the arriving time, the target SOC and the SOC at the leaving time of the ith EV, respectively.

b) EV's economic satisfaction for charging service

Based on Fig. 1, we define an index, denoted by $G_{c2,i}\%$, to describe the ith EVs' economic satisfaction for charging service as follows.

$$G_{c2,i}\% = \frac{E_{c,i}}{E_{c,i} + R_{c,i}} \tag{7}$$

$$E_{c,i} = \sum_{t=t_{c,begin}}^{t_{c,end}} \left(P_{c,t}' \cdot C_{B,i} \cdot \Delta SOC_{i,t}^{+} \right) \tag{8}$$

$$R_{c,i} = \sum_{t=t_{c,begin}}^{t_{c,end}} \left(R_{c,t} \cdot C_{B,i} \cdot \Delta SOC_{i,t}^{+} \right) \tag{9}$$

$$P_{c,t}' = P_{c,t} + P_{add,t} \tag{10}$$

where the ith EV need to pay $(E_{c,i} + R_{c,i})$ for the charging service provided by the aggregator. $E_{c,i}$ is the charging cost of the ith EV without consideration of policy punishment for charging during peak load hour; $C_{B,i}$ is the rated capacity of battery; $R_{c,i}$ is the total policy punishment of the ith EV when the loading level is above a given value; $t_{c,begin}, t_{c,end}$ are the charging starting and ending time. During the charging period, when the loading of the system is above 80% of the peak loading level, $R_{c,t} \neq 0$; otherwise, $R_{c,t} = 0$. $\Delta SOC_{i,t}^{+}$ is the SOC increment due to charging behavior within one scheduling time slot. Superscript "+" indicates charging. $P_{c,t}'$ is the charging price for per kWh given by the aggregator without considering the penalty during high load period, which is announced before the transaction due to the commercial nature of the aggregator; $P_{c,t}$ is the forecasted real-time electricity price; $P_{add,t}$ is the service fee for per kwh of electricity charged/discharged, which is collected by the aggregator.

c)   EV's economic satisfaction for discharging service

Based on Fig. 1, we define an index, denoted by $G_{d2,i}\%$, to describe the ith EVs' economic satisfaction for discharging service as follows.

$$G_{d2,i}\% = \frac{I_{d,i} + R_{d,i}}{I_{d,i} + R_{dmax}} \tag{11}$$

$$R_{d,i} = \sum_{t=t_{d,begin}}^{t_{d,end}} \left(R_{d,t} \cdot C_{B,i} \cdot (-\Delta SOC_{i,t}^-) \right) \tag{12}$$

where $R_{d,t}$ is the policy award for V2G at time t. R_{dmax} is the maximum policy award an EV could obtain, which is when it discharges at the same discharging rate during the whole policy award period. $t_{d,begin}$ and $t_{d,end}$ represent the starting and ending time of V2G service. $\Delta SOC_{i,t}^-$ is the SOC increment due to the discharging behavior within one scheduling time slot. $\Delta SOC_{i,t}$ is calculate by deducting SOC_i at the end of the tth time slot from SOC_i at the beginning of the tth time slot. Superscript (-) means discharging, because $\Delta SOC_{i,t}^- \leq 0$.

$I_{d,i}$ in (13) is the ith EV's V2G revenue paid by the aggregator. The revenue of EV's participating in V2G is closely related to the amount of energy discharged and the discharging time span. The discharging time span with policy incentives usually coincides with peak load hours. For example, the policy incentives will be higher when the load level is higher. If the discharging time span is determined, the income of EV's participation in V2G is only determined by the amount of energy discharged. $I_{d,i}$ is defined as follow:

$$I_{d,i} = \sum_{t=t_{d,begin}}^{t_{d,end}} \left((\theta + P_{add,t}) \cdot C_{B,i} \cdot (-\Delta SOC_{i,t}^-) \right) \tag{13}$$
$$\theta > 0$$

where θ is the purchasing price of per kWh given by the distribution network. It is decided by the policies of state and local government. Since right now in most of local distribution networks in China, no policy has been made on the purchase prices of V2G electricity, we set it to be a constant, similarly to the case of distributed photovoltaics.

Then the purchasing price given by aggregator without considering the policy award is given by the following:

$$P_{d,t}^{'} = \theta + P_{add,t} \tag{14}$$

d)   EV uses' satisfaction as a weighted summation of SOC satisfaction and economic satisfaction

The satisfaction of the ith EV for charging service and discharging service are denoted by $G_{c,i}\%$ and $G_{d,i}\%$ respectively, and are expressed by:

$$G_{c,i}\% = w_{1,i}G_{1,i}\% + w_{2,i}G_{c2,i}\% \tag{15}$$
$$G_{d,i}\% = w_{1,i}G_{1,i}\% + w_{2,i}G_{d2,i}\% \tag{16}$$

where $w_{1,i}, w_{2,i}$ are weights of the ith EV for SOC and economic satisfaction respectively, with $w_{1,i} + w_{2,i} = 1$. They are determined by user's preference. For example, $w_{1,i} < w_{2,i}$ could be set when the EV user care more about the cost paid or revenue gained at the aggregator; while $w_{1,i} > w_{2,i}$ is set when the EV user care more if their target SOC are reached when leaving the aggregator. When the ith EV users' show no preference for any of the factors, $w_{1,i} = w_{2,i}$ could be set. In this study, due to the limitation of length, we do not provide further discussion on the choice of weighting coefficients and set $w_{1,i} = w_{2,i} = 0.5$.

The mean value of all users' satisfaction, $G\%$, is adopted in this paper to describe the satisfaction of the whole user group in a given period of time.

$$G\% = \frac{1}{n}\sum_{i=1}^{n} G_{c,i}\% + \frac{1}{m}\sum_{i=1}^{m} G_{d,i}\% \tag{17}$$

where n is the number of EVs for charging service; m is the number of EVs for discharging service during the evaluation period.

C.   The Aggregator's profit

In this study, we assume that the prices that the aggregator buys and sells electricity to the distribution network are the same as those that the aggregator buys and sells electricity to EV users. Therefore, the profit of the aggregator includes service fee for charging and V2G services and equivalent income from V2V and DR.

According to [31], EV could be charged from some other EVs if the collected capacity from the intra-grid within the aggregator allows. We denote this technology as V2V. Even though no detail or further study is found in [31], we can still see some advantages of this concept. For example, if the aggregator is equipped with V2V technology, it can serve more EVs when there are not enough charging/discharging poles directly connected to distribution grid. Therefore, EVs satisfaction can be improved and aggregator can attract more customers.

Aggregator's profit for the latest 24 hours is given by (18)-(22).

$$F = \sum_{t=-T}^{0} \left[\sum_{i=1}^{m} F_{c,t,i} + \sum_{i=1}^{n} F_{d,t,i} + F_{V2V,t} \right] + F_{DR} \tag{18}$$

$$F_{V2V,t} = P_{m,t}(P_{c,t}^{'} - P_{d,t}^{'}) \cdot \Delta t \tag{19}$$

$$F_{DR} = \mu M_{day}\% \tag{20}$$

$$F_{c,t,i} = P_{add,t} \cdot C_{B,i} \cdot \Delta SOC_{i,t}^{+} \tag{21}$$

$$F_{d,t,i} = P_{add,t} \cdot C_{B,i} \cdot \left(- \Delta SOC_{i,t}^{-} \right)^{\delta} \tag{22}$$

where subscript "0" means the current times slot, "-T" means the previous T slot. Current time slot is the slot whose scheduling scheme is about to be decided. $F_{c,t,i}, F_{d,t,i}$ are service fees for charging and V2G service collected from the ith EV at time slot t; $F_{V2V,t}$ is the equivalent savings from purchasing electricity through V2V at time slot t; $P_{c,t}'$ and $P_{d,t}'$ are the charging price and V2G price for aggregators at time slot t given by (10) and (14) respectively; $P_{m,t}$ is the whole V2V power available at time slot t; F_{DR} is the revenue came from DR; μ is defined to reflect the economic benefit of aggregator's performance; m, n represent the numbers of EVs which order charging and V2G services respectively.

III. OPTIMAL SCHEDULING STRATEGY

A. The optimal scheduling model of aggregator

The optimal scheduling is real-time scheduling and is called at the beginning of each time slot to decide the scheduling scheme for the following several minutes. In this paper, the time slot is 15 minutes.

The optimal scheduling model for the coming time slot is given by (23)-(29) as follows.

$$Max \left\{ \sum_{i=1}^{m} F_{c,t,i} B_{c,t,i} + \sum_{i=1}^{n} F_{d,t,i} B_{d,t,i} + F_{V2V,t} \mp \mu P_{DR,t} \right\} \tag{23}$$

The constraints include:

$$P_{DR,t}^{min} \leq P_{DR,t} \leq P_{DR,t}^{max} \tag{24}$$

$$P_{DR,t} - P_{DR,t-1} \leq r_i \Delta t \tag{25}$$

$$G\% \geq G_{min}\% \tag{26}$$

$$M_{day}\% \geq M \tag{27}$$

$$n + m \leq N \tag{28}$$

$$B_{c,t,i} + B_{d,t,i} \leq 1 \tag{29}$$

where $P_{DR,t}$ and $P_{DR,t-1}$ are the load of the aggregator at adjacent time slot t and t-1. Eq. (24) is the constraints of the equivalent load of the aggregator $P_{DR,t}$ at t. $P_{DR,t}^{min}$ and $P_{DR,t}^{max}$ are set by the distribution system operator (DSO) according to the optimized operation of the whole network, and refer to the minimum and maximum power consumption by the aggregator at time slot t. Eq. (25) is the constraint of the ramping rate of aggregator's equivalent load, where r_i is the maximum changing rate of $P_{DR,t}$. The purpose of the constraint is to prevent a sudden increase of charging load at time slot t from causing the operation risk of the distribution network. It is also set by DSO. $G_{min}\%$ in (26) is the minimum users' satisfaction requirement of the whole EV group for services provided by the aggregator. M in (27) is the minimum DR capacity requirement for the aggregator during 24 hours. $M_{day}\%$ could be positive or negative and is calculated by Eq. (1). Positive DR capacity is preferred. Eq. (28) is the constraint of the no. of EVs which are ordering charging (m) and V2G services (n) at the aggregator at current time. N is the summation of the no. of piles and the no. of EVs that being served by V2V. $B_{c,t,i}$ and $B_{d,t,i}$ in Eq. (29) are binary optimization variables. $B_{c,t,i} = 0$, $B_{d,t,i} = 0$ means that EV does not participate in either charging or discharging service; $B_{c,t,i} = 1$ means that EV participates in charging service; and $B_{d,t,i} = 1$ means that EV participates in discharging service. Eq. (29) means that the same EV cannot participate in both charging and discharging services at the same time.

The objective function given in (23) is to maximize the aggregator's profit in current time slot. $\mu\left(L_t - \left(L_t + P_{DR,t}\right)\right) = \mu P_{DR,t}$ in (23) is the difference between base load and load with EV participating in DR programs. We can see from Fig.2 that the larger the difference, the flatter the load curve will be, and the higher F_{DR} in 24-hour period of time will be. Calculating $\mu P_{DR,t}$ instead of F_{DR} defined in (20) has two benefits: Firstly, we can estimate the DR effect in a single time slot, because F_{DR} defined in (20) needs data of 24-hour period of time. Secondly, we make the objective function linear. During the daily time, " − " is taken for " $\mp$ ", otherwise, " + "is taken for " $\mp$ ".

$M_{day}\%$ in (27) is calculated by aggregator's data in the latest 24 hours, including the time slot being optimized. Constraint (26) calculates the satisfaction of EV users which had been served in latest 24 hours, including the time slot being optimized. Constraint (27) can be linearized by method given in the Appendix.

B. Application of V2V in aggregator's optimal scheduling

When V2V is available at the aggregator, the charging energy required by a single EV could come from other EVs who are discharging. During the peak load hour, the penalty due to charging could be lowered by the application of V2V. Theoretically, the number of piles required in the aggregator can be decreased. EVs satisfaction can be improved because more EV customers can be served when no extra charging/V2G poles are available.

We set that all EVs for V2G participate in V2V when the total energy of charging at the tth scheduling moment is greater than that of V2G ($\Sigma\left(C_{B,i} \cdot \Delta SOC_{i,t}^{+}\right) > \Sigma\left(C_{B,i} \cdot \left(- \Delta SOC_{i,t}^{-}\right)\right)$); while all EVs for charging service participate in the V2V when

$\Sigma\left(C_{B,i} \cdot \Delta SOC_{i,t}^{+}\right) < \Sigma\left(C_{B,i} \cdot \left(-\Delta SOC_{i,t}^{-}\right)\right)$. The rest of EVs will exchange electricity with distribution network. In this way, the aggregator could have as many as possible free charging/V2G poles to cope with the situation when a large amount of EVs arrive within the same time slot in the near future.

We set the charging and V2G prices per kWh through V2V to be the same as the charging and V2G prices through distribution network because the aggregator needs to treat all customers equally.

C. *The priority in charging and V2G services*

Charging/discharging priorities are normally related to the SOC of EV's battery and charging time. For example, ref. [11] defines a weight factor which is inversely proportional to the multiplication of SOC and the remaining charging time. In our study, we decide the charging and discharging priority by 3 factors: initial SOC, initial SOH and charging or discharging rate. The first two are given directly by EV users to the aggregator at arriving time, while the last one can be calculated by the target SOC and leaving time given by EVs.

For charging service, the lower the initial SOC is, the higher the charging need is; the lower the charge rate is, the longer the time that EV needs to meet the target SOC, therefore, the longer the charging facility will be occupied by the EV, or the higher the probability that the target SOC cannot be reached when leaving time is up, which will cause the decrease of EV user's satisfaction. Therefore, the priority of EV's accepting charging service is decided based on the following rule: the lower its initial SOC is, and the lower the charging rate is, the higher its priority will be.

Then i^{th} EV's priority of charging is calculated as follows.

$$N_{t,i}^{c} = \frac{1}{SOC_{t,i} \cdot CR_{t,i}} \tag{30}$$

where $SOC_{t,i}$ is SOC of the ith EV at time t;

Similarly, the priority of EV's discharging is decided based on the following rule: the higher its SOH and the initial SOC are, the slower the discharging rate is, the higher the priority of the EV to discharge electricity is. Then the priority of the ith EV for V2G service is given by (31).

$$N_{t,i}^{d} = \frac{SOH_i}{SOC_{t,i} \cdot CR_{t,i}} \tag{31}$$

Because V2G brings extra cycle loss and it may not profitable for the EV when battery's SOH is low, SOH is considered in (31).

The application of priority of charging service and V2G service in solving the optimal scheduling problem is given in the next subsection.

D. *Solving the optimal scheduling problem*

Owing to the fact that the no. of EVs and the no. of charging/V2G piles in the aggregator are finite and countable, the aggregator's possible scheduling schemes are finite at any time. Through the approximation given in the Appendix, the nonlinear constraint (27) can be linearized. Therefore, we use integer programming to solve the proposed model, the 0-1 optimization variables are introduced, and the objective function is solved through the MILP solver intlinprog in MATLAB [32-34].

We define the rest of power needed after V2V to be the difference between total charging power and total V2G power. When it is positive, candidate EVs that accept energy from other EVs are chosen according to the ranking of their priority for charging service $\{N_{t,i}^{c}\}$ as defined in section III-C. When it is negative, candidate EVs that discharge energy to other EVs are chosen according to the ranking priority for V2G service $\{N_{t,i}^{d}\}$ as defined in section III-C. The rest of EVs will be served by charging or V2G piles through transactions between the aggregator and the grid. In this study, no other priorities than those defined in (30) and (31) are considered.

Each EV at the aggregator may be one of the possible status: *charging*, *V2G*, or *idle*. Theoretically, an EV could receive energy from another EV in the aggregator for V2G service (V2V), or a charging pile. When there is no enough piles for EVs in the aggregator even after V2V is considered, or the total power that will be exchanged with distribution network in current time slot do not meet constraints (26) and (27), EVs with lower priority cannot be served by a charging/discharging pile, and the status of the EV in current time slot is *idle*, no matter what service it orders originally.

The solution algorithm is given in Fig. 3. The optimal possible scheme can be found through 2 steps: 1) choosing V2V candidates. 2) Find the optimal scheme by solving the 0-1 knapsack problem. In step 1, EVs served by V2V are decided by the serving priority of each EV and constraints (24)-(29) (shaded module in Fig. 3). The constraints include users' satisfaction $G\%$, which represents the users' benefit, and $M_{day}\%$, which represents the distribution network's benefit. Finally, the aggregator's profit F, $G\%$ and $M_{day}\%$ are calculate and output.

If the no. of charging piles or V2G piles are not enough for ordering, we use MILP solver intlinprog in MATLAB to find the optimal scheduling scheme with the maximum profit. In this step, no charging or V2G priority is considered in order to give EVs with lower priorities chances to be served. If no scheme that meets constraints (26) and (27) are available, the nonlinear constraints will be loose to find the maximum F and minimum violation of constraints of (26) and (27) considering the practicability of the scheduling algorithm. The actual $M_{day}\%$ and $G\%$ will be recorded and considered in aggregators' upgrade decision in the future.
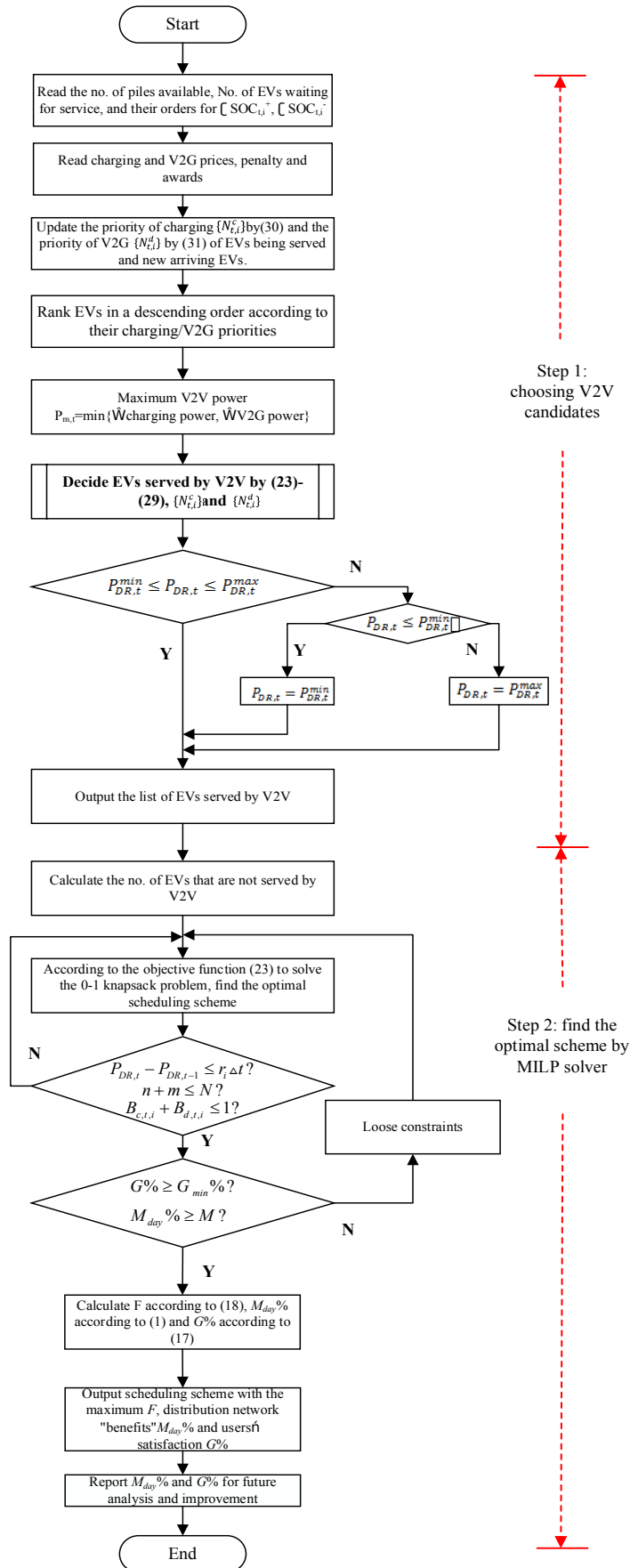
```
                          ┌─────────┐
                          │  Start  │
                          └─────────┘
                               │
┌──────────────────────────────────────────────┐
│ Read the no. of piles available, No. of EVs   │
│ waiting for service, and their orders for      │
│ 〔SOC_{t,i}^{+}, 〔SOC_{t,i}^{-}                │
└──────────────────────────────────────────────┘
                               │
┌──────────────────────────────────────────────┐
│ Read charging and V2G prices, penalty and      │
│ awards                                          │
└──────────────────────────────────────────────┘
                               │
┌──────────────────────────────────────────────┐
│ Update the priority of charging $\{N_{t,i}^{c}\}$ by(30) │
│ and the priority of V2G $\{N_{t,i}^{d}\}$ by (31) of EVs │
│ being served and new arriving EVs.             │
└──────────────────────────────────────────────┘
                               │
┌──────────────────────────────────────────────┐
│ Rank EVs in a descending order according to    │
│ their charging/V2G priorities                  │
└──────────────────────────────────────────────┘
                               │
┌──────────────────────────────────────────────┐
│ Maximum V2V power                              │
│ $P_{m,t}=\min\{\hat{W}$charging power, $\hat{W}$V2G power$\}$ │
└──────────────────────────────────────────────┘
                               │
┌──────────────────────────────────────────────┐
│ **Decide EVs served by V2V by (23)-(29),**      │
│ **$\{N_{t,i}^{c}\}$ and $\{N_{t,i}^{d}\}$**     │
└──────────────────────────────────────────────┘
```

Step 1: choosing V2V candidates

Decision: $P_{DR,t}^{min} \leq P_{DR,t} \leq P_{DR,t}^{max}$ — N / Y

Decision: $P_{DR,t} \leq P_{DR,t}^{min}$ — Y / N

$P_{DR,t} = P_{DR,t}^{min}$

$P_{DR,t} = P_{DR,t}^{max}$

Output the list of EVs served by V2V

Calculate the no. of EVs that are not served by V2V

Step 2: find the optimal scheme by MILP solver

According to the objective function (23) to solve the 0-1 knapsack problem, find the optimal scheduling scheme

Decision (N / Y):
$P_{DR,t} - P_{DR,t-1} \leq r_i \Delta t$?
$n + m \leq N$?
$B_{c,t,i} + B_{d,t,i} \leq 1$?

Decision (Y / N):
$G\% \geq G_{min}\%$?
$M_{day}\% \geq M$?

Loose constraints

Calculate F according to (18), $M_{day}\%$ according to (1) and $G\%$ according to (17)

Output scheduling scheme with the maximum F, distribution network "benefits" $M_{day}\%$ and users' satisfaction $G\%$

Report $M_{day}\%$ and $G\%$ for future analysis and improvement

```
  ┌─────────┐
  │   End   │
  └─────────┘
```

Fig. 3. Flowchart.

IV. SIMULATION RESULTS

A. EVs' parameters and statistics of EVs' driving behavior

We assume that there are 300 EVs and 2 aggregators in the study area.

300 EVs are randomly chosen from 9 different manufactures and their parameters for the simulation are given in Table I. Two aggregators, Aggregator 1 in commercial area and Aggregator 2 in residential area, are chosen in order to study EVs' scheduling at different time period. The location of the two aggregators and the rate of the charging and discharging piles are shown in Table II. Among them, the charging and discharging rate is controlled by the aggregator. When EV is connected to the charging and discharging pile, the aggregator can optimize the charging and discharging rate according to the current load of the grid and the EV users' ordering information.

The model and scheduling strategy proposed in our study can be applied in all kinds of commuting situations. However, in order to highlight the performance correlation between the two aggregators, we especially perform the simulation and analysis with a travel behavior as given in Fig. 4 [35,36].

According to the law of large numbers, when the amount of EVs arriving at the aggregator for charging and discharging service is large enough, their arriving time follows the normal distribution, as shown in Fig. 6.

Statistics of the decommissioning time of EV batteries for different types of EVs are given in Table III. We simulate the driving behaviors and V2G behaviors of 300 EVs of each day for a period of 5 years. Aggregators' optimal scheduling schemes are calculated every 15 minutes.

The IEEE-13 distribution system is taken as the test system to study the interaction between aggregators and the distribution system. Aggregators purchase electricity from the grid at real time price.

According to the average residential electricity price in China, we define that the mean value of the price is 0.5 Yuan/kWh, and the service fee collected by aggregators is assumed to be 0.2 times the 24-hour forecasted price. Policy award or penalty accrues when the load level is higher than 0.8, and it is 0.4 Yuan/kWh. We assume that the forecasted price is accurate.

TABLE I
THE INFORMATION OF 9 TYPES OF EVS

Name	Type	Capacity (Ah)	Energy (kWh)
Mitsubishi i-MiEV	BEV	50	16
BMW i3 eDrive Range Extender	BEV	94	33
Chevrolet Spark EV	BEV	60	20
2014 Nissan Leaf	BEV	66	30
Tesla Model-S	BEV	320	60
Toyota Prius Plug-In	HEV	21.5	4.4
Ford C-Max Energi SEL 2.0ATK	HEV	22.6	7.6
Chevrolet Malibu Eco 2.4L	PHEV	44	22
Ford Fusion Hybrid 2.0	PHEV	46	23

TABLE II
THE INFORMATION OF 2 AGGREGATORS

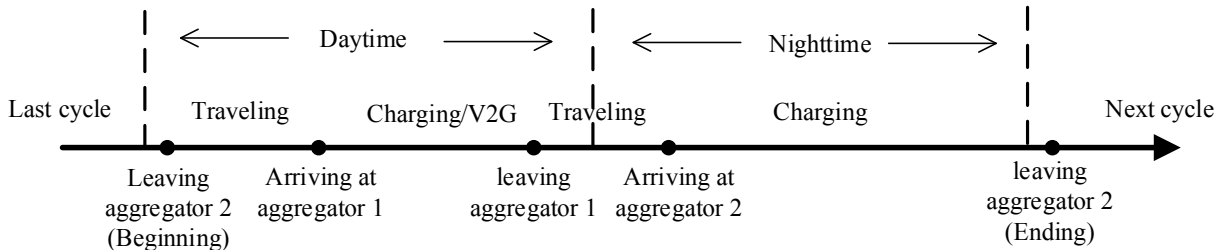| Name	Location	Charging rate	Discharging rate
Aggregator 1	Commercial	0.1C,0.12C,0.15C,0.2C, 0.25C,0.3C,0.35C,0.4C	0.02C,0.05C,0.08C,0.1C, 0.12C,0.15C,0.18C,0.2C
Aggregator 2	Residential	0.1C,0.12C,0.15C,0.2C, 0.25C,0.3C,0.35C,0.4C	0.02C,0.05C,0.08C,0.1C, 0.12C,0.15C,0.18C,0.2C

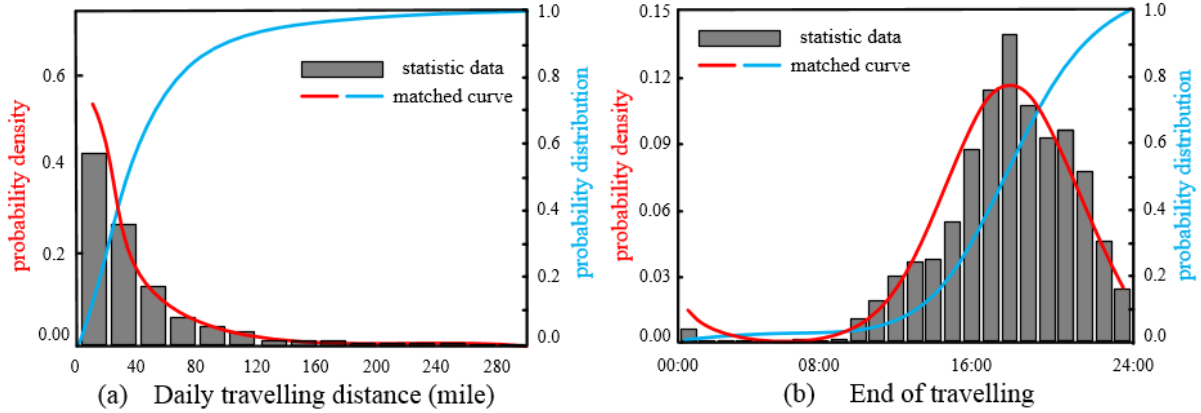Fig. 4. The behavior of EVs in temporal dimension

Fig. 5. The distribution of driving distance (a) and end of travelling time (b)
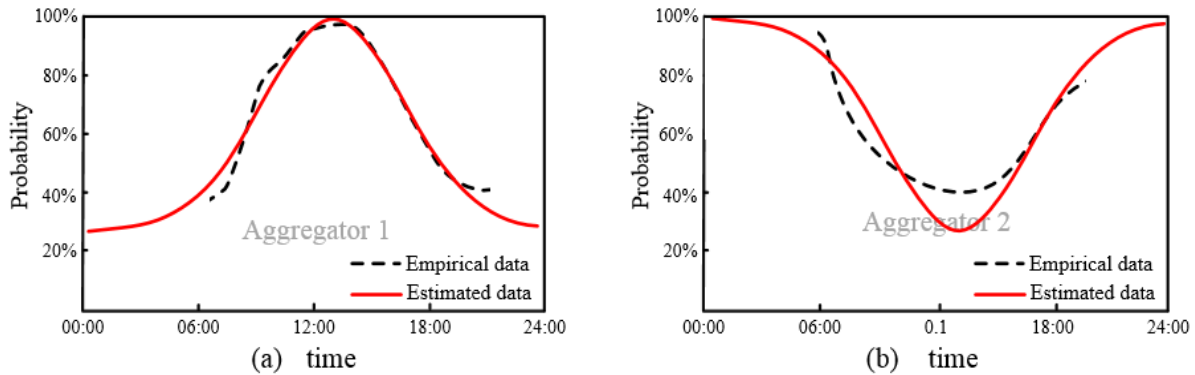

Fig. 6. The parking rate vs. time for 2 aggregators. Dashed lines are from the empirical data [35], and the red lines follow normal distribution.

TABLE III
STATISTICS OF DECOMMISSIONING TIME OF EV BATTERIES

year	1	2	3	4	5	≥ 6
Retired rate for total EV	26%	22%	9%	11%	15%	17%
Retired rate for BEV	17.95%	15.38%	10.26%	7.69%	10.26%	38.46%
Retired rate for HEV	63.16%	36.84%	0%	0%	0%	0%
Retired rate for PHEV	16.67%	21.43%	11.9%	19.05%	19.05%	11.9%

The IEEE-13 distribution system is taken as the test system to study the interaction between aggregators and the distribution system. Aggregators purchase electricity from the grid at real time price.

According to the average residential electricity price in China, we define that the mean value of the price is 0.5 Yuan/kWh, and the service fee collected by aggregators is assumed to be 0.2 times the 24-hour forecasted price. Policy award or penalty accrues when the load level is higher than 0.8, and it is 0.4 Yuan/kWh. We assume that the forecasted price is accurate.

B. Optimization efficiency

According to subsection III-D and Fig.5, the computation burden in solving the optimal scheduling problem lies in the chosen of V2V candidates and the calculation of the benefit of every possible scheduling scheme to serve n EVs by m charging/discharging piles. We take the latter as an example to explain the computation burden. When $n > m$, the no. of possible scheduling schemes is $n!/[m!(n-m)!]$ without considering the constraints given in (24)-(28). In order to minimize the users' discontent, we assume that EV users will not be unplugged until their transactions with the aggregator are closed. Therefore, the computation burden of optimization can be substantially decreased because possible scheduling schemes of the tth time slot is based on the scheduling scheme of the $(t-1)^{th}$ time slot. For the tth moment, we only need to consider the difference caused by new joining EVs and just leaving EVs within the 15-minute interval. The computation burden of the first 15-minute slot is different from that of the subsequent 15-minute intervals. However, by carefully choosing the starting time of the optimal scheduling program of the aggregator, the computation burden of the first 15-minute can also be decreased substantially. According to the driving patterns, for aggregator 1 located in commercial area, we choose the stating time to be 0:00 when almost no EVs is in Aggregator 1, while for Aggregator 2 located in residential area, we choose the starting time to be 9:15 when most of EVs already leave home.

C. Analysis of simulation results

The rules in designing the optimal scheduling model of the aggregator are explained in detail in previous sections. In this section, we will discuss the effect of changing conditions (the Aggregator's facility level and V2V technology) on the "benefits" of three parties under the proposed optimal scheduling model. In this section, we give the benefits of three parties under 14 different scenarios, also analysis and implication are given based on the results as follows:

- Effect of EV users' driving behavior and profit-pursuing nature on service type in 2 aggregators. Through simulation, we show that, services ordered at aggregators are mainly decided its location.

- Effect of Aggregator's facility level on users' satisfaction and DR capability. The objective of an Aggregator's optimal scheduling is to maximize its benefit under the premise of meeting the requirement of thresholds of EV users' benefit and distribution network's benefit. An aggregator benefits from the service fee, charging/discharging price differences with EV users and distribution system, and the revenue from participating DR. These 3 items are related to EV users' satisfaction and distribution system's benefit. In the simulation, the effect of changing of aggregator's facility and technological level, which is decided by the Aggregator's investment, on the benefits of EV users and distribution system is analyzed.

- Profit of aggregator group. EV users' charging load and V2G energy show temporal and locational correlation, which further affect the performances of aggregators at different areas. Simulation suggests that investment in aggregator group as a preferable mode.

a) Effect of EV users' driving behavior and profit-pursuing nature on service type in 2 aggregators

According to the statistics from the simulation result, without V2V technology, Aggregator 1 and 2 need at least 154 and 189 piles respectively in order to fully satisfy all EV users' needs. Therefore, we compare the benefit or satisfaction of each party in 14 scenarios:

Scenario 1-7: Both Aggregator 1 and 2 have 100, 130, 140, 150, 160, 180 and 190 piles respectively. V2V technology is adopted in both aggregators; Scenario 8-14: Both Aggregator 1 and 2 have 100, 130, 140, 150, 160, 180 and 190 piles respectively. V2V technology is not adopted in both aggregators.

Simulation results show that 15.3% of EVs orders charging services and 57% orders V2G services at Aggregator 1. The remaining 27.7% of EVs were not scheduled at the aggregator due to lack of economic motivation and high remaining SOC. In other words, their charging cost cannot be recovered from the V2G process due to higher charging price in their previous charging order. For Aggregator 2, 99% percent of EVs orders charging services, while 1% of EVs doesn't join the aggregator due to an idle time of over 24h. This result is due to users' driving habits and low electricity price at night.
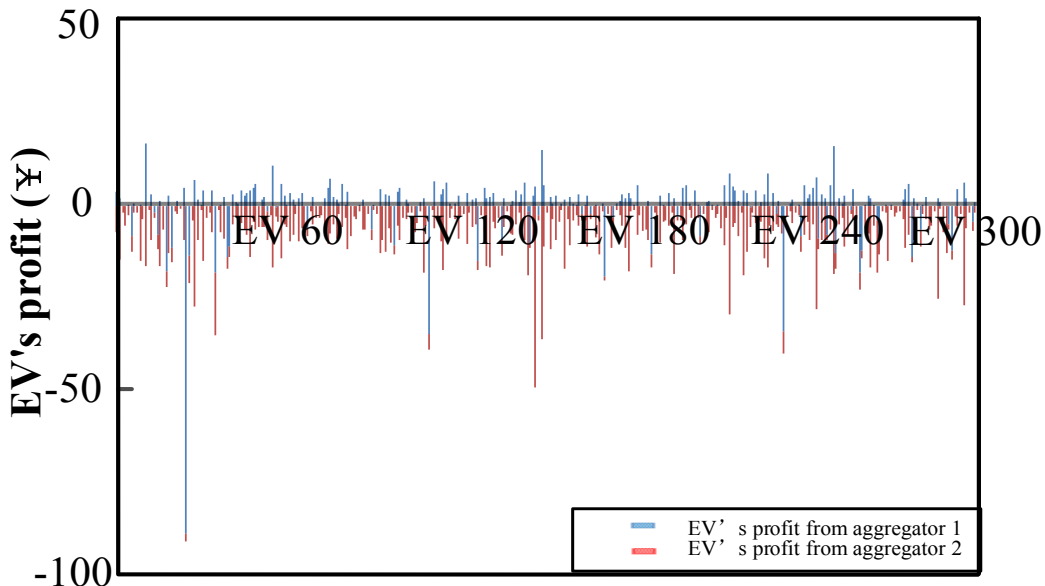

Fig. 7. EVs' profit in Aggregator 1 and Aggregator 2 in one random day.

Fig. 7 gives profits of 300 EVs in Aggregator 1 and 2 in one random simulation day. For some EVs, their profit is negative because of the purchase of charging service in Aggregator 1 during the time period of high tariff.

b) Effect of Aggregator's facility level on users' satisfaction and DR capability
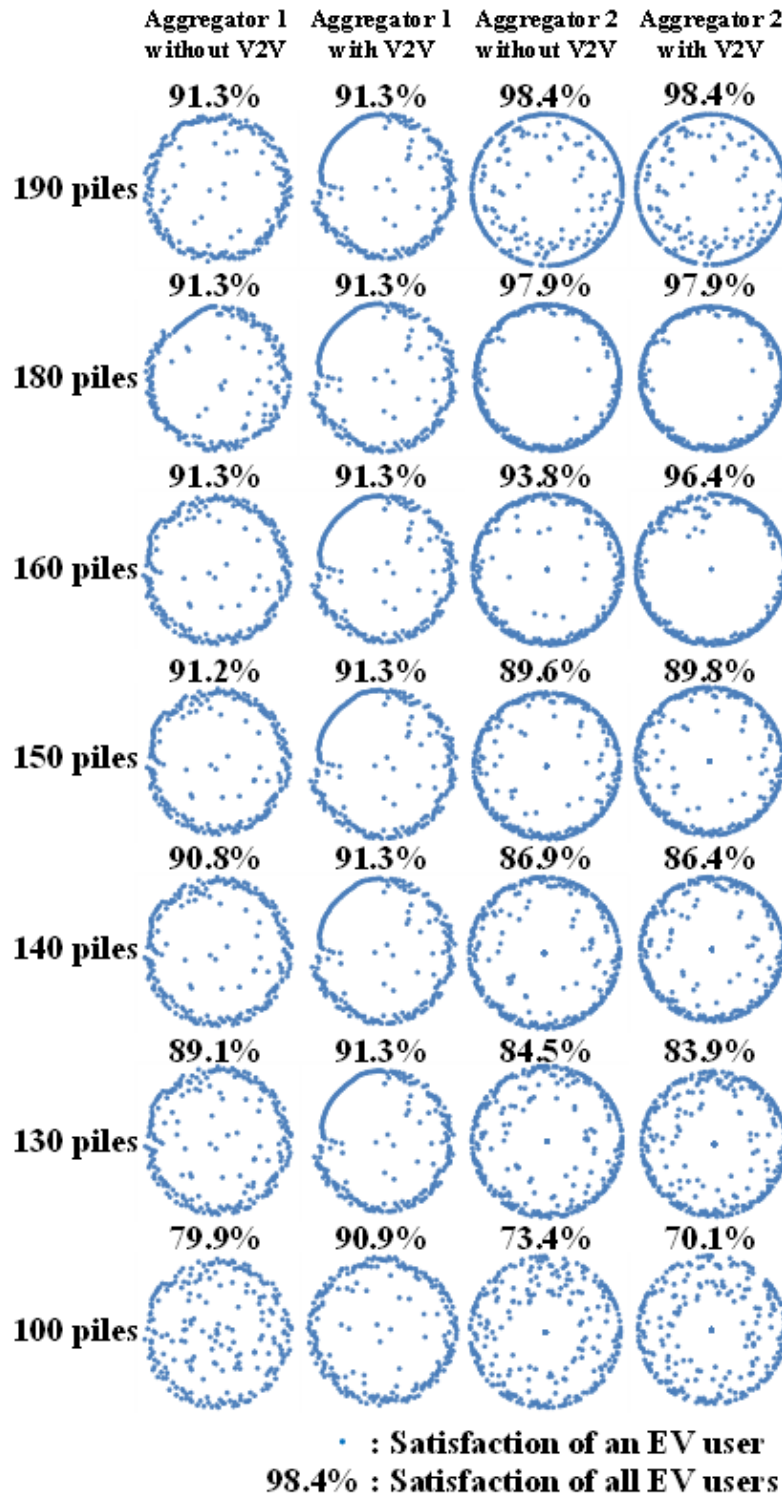
i) Analysis on users' satisfaction

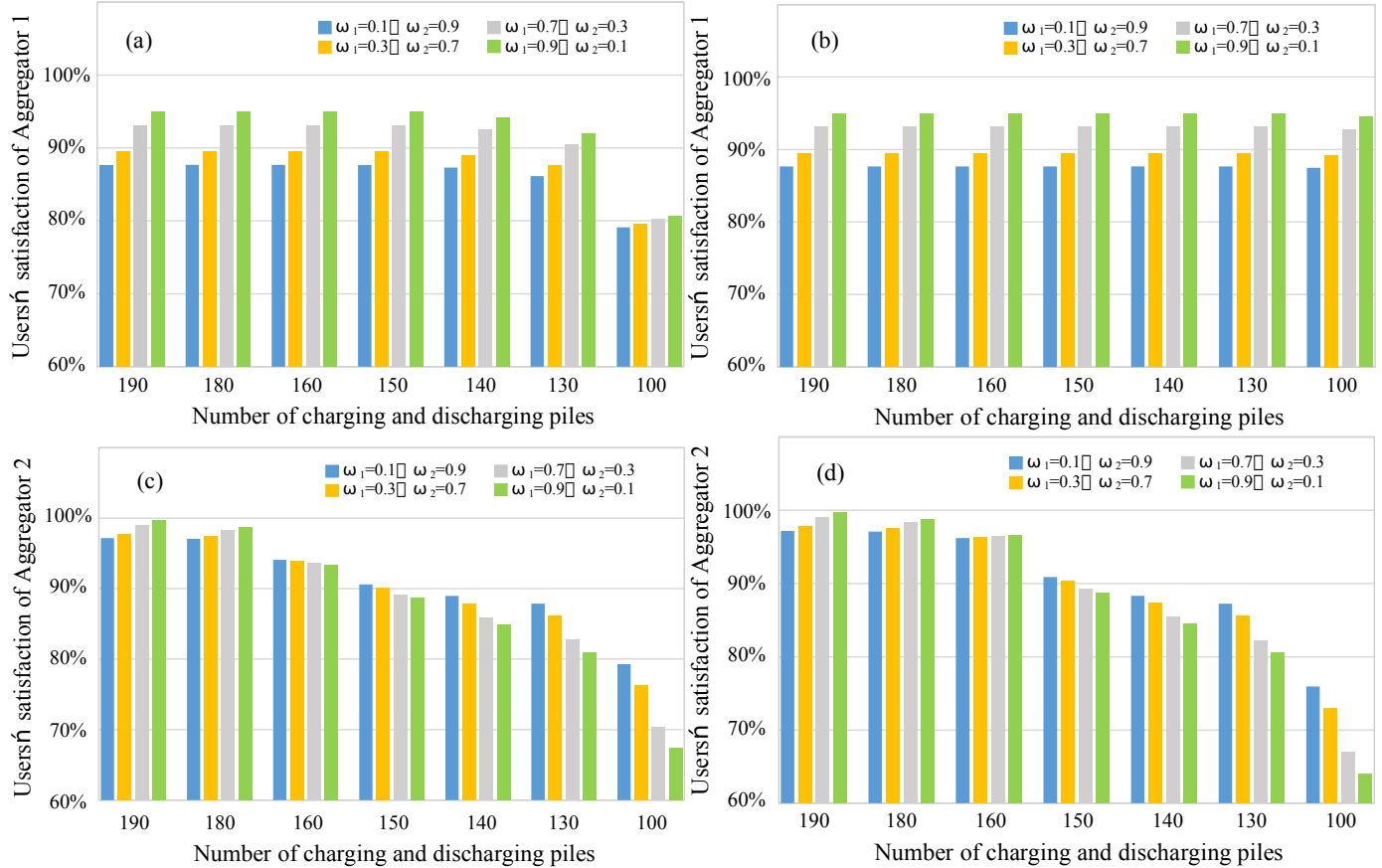|	Aggregator 1 without V2V	Aggregator 1 with V2V	Aggregator 2 without V2V	Aggregator 2 with V2V
190 piles	91.3%	91.3%	98.4%	98.4%
180 piles	91.3%	91.3%	97.9%	97.9%
160 piles	91.3%	91.3%	93.8%	96.4%
150 piles	91.2%	91.3%	89.6%	89.8%
140 piles	90.8%	91.3%	86.9%	86.4%
130 piles	89.1%	91.3%	84.5%	83.9%
100 piles	79.9%	90.9%	73.4%	70.1%

· : Satisfaction of an EV user

98.4% : Satisfaction of all EV users

Fig. 8. Satisfaction of the whole EV user group with Aggregator 1 and Aggregator 2 in each scenario

The users' satisfaction under 14 scenarios are given in Fig. 8. The distance of each dot to the center represents the satisfaction of each EV. The overall satisfaction $G\%$ is given in number on top of each subplot. A smoother circle indicates a higher overall satisfaction of all users. In Fig. 8, for cases with ≥160 piles, whether adopting V2V technology only affects the satisfaction of Aggregator 2. This is because with ≥160 piles, even without V2V technology, Aggregator 1 already possesses enough piles to meet the needs of EVs.

We can also find in Fig. 8 that the users' satisfaction for Aggregator 1 is affected by both the number of piles and the adoption of V2V technology; however, that for Aggregator 2 cannot be effectively increased by the adoption of V2V technology because 99% of EVs orders charging service in Aggregator 2. Therefore, the V2V technology cannot be utilized effectively at Aggregator 2.

Since EVs order services in both aggregators according to their SOC and economic motivations, operations of Aggregator 1 and Aggregator 2 are interacted. For example, V2V technology improves the number of EVs scheduled in Aggregator 1. Since EVs in Aggregator 1 are mainly discharging load, the initial SOC of an EV when it arrives at Aggregator 2 will be decreased, which increases the difficulty in Aggregator 2's scheduling. Therefore, the adoption of V2V technology in both aggregators reduces users' satisfaction for Aggregator 2, as users' satisfaction of 100-140 piles cases given in Fig. 8.

We also change $w_{1,i}$ and $w_{2,i}$ to analyze the users' satisfaction of Aggregator 1 and Aggregator 2.

Fig. 9. Satisfaction of the whole EV user group with Aggregator 1 and Aggregator 2 in each scenario under different coefficients. (a) users' satisfaction of Aggregator 1 (Aggregator 1 without V2V), (b) users' satisfaction of Aggregator 1 (Aggregator 1 with V2V), (c) users' satisfaction of Aggregator 2 (Aggregator 1 without V2V) and (d) users' satisfaction of Aggregator 2 (Aggregator 1 with V2V)

Fig.9 shows how the effect of different weight combination in (15) and (16) on users' satisfaction. Through fig.9, the following conclusions could be drawn:

- Aggregator 1 has enough piles (≥ 150 piles in this case): users' SOC requirement will always be met, therefore, increasing piles doesn't increase users' satisfaction, and the higher w_1 is, the higher users' satisfaction. With or without V2V doesn't make change.

- Aggregator 1 doesn't have enough piles (<150 piles in this case): Aggregator 1 without V2V can no longer meet the users' charging and discharging need, so the users' satisfaction drops. Fig.9(a) shows that, in 100-pile case, different weight combinations have similar users' satisfaction. With V2V, cases with fewer piles (<150) give similar users' satisfaction as those with more piles (≥ 150).

- Aggregator 2 has enough piles (≥ 180 piles in this case): Since in Aggregator 2, 99% of EV order charging service, therefore V2V has no effect in improving users' satisfaction. The higher w_1 is, the higher users' satisfaction. During night hour, no incentive-based DR program is available, therefore, the economic satisfactions of EV users under different weight combinations are the same. Therefore, the difference of users' satisfaction with the changing of w_1 is fewer comparing to Fig.9(a).

- Aggregator 2 doesn't have enough piles (<180 piles in this case): If an EV discharges more in Aggregator 1, it needs to charge more in Aggregator 2 at night. Therefore, when there are no enough piles in Aggregator 2, with the increase of w_1, the users' satisfaction drops. That is why in Fig.9(c) and (d), different pattern from that in Fig.9(a) and (b) show with the increase of w_1.

ii) The performance of aggregators' participation in DR

The evaluation of the DR capability of Aggregator 1 and 2 by $M_{day}\%$ is given in Table IV. Fig. 10 and Fig. 11 give the DR curves of Aggregator 1 and 2 under different scenarios. Fig. 11 shows the total economic benefit of aggregator 1 and 2.

Benefits of aggregators from the same kind of services, for example, charging service at both aggregators, are negatively correlated, while benefits of aggregators from different services are positively correlated. Under market environment and real time pricing scheme, the charging price at night is lower due to lower load demand. When an EV arrives at Aggregator 2, its initial SOC is smaller than any other time during the day. Therefore, the majority of EVs in Aggregator 2 order charging service. EVs' participation in V2G at Aggregator 1 results in more charging load at Aggregator 2. The benefit of Aggregator 2 from charging service will increase. On the contrary, if an EV charges less in Aggregator 2, the charging load in Aggregator 1 will increase and the discharging load will decrease due to the facility limit in the aggregator. As a result, $M_{day}\%$ will be lower, and Aggregator 1's income from peak load shifting will decrease. Therefore, Aggregator 1 and 2 should operate cooperatively to seek the maximization of the overall benefit of two aggregators.

TABLE IV
$M_{day}\%$ UNDER DIFFERENT SCENARIOS

Number of piles	190	180	160	150	140	130	100
No V2V	45.33%	45.52%	46.06%	46.41%	46.65%	46.04%	39.54%
V2V	45.33%	45.52%	46.09%	46.36%	46.64%	46.79%	46.09%

The charging/discharging facilities decide is one of factors that decide aggregators' DR capability. According to Fig. 10, DR capacity of aggregator 1 and 2 (aggregator group), no matter without V2V or with V2V, decreases as the number of piles decreases.

When Aggregator 1 has enough piles (Fig. 11(a)), V2V has no effect on both aggregators' DR capability. When there is no enough pile for aggregator 1 and 2 (Fig. 11(b)), V2V's effect during daytime increases as the number of piles decreases, as shown by the shaded areas. DR during nighttime, as the complement to the DR in daytime, only varies little (areas in green) along the changes of the facilities, because almost only V2G services are ordered at Aggregator 1 in residential area, and V2V cannot be performed effectively.

Aggregators' DR capability is also affected by the no. of EV's it attracts to come for services. In our study, we assume that aggregators secure their customers by improving EV's satisfaction for services in aggregators.

Fig. 12 gives the comparison of aggregators' DR capability with and without DR program. Without DR program, no award/penalty for V2G/charging is performed when loading level of the system is above 0.8. Real time tariff is taken for both cases.

Since the main responsibility of EV is as a travelling tool and participating in DR is only for making extra money. Therefore, in our study, EVs driving behavior and parking behavior won't be changed and follow the distributions given by Fig. 4-9 for cases with or without DR program. Without DR award, EVs earn less through V2G, and EVs' satisfaction to V2G service in Aggregator 1 decreases. When other aggregators in the same area could provide better V2G prices or awards, aggregator 1 will lose its customers to its competitors, and its DR capability will be damaged. In Fig. 12, DR capability of 3 scenarios are given. We assume that EV users with a satisfaction lower than a given threshold will go to other aggregators. 2 different thresholds, 70% and 80%, are chosen. When there is no DR, and with consideration of loss of EV customers, the drop of Aggregator 1's DR capability increase as the increase of EV users' satisfaction threshold. When no loss of customer is considered, Aggregator 1's DR capability is as the same as that of simulation with DR program.

c) Profit of aggregator group

The profit of 2 aggregators, the income of DR ($\mu M_{day}\%$) for Aggregator 1 and Aggregator 2 without and with V2V are given in Fig. 13, Table V and Table VI, respectively.

In Fig. 13, the profit of Aggregator 1 (green line) is greater than that of Aggregator 2 (purple line), while the DR income of Aggregator 1 (dark blue bar) is less than that of Aggregator 2 (light blue bar). The total profit of the aggregator group increases with V2V when for 100-140 piles cases when no enough piles in aggregator 1 and 2, due to the increase of DR capability of both aggregators by adopting V2V.
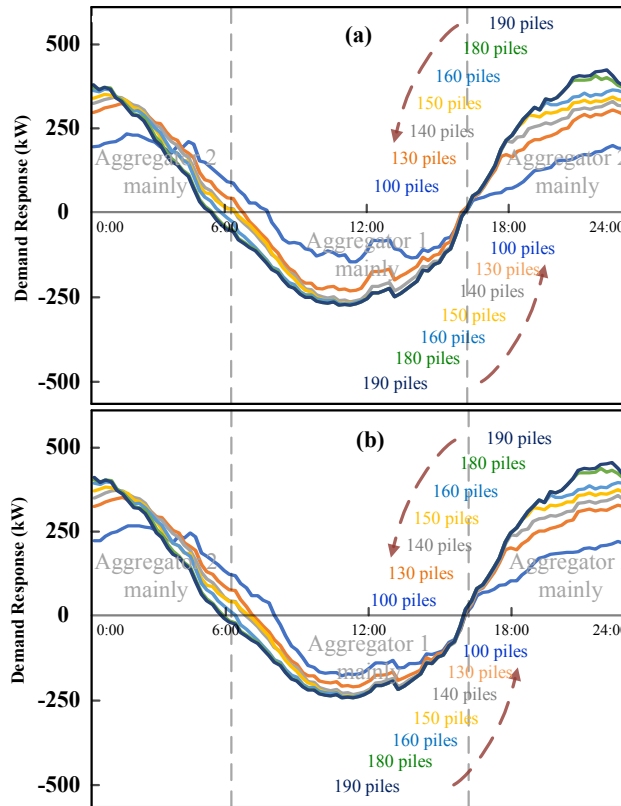
Fig. 10. DR by 2 aggregators. (a) without V2V, and (b) with V2V
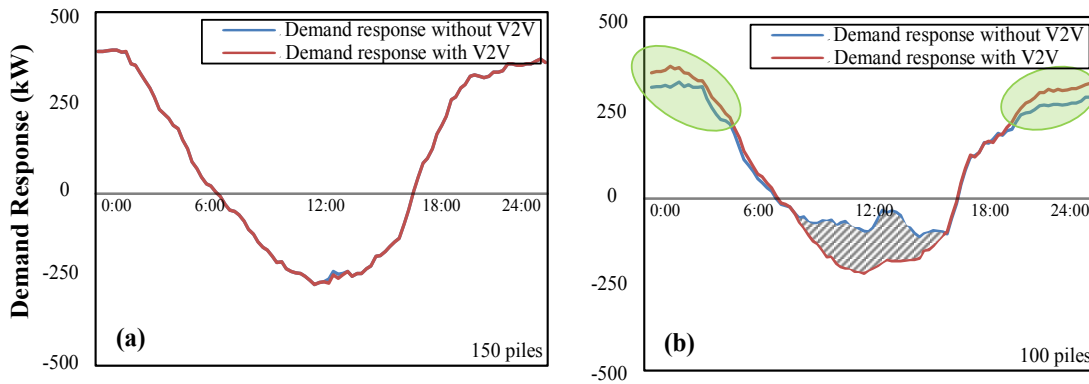

Fig. 11. DR of 2 aggregators under 150-pile and 100-pile scenarios. Shaded area indicates increase in DR capability during daytime by adopting V2V.
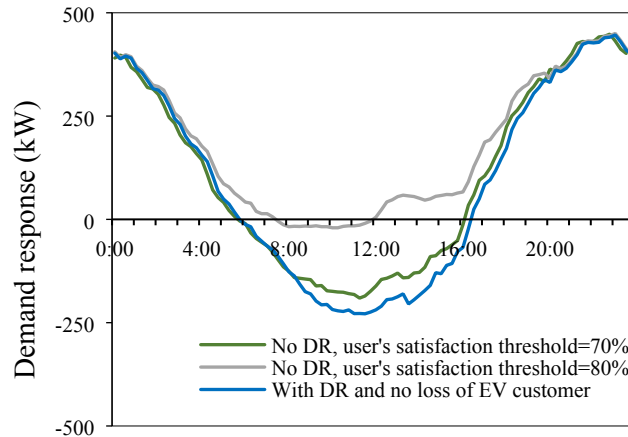

Fig. 12. Comparison of aggregator 1's DR capability of 3 scenarios when aggregator 1 has 190 piles and V2V technology. a) No DR, user's satisfaction threshold is 80%; b) No DR, user's satisfaction threshold is 70%; c) With DR and no loss of customer
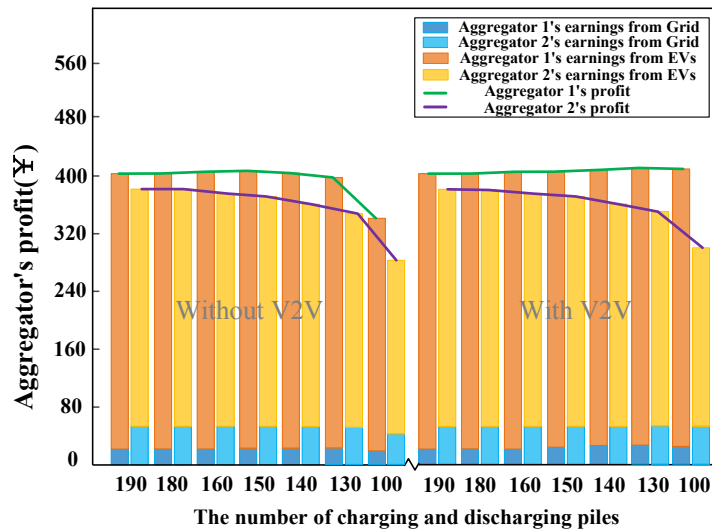
Fig. 13. Profit analysis of Aggregator 1 and Aggregator 2 of 14 scenarios

TABLE V
$\mu M_{day}\%$ OF AGGREGATOR 1 AND AGGREGATOR 2
FROM DR OF 7 SCENARIOS (WITHOUT V2V) (DARK BLUE BAR IN FIG.14)

Number of piles	190	180	160	150	140	130	100
Aggregator 1	28.07	28.36	29.53	30.35	30.77	30.60	23.94
Aggregator 2	62.59	62.67	62.58	62.47	62.53	61.48	55.13

TABLE VI
$\mu M_{day}\%$ OF AGGREGATOR 1 AND AGGREGATOR 2
FROM DR OF 7 SCENARIOS (WITH V2V) (LIGHT BLUE BAR IN FIG.14)

Number of piles	190	180	160	150	140	130	100
Aggregator 1	28.08	28.36	29.56	30.42	31.40	32.30	35.45
Aggregator 2	62.59	62.67	62.61	62.30	61.86	61.26	56.72

V. CONCLUSIONS

In this paper, an optimal scheduling strategy of an EV aggregator considering triple level benefits of EV users, aggregator and distribution grid has been proposed, which is crucial for the sustainable development of aggregators, the integration of large scale EVs and the adoption of DR programs. The operation of two aggregators, Aggregator 1 in a commercial area and Aggregator 2 in a residential area, and 300 EVs of different manufactures are studied under different facility and technology levels.

Several conclusions can be deduced as listed below through a synthetic consideration of the simulation results.

1) For the same group of EV users, due to the mobility and the temporal statistics of EVs driving behaviors, services ordered at aggregators located at different areas (commercial or residential) are different. For example, more V2G service is ordered in Aggregator 1 at the commercial area, while almost only charging service is ordered in Aggregator 2 at the residential area. Moreover, the improvement of service quality and benefit of Aggregator 1, for example satisfying the needs for V2G of more EV users, will increase the difficulty of the scheduling at Aggregator 2.

2) The requirement of the facility level (no. of piles) of aggregators at the commercial area are lower than that in the residential, because more V2G services are ordered during the daytime, which can be performed by V2V technology. Aggregators' capability for demand response, aggregators' benefit, and users' satisfaction increase as the no. of piles increases, but the rate of increase slows down as the no. of piles increases.

3) Conceptually, V2V technology acts as backup batteries equipped at aggregators, but with lower investment requirements compared with purchasing backup batteries. The effectiveness of V2V for the improvement of aggregators' DR capability, users' satisfaction and aggregators' benefit are related to the facility level of and the position of aggregators. With enough piles, V2V is no longer effective for the abovementioned improvement. Especially, for the simulation case in the paper, the improvement of service by V2V in Aggregator 1 brings negative impact on the performance of Aggregator 2.

4) Aggregator's DR capability is also affected by the volume of EVs it can secure. When no DR program is available, EV users' satisfaction for V2G revenue will be lower. However, the aggregator's DR capability will be damaged only when customers with lower satisfaction are attracted and taken away by aggregators with higher prices for V2G.

In final words, this study proposes models of benefits of three parties and an optimal scheduling strategy of aggregators considering benefits of three parties. The outcomes from the simulation could provide useful insights on the effect of aggregators' facility and technology levels on the benefits of each party and different operational modes under various application scenarios.

Given the fact that the benefits of distribution network integrated large amount EVs are evaluated by aggregator's load shifting capability through DR program in this paper, the influences caused by electricity consumption patterns, daily weather classification [37-39], the aggregator's revenue in wholesale market [40-42] and transmission expansion planning [43] are not taken into account yet. In addition, the incentive-based DR program [44-48], another popular way for flexible loads to participate the operation of power grid and multi-carrier energy system that can impact the satisfaction of EV owners in different aspects, will be further studied in the future work.

APPENDIX

A.1 Approximation and Linearization of constraint (27)

The nonlinear constraint $M_{day}\% \geq M$ can be simplified and linearized by the following transformation and approximation:

$$M_{day}\% = \frac{M_e - M_a}{M_e} \geq M \Rightarrow M_a \leq \text{Thres} \tag{A-1}$$

where $M_a = \sqrt{\frac{1}{T}\sum_{t=0}^{T}[\frac{L_t - \overline{L} + P_{DR,t} - \overline{P_{DR}}}{\overline{L} + \overline{P_{DR}}}]^2}$; M_e is calculated by the base load profile, which is known. M is a known constant, given by the distribution system. $\text{Thres} = (1 - M)M_e$.

According to the design given by (1)-(5), M_a can be calculated by the $P_{DR,t}$ of previous 95 time slots ($t = -T \sim -1$) and the current time slot ($t = 0$).

$$M_a^2 = \frac{1}{T}\left\{\left[\sum_{t=-T}^{-1}\left[\frac{L_t - \overline{L} + P_{DR,t} - \overline{P_{DR}}}{\overline{L} + \overline{P_{DR}}}\right]^2\right]\right.$$

$$\left.\left(\frac{L_T - \overline{L} + P_{DR,0} - \overline{P_{DR}}}{\overline{L} + \overline{P_{DR}}}\right)^2\right\} +$$

$$\approx C + f(P_{DR,0})$$

(A-2)

where $C = \frac{1}{T}\left[\sum_{t=-T}^{-1}[\frac{L_t - \overline{L} + P_{DR,t} - \overline{P_{DR}}'}{\overline{L} + \overline{P_{DR}}}]^2\right]$. $\overline{P_{DR}}'$ is the approximation of $\overline{P_{DR}}$ by using $P_{DR,0}$ of the same moment in the previous day and the known $P_{DR,t}$ of previous T time slots (there are $T+1$ time slots in total). Therefore, C is known. $f(P_{DR,0}) = \left(\frac{L_t - \overline{L} + P_{DR,0} - \overline{P_{DR}}}{\overline{L} + \overline{P_{DR}}}\right)^2$.

In the following, we use x to represent $P_{DR,0}$, and a, b, d, and e to represent other known parts in (A-2) to simplify the deduction.

Let $a = \sum_{t=0}^{T-1}P_{DR,t}$, $b = L_t - (\overline{L} + \frac{a}{T+1})$, $d = \frac{1}{T+1}$, and $e = (\overline{L} + \frac{a}{T+1})$, then

$$f(x) = \left(\frac{L_T - \overline{L} + x - \frac{a + x}{T + 1}}{\overline{L} + \frac{a + x}{T + 1}} \right)^2$$

$$= \left(\frac{L_T - \left(\overline{L} + \frac{a}{T + 1} \right) + \left(1 + \frac{1}{T + 1} \right)x}{\left(\overline{L} + \frac{a}{T + 1} \right) + \frac{1}{T + 1}x} \right)^2 \tag{A-3}$$

$$= \left(\frac{b + (1 + dx)}{e + dx} \right)^2$$

Let $K = \sqrt{\text{Thres}^2 - C}$, then

$$M_a \leq \text{Thres} \Rightarrow (M_a)^2 \leq \text{Thres}^2 \Rightarrow \frac{b + (1 + dx)}{e + dx} \leq K \tag{A-4}$$

$$b + (1 + dx) \leq (e + dx)K \tag{A-5}$$

$$d(K - 1)x \geq b - eK \Rightarrow x \geq \frac{b - eK}{d(K - 1)} \tag{A-6}$$

Then the DR power of the aggregator at the current scheduling moment should meet the following constraint:

$$P_{DR,0} \geq \frac{b - eK}{d(K - 1)} \tag{A-7}$$

Therefore, since the loads at the aggregator of the previous T time slots are already known, the non-linear constraint (27) can be simplified to be a linear one given by (A-7).

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