Citation for published version:
Xie, D, Chu, H, Gu, C, Li, F & Zhang, Y 2017, 'A Novel Dispatching Control Strategy for EVs Intelligent Integrated Stations', IEEE Transactions on Smart Grids, vol. 8, no. 2, pp. 802-811. https://doi.org/10.1109/TSG.2015.2463819

DOI:
10.1109/TSG.2015.2463819

Publication date:
2017

Document Version
Peer reviewed version

Link to publication

University of Bath

A Novel Dispatching Control Strategy for EV's Intelligent Integrated Stations

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***Abstract*—In order to provide a cost-effective solution for accommodating the increasing electric vehicles (EVs) and maximizing their benefits to the grid, a novel EV intelligent integrated station (IIS), making full use of ex-service batteries, is proposed in this paper. It first presents the framework and characteristics of IISs by describing its components, including a dispatching center, multi-purpose converter devices, a charge exchange system, and an echelon battery system. The grid status, batteries exchanging requests, and energy capacity of IISs are monitored timely to offer inputs for its optimal operation. The concept of generalized energy is thereby introduced to systematically understand the energy/power flow between IISs and EVs as well as between IISs and power grids. Then, a novel charging and discharging control strategy for managing EVs is presented. Compared to existing approaches, the proposed control strategy can offer peak load shifting when meeting EV battery charging/exchanging requests. The experimental results demonstrate the effectiveness and benefits of the control strategy in terms of providing peak load shifting for the power grid. This integrated station concept can maximize the benefits of EVs and the retired batteries more flexibly and effectively.**

***Index Terms*—Electric vehicle, generalized energy, intelligent integrated station, optimal charging, smart grid**

I. INTRODUCTION

WITH the deterioration of the environment and concerns of energy security and fossil energy reserves, electric vehicles (EVs) have received increasing attention because of their high efficiency and low pollution emissions. China is making a major commitment to the development of plug-in EVs (PEVs) by offering large subsidies for buyers and sellers [1]. It aims at 500,000 cumulative PEV sales by 2015 and 5 million by 2020.

As EVs rely on electricity from the power grid to run, they could bring severe adverse impact on power generation, transmission, and distribution, if their charging and discharging are not properly managed [2], [3]. The impact of EVs on distribution networks can be determined according to the following inputs: driving patterns, charging characteristics, charge timing, and vehicle penetration, etc [4]-[6]. [2] suggests that the introduction of EVs would likely bring substantial changes to the grid, impacting demand peaks, reducing reserve margins, and increasing electricity prices. The distributed features of EV plug-in/off time have more significant effects on aggregated load [7], [8]. The experimental results in [9] suggest that a 10% penetration of EVs would result in an increase in daily peak by 17.9%, while a 20% level of EV penetration would lead to a 35.8% increase in peak load. The simulation results in [10] indicate that when the penetration of plug-in hybrid EVs (PHEVs) is of interest to some degree, new load peaks will be created, which in some cases may exceed the capacity of local distribution transformers.

The impacts of EVs on power grids have been investigated as well to find the best solutions to eliminate them [11], [12]. Considering randomness in individual charging start-time and battery state-of-charge (SOC), [13] presents a method for predicting the net harmonic currents produced by a large number of EV battery chargers. [14] proposes an algorithm for optimally managing a large number of PHEVs charging at a municipal parking station and uses the estimation of distribution algorithms to intelligently allocate electrical energy to the PHEVs. [15] and [16] use centralized control strategies to optimize various objectives in managing EVs, including minimizing power losses and load variance, maximizing the grid load factor, and maximizing supportable EV penetration.

On the contrary, a number of studies have investigated vehicle to grid (V2G) technologies. [17] presents a strategy for grid power peak shaving and valley filling by using V2G systems to store the energy during off-peak hours and injecting it back to the grid during peak hours. Moreover, V2G technology has drawn great interests to smooth the natural intermittency of renewable energy to ensure grid frequency stability [18], [19]. Profound work has been dedicated to the optimal sizing and planning of EVs charging stations [20] and the auxiliary service for renewables [21].

Considering the importance of energy supply facilities in EV industry, charging stations have significant impact on the development of EV industry as well as power network planning and operation [22], [23]. Most existing charging stations focus

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This work was supported by National High Technology Research and Development Program 863 of China (2011AA05A108).

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on minimizing waiting times for drivers or avoiding charging during critical peak periods. [24] investigates the effect of high electricity prices during peak hours on EV load shifting, but does not provide strategies for setting the prices. A real-time smart load management strategy is proposed and developed for coordinating plug-in EV charging in order to minimize the total costs to generate energy [25].

In China, most cities do not have public charging infrastructure to support EVs due to factors such as expensive costs of plant areas and restrict integration standards to the power grid, etc. This lack of infrastructure is one major barrier to mass household adoption of EVs. Even worse, EVs battery is not suggested to be used for EVs when its capacity drops below 80% of its initial value. These retired batteries, are called ex-service batteries.

In order to accommodate large-scale integration EVs, three major challenges still exist:

- Although researchers have analyzed the positive impacts of EV batteries to the grid, the operation of a virtual power plant composed of a large number of charging EVs or a charging station still needs investigation.
- Although rapid charging stations provide a solution to reduce customers' waiting time, it is very difficult to implement centralized charging control since much of EV load coincides with normal residential load peaks.
- Normally, ex-service batteries are abandoned in most charging stations, a severe sacrifice for EV customers.

One option to reduce initial battery cost is to reuse them after retirement to exploit credits from residual value [26]. The research concerning battery reuses mainly focuses on the technical and economic feasibility and studies the impact on initial cost [27], [28]. However, there are still some barriers such as sensitivity to uncertain degradation rates in second use and high cost of battery refurbishment and integration [26]. A promising model for eliminating the adverse impacts of EVs charging on power grids is to build battery swap stations. By far, the research concerning battery swap stations mainly focus on: i) the investment of batteries exchanging requests [29], ii) service capacity [30], iii) facility location [31], iv) and the cost-benefit analysis [32]. They however, only considers a certain aspect of EV charging/discharging, battery swap stations or reuse of retired batteries. They are not economical and the constructions could cover a large area due to their independence. Therefore, there is a need to study an integrated system covering above functionalities for economic and effective purposes.

Instead of treating every part of EV charging/discharging, battery swapping, reuse of retired batteries, etc. in an isolated way, this paper proposes a new concept of intelligent integrated station (IIS) to bring all these discrete elements together. As part of the 'EVs Intelligent Charging-exchanging-storage Integrated Station and Engineering Demonstration' project commissioned by China's Ministry of Science and Technology in 2011, this paper presents the framework of the IIS and proposes dispatching control strategies for the power flow. The most outstanding feature of this type of stations is that EV batteries can be replaced by charged batteries to minimize waiting times for drivers. Besides, the stations make full use of ex-service batteries to work as energy storage to improve the performance of the grids in terms of efficiency, stability, reliability, etc. The concept of generalized energy, which considers both the integral of power flow and energy step change due to EV battery exchange, is proposed to systematically and comprehensively study the energy/power flow inside and outside a station. The energy is classified into three parts: energy in the charge exchange system, energy in the echelon battery system, and energy in on-board batteries of EVs. According to loading level and EV battery charging/exchanging requests, a novel control strategy is proposed to optimize the charging and discharging of the batteries in the IIS. The proposed control strategy can effectively offer peak load shifting and valley filling when meeting EV battery charging/exchanging requests. Battery charging is optimized to minimize charging costs and to achieve optimal power balancing. The effectiveness of the control strategy is demonstrated on a real IIS in Shanghai, China serving 15 EVs.

Except for the dispatching control of the power flow, the IIS system also provides auxiliary services to the power grid such as reactive power and voltage control, active power and frequency control, and harmonic suppression. The major contribution of this paper is: i) it proposes a novel EV's integrated station to offer EV batteries charging and exchange conveniences, which minimizes waiting time for drivers and shifts EV load during peak hours; ii) it uses generalized energy to study energy distributions inside and outside IISs to estimate the energy capacity of each part precisely; iii) the echelon battery system can serve as energy storage system to support the grid, such as peak load shifting; iv) the discharged batteries replaced from EVs can be charged at various charging rates considering different load profiles.

The rest of the paper is organized as follows: Section II introduces the framework of IISs. Section III discusses the energy/power flows in IIS and analyzes the generalized energy in IIS. In Section IV, the dispatching control strategy for IIS charging and discharging is discussed. Section V presents the experimental results of charging and discharging in an IIS. Conclusions are drawn in Section VI.

II. STRUCTURE OF AN INTELLIGENT INTEGRATED STATION

Most existing operation models in EV charging stations are in a decentralized manner. Here, the concept of novel EV's charging-exchanging-storage IIS is proposed. An IIS is an electric system cluster, consisting of a charge exchange system (CES), an echelon battery system (EBS), multi-purpose converter devices, and a dispatching center. The power flow and information flow in the IIS are shown in Fig.1, in which the solid lines depict the power flow and the short dash lines depict the information flow. Whereas the long dash line suggests the energy step changing during EV batteries exchanging process. Considering the load profile of the power grid, the IIS promises to bring many significant advantages in terms of reuse of ex-service batteries, coordination with the power grid, and optimal allocation of energy. The control algorithm of the IIS includes two parts: i) dispatching control, which aims to satisfy

EVs battery charging/exchanging and optimize IIS's charging/discharging to achieve peak shaving and valley filling; ii)auxiliary control, which aims to provide auxiliary services to the power grid such as reactive power and voltage control, active power and frequency control, and harmonic suppression. This paper focuses on the dispatching control of the IIS.

A. *Dispatching Center*

The dispatching center has two functions: i) monitoring battery SOC, operating state of the power grid and converters in the IIS, and ii) operating multi-purpose converter devices and battery charging/exchanging. The dispatching center is able to collect and deal with information from EVs, IIS and the grid. Based on the information above, the dispatching center is able to regulate the power exchanged between the grid and IIS by controlling the multi-purpose converter devices.

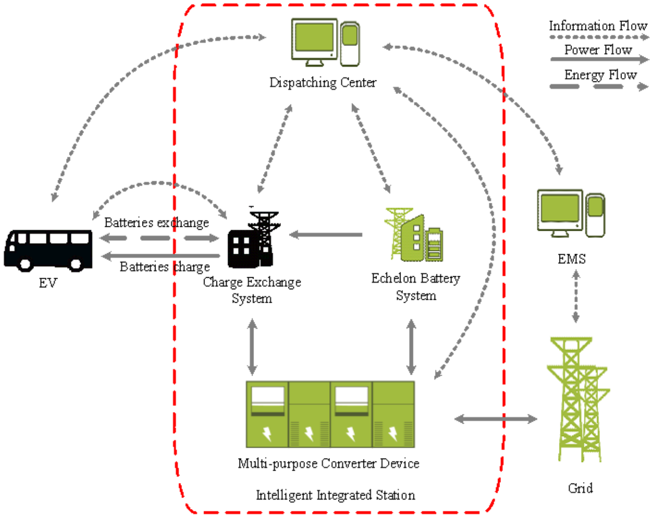


Fig. 1. Power flow and information flow in IIS

B. *Multi-purpose Converter Device*

The multi-purpose converter device allows the grid to exchange electricity with the CES and EBS, permitting batteries charging during valley periods and discharging during peak periods. The multi-purpose converter device is composed of two parts: a DC/DC converter and a DC/AC converter. The two converters present several advantages for energy exchanging, such as high control precision, wide range of output currents, and low harmonics. There is battery detecting device in the multi-purpose converter devices. Once the battery pack in IIS connects to the converter, the battery detecting device is able to obtain the SOC of the battery pack and send it to the dispatching center.

C. *Charge Exchange System*

The CES can provide batteries exchanging services for EVs and manage the charging of replaced batteries. In EV charging scheduling, the charging efficiency and service quality are two conflicting aspects. Charging efficiency generally depends on the charging rate and fast charging is harmful to battery performance, potentially leading to challenges to the grid. The battery exchanging mode, which takes advantage of the energy storage of the CES, is very promising to improve the efficiency and safety of EV charging, allowing for higher customer satisfaction and utility financial profits. Besides, the replaced batteries are controlled to be charged during valley periods to avoid undesirable peak loads, reducing operational costs.

D. *Echelon Battery System*

The echelon battery system provides a platform for reusing of the retired batteries from the CES or EVs. Under normal operating conditions, a battery can withstand a certain number of charging/discharging cycles before reaching end-of-life. But the limitation of energy density constrains its application in EVs after certain charging/discharging cycles. It is defined that a battery is sent to the EBS from the CES when its capacity drops below 80% of its initial value. Furthermore, when it drops to 40% of the initial value, it can be disassembled, optimized, and resembled in specialized factories to be reused in the EBS.

III. GENERALIZED ENERGY OF IIS

In this study, the concept of generalized energy is introduced to analyze the power/energy flow in an IIS. The generalized energy is defined as the combination of all types of electrical energies in the IIS and EVs, including energy consumption of EVs, the integral of power flow between the IIS and the power grid, and energy step changing during EV batteries exchanging process. It includes three parts: 1) energy in the CES; 2) energy in the EBS; 3) energy in EVs on-board batteries. The generalized energy in each system is helpful to obtain accurate information of the CES and the EBS, and SOC of EVs batteries, which is important to the forecast of batteries exchanging requests as well as the operating state of the IIS.

The energy/power flow in one cycle (24 hours) is divided into 24 periods, with the time interval of one hour. In the following, T_j is the jth time interval, T_{j0} is the initial time of time interval T_j, T_{jEND} is the end of time interval T_j. $E_{CES}^{(T_j)}(t)$ is the generalized energy of the CES at time point t in time interval T_j, respectively; $E_{EBS}^{(T_j)}(t)$ and $E_{EV}^{(T_j)}(t)$ are the generalized energy of the EBS and EVs on-board batteries.

A. *Generalized Energy of the Charge Exchange System*

The generalized energy of the CES is a function of the current time point and the time interval T_j

$$E_{CES}^{(T_j)}(t)=F_1(T_j,t)\ \ T_j\in\{0,1,2,...,23\},t\in[T_{j0},T_{jEND}] \quad (1)$$

The initial value of time interval T_j is a deterministic variable equal to the final value of time interval T_{j-1}

$$E_{CES}^{(T_j)}(t)\Big|_{t=T_{j0}}=E_{CES}^{(T_{j-1})}(t)\Big|_{t=T_{(j-1)END}} \quad (2)$$

The generalized energy of the CES can be written as

$$
\begin{aligned}
E_{CES}^{(T_j)}(t) &= E_{CES}^{(T_j)}(t)\Big|_{t=T_{j0}} - \sum_{i=1}^{n_{CES}^{(T_j)}} e_{CES\_i}^{(T_j)} + \sum_{k=1}^{n_{CES}^{(T_j)}} e_{EV\_k}^{(T_j)} + \sum_{l=1}^{m_{CES}} \int_{T_{j0}}^{t} P_{CES\_l}(t)dt \\
&= E_{CES}^{(T_{j-1})}(t)\Big|_{t=T_{(j-1)END}} - \sum_{i=1}^{n_{CES}^{(T_j)}} e_{CES\_i}^{(T_j)} + \sum_{k=1}^{n_{CES}^{(T_j)}} e_{EV\_k}^{(T_j)} + \sum_{l=1}^{m_{CES}} \int_{T_{j0}}^{t} P_{CES\_l}(t)dt
\end{aligned} \tag{3}
$$

where $n_{CES}^{(T_j)}$ is the number of batteries installed on-board from the CES in the time interval T_j, and $e_{CES\_i}^{(T_j)}$ is the energy of the ith one; $e_{EV\_k}^{(T_j)}$ is the energy of the kth battery replaced from EVs; m_{CES} is the number of converters between the grid and the CES; $P_{CES\_l}(t)$ is the power exchanged between the CES and the grid of the lth converter, and the CES charges from power grid when $P_{CES\_l}(t)$ is positive and discharges to the grid when $P_{CES\_l}(t)$ is negative.

The generalized energy of the CES in time point t_1 is assumed to be the initial value of the day, E_{iniCES}. To guarantee the continuous operation of the CES, E_{iniCES} should be equal in different cycles, and the following aspects should be met: 1) the initial generalized energy E_{iniCES} is able to satisfy EVs battery exchanging requests even without the support of the grid; 2) the CES is able to coordinate with the power grid to provide auxiliary services such as peak load shifting; 3) E_{iniCES} is less than the maximum capacity of the CES. These three conditions can be modelled as the following inequalities.

$$
\begin{cases}
E_{iniCES} - \sum_{j=0}^{23} \sum_{i=1}^{n_{CES}^{(T_j)}} e_{CES\_i}^{(T_j)} + \sum_{j=0}^{23} \sum_{k=1}^{n_{CES}^{(T_j)}} e_{EV\_k}^{(T_j)} \geq E_{CES\min} \\
E_{iniCES} - \sum_{j=0}^{23} \sum_{i=1}^{n_{CES}^{(T_j)}} e_{CES\_i}^{(T_j)} + \sum_{j=0}^{23} \sum_{k=1}^{n_{CES}^{(T_j)}} e_{EV\_k}^{(T_j)} + \sum_{l=1}^{m_{CES}} \int_{t_0}^{t_1} P_{CES\_l}(t)dt \geq E_{CES\min} \\
E_{iniCES} \leq E_{CES\max}
\end{cases} \tag{4}
$$

where, $E_{CES\min} / E_{CES\max}$ is the minimum/ maximum capacity of the CES to sustain its operation.

The full discharging and charging will have adverse effect on batteries, and therefore are not recommended. In practice, E_{iniCES} is about 90% of $E_{CES\max}$:

$$
E_{iniCES} = E_{CES\max} \cdot (90\% + \varepsilon_{CES}) \tag{5}
$$

where, ε_{CES} is a variable determined by the IIS operators and dispatching orders considering battery's state of health (SOH), energy capacity of the IIS, EVs batteries charging/exchanging requests and the grid loading level in the previous cycle. For a new battery in the CES, the initial SOC can be 90%~95% after charging.

B. Generalized Energy of the Echelon Battery System

The generalized energy of the EBS in time interval T_j is

$$
\begin{aligned}
E_{EBS}^{(T_j)}(t) &= E_{EBS}^{(T_j)}(t)\Big|_{t=T_{j0}} + \sum_{l=1}^{m_{EBS}} \int_{T_{j0}}^{t} P_{EBS\_l}(t)dt \\
&= E_{EBS}^{(T_{j-1})}(t)\Big|_{t=T_{(j-1)END}} + \sum_{l=1}^{m_{EBS}} \int_{T_{j0}}^{t} P_{EBS\_l}(t)dt
\end{aligned} \tag{6}
$$

where m_{EBS} is the number of converters between the grid and the EBS, P_{EBS_l} is the power exchange between the EBS and the grid of the lth converter. The EBS charges from the grid when P_{EBS_l} is positive and discharges to the grid when P_{EBS_l} is negative.

The charging/discharging strategy of the EBS is to achieve two goals: i) maintaining the continuous operation of the EBS; and ii) providing auxiliary services to the grid.

The generalized energy of the EBS in time point t_2 is assumed to be the initial value of the day, E_{iniEBS}. It should be equal in different cycles. Based on the load curve of the grid, strategies are proposed for batteries in the EBS to charge from the power grid during valley periods and discharge to the grid during peak periods. The initial value E_{iniEBS} is about 90% of $E_{EBS\max}$

$$
E_{iniEBS} = E_{EBS\max} \cdot (90\% + \varepsilon_{EBS}) \tag{7}
$$

where, ε_{EBS} is a variable determined by the IIS operators and dispatching orders considering battery's SOH, energy capacity of the IIS, and the grid loading level in the previous cycle.

C. Generalized Energy of EVs Batteries on-board

The generalized energy of EVs on-board batteries in time interval T_j is

$$
\begin{aligned}
E_{EV}^{(T_j)}(t) &= E_{EV}^{(T_j)}(t)\Big|_{t=T_{j0}} + \sum_{i=1}^{n_{CES}^{(T_j)}} e_{CES\_i}^{(T_j)} - \sum_{k=1}^{n_{CES}^{(T_j)}} e_{EV\_k}^{(T_j)} - \sum_{n=1}^{p_{EV}} \int_{t_0}^{t} W_{EV\_n}(t)dt \\
&= E_{EV}^{(T_{j-1})}(t)\Big|_{t=T_{(j-1)END}} + \sum_{i=1}^{n_{CES}^{(T_j)}} e_{CES\_i}^{(T_j)} - \sum_{k=1}^{n_{CES}^{(T_j)}} e_{EV\_k}^{(T_j)} - \sum_{n=1}^{p_{EV}} \int_{t_0}^{t} W_{EV\_n}(t)dt
\end{aligned} \tag{8}
$$

where, $n_{CES}^{(T_j)}$ is the number of batteries exchanged from the CES in time interval T_j, $e_{CES\_i}^{(T_j)}$ is the energy of the ith battery exchanged from the CES, $e_{EV\_k}^{(T_j)}$ is the energy of the kth battery replaced from EVs, p_{EV} is the number of EVs, and $W_{EV\_n}(t)$ is the power consumption of the nth EV.

The generalized energy of on-board batteries is the energy of all EVs batteries. Considering the energy consumption, the generalized energy of the kth EV outside the IIS in time interval T_j is

$$
E_{EV\_k}^{(T_j)}(t) = E_{EV\_k}^{(T_j)}(t)\Big|_{t=T_{j0}} - \int_{T_{j0}}^{t} W_{EV\_k}(t)dt \tag{9}
$$

The initial energy capacity of EVs is related to the that of the CES, denoted by E_{iniEV}, is

$$
E_{iniEV} = E_{EV\max} \cdot (90\% + \varepsilon_{CES}) \tag{10}
$$

IV. DISPATCHING OF THE IIS

The principle of the dispatching control is to maintain the energy capacity of the CES, and coordinate the CES with the grid. The charging/discharging of batteries can be controlled by changing the charging/discharging rate, i.e., the power required/available to charge/discharge the batteries in the IIS. The generalized energy of the CES and loading level of the power grid are two important factors in determining the charging/discharging of the IIS. Based on the periodic characteristics of load profiles and operation mode of the IIS, Fig. 2 shows the charging/discharging algorithms of the CES under three load conditions: i)during valley loading periods, the CES charges from the grid, working at rated charging rate; ii)during mediate loading periods, the CES charges from the grid at relatively low charging rate; iii)during peak loading periods, the CES may discharge to the grid if its energy capacity is high enough.

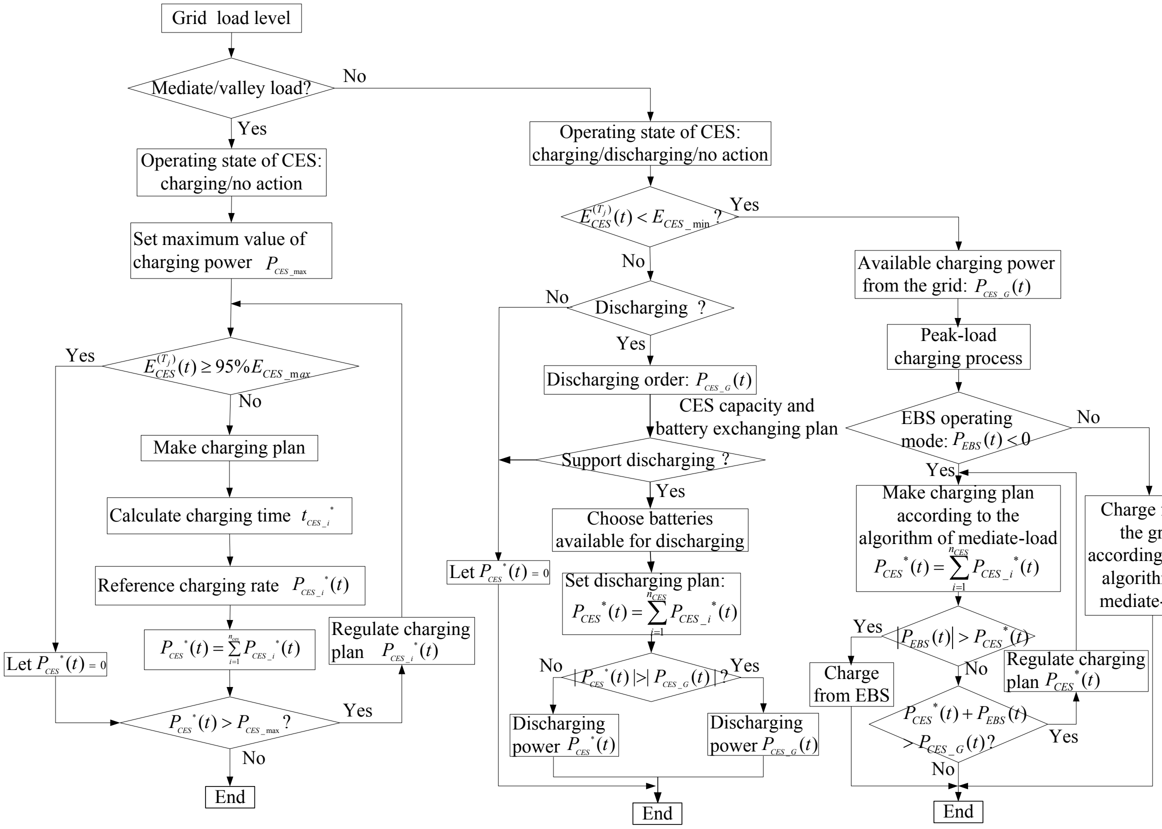


Fig. 2. Charging/discharging algorithm of CES at different load status

Normally, the power flow between the CES and EBS is unidirectional from the CES to EBS. If the energy capacity of the CES is low, the EBS charges the CES in two cases: i)the grid loading level is high and the EBS operates in discharging state; or ii) the IIS disconnects from the grid and the energy capacity of the EBS is high enough. During peak load periods, if the energy capacity of the CES is high enough, the batteries suitable for discharging are controlled to discharge to the grid according to the charging plan $P_{CES}^*(t)$ and the discharging order $P_{CES\_G}(t)$ from the dispatching center. If the energy capacity of the CES is less than the limited value E_{CES_min}, the CES operates in charging mode considering the operating mode of the EBS. In this condition, it is optimal to charge from the EBS rather than the grid if the EBS operates in discharging mode. The CES may charge from both the EBS and the grid if the EBS is unable to satisfy the charging plan of the CES. However, when the energy capacity of the EBS is poorly low, the CES charges from the grid at a reasonable charging rate.

Fig. 3 shows the charging/discharging algorithm of the IIS in one period (24 hours). Where flow 1 is the charging/discharging process during peak periods, flow 2 and flow 3 are the charging process during mediate and valley periods.

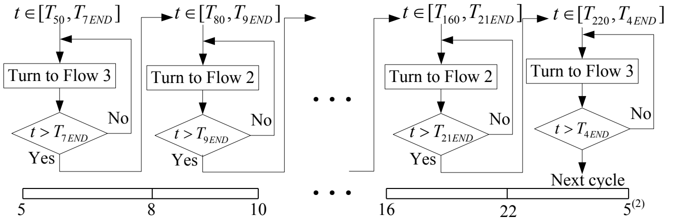


Fig.3. Basic charging/discharging algorithm of IIS in one period

TABLE I
VARIABLE TABLE OF DISPATCHING STRATEGY

Subsystem	Variable name	Code
EVs	EV route	n_a
	The opening time of the ith EV route	T_{im}
	The closing time of the ith EV route	T_{in}
	The departing time interval of the ith EV route	t_{sepi}
	Single-trip time of the ith EV route	T_{iD}
IIS	The time point of battery delivered into IIS	T
	Time interval of battery in IIS	T_a
	Time interval of battery being placed	T_m

	Time interval of battery being charged in IIS	T_e
	Time interval reserved for emergency	T_w
	Number of batteries	n_s
	Rated capacity of battery	E_c
	SOC of battery before charged	$S(t)$
	Maximum charging power of converter	P^*_{max}
	Rated charging power	P_c
	Time interval of dynamic programming process	Δt
Power grid	Load forecast in the next time interval T_c	$P^*{}_G(t), t \in [0, T_c]$
	Present load level	$P_G(t), t \in [0, T_c]$

In scheduling the power exchange between the IIS and the grid, cost minimization and service quality improvement are two conflicting targets. Batteries' charging is optimized to minimize charging costs with satisfactory energy levels and optimal power balancing. Thus, batteries scheduling is formulated as an optimal control problem to fill/cut the electric load valley/peak. Table I shows the dispatching parameters used.

For a system with parameters in Table I, the available charging time T_c can be written as

$$T_c = T_a - T_m - T_w \tag{11}$$

The rated charging power P_c can be expressed by the relation between the energy storage and charging efficiency

$$(\eta_a / \eta_b) \cdot T_c \cdot P_c = [1 - S(t)] \cdot E_c \tag{12}$$

where, η_a and η_b are charging efficiency and system redundancy rate.

Since electricity price is usually high during peak hours, batteries charging scheduling should avoid critical peak periods. Therefore, a prediction-based charging scheme is proposed, which predicts the load curve based on the exchanged information with the grid.

Here we consider the charging power in time interval T_C. Suppose $P^*(0)$ is the initial charging power of the battery, P_c is the mean value of the charging power in time interval T_C. $P_G(0)$ is the initial load level and $P^*{}_G(t)$ is the forecasting load curve of the grid. Using dynamic incremental method, we can get optimal charging rate profile $P^*(t)$ of the battery replaced from EVs.

By considering the charging rate of each battery, we can get the total charging rate of all replaced batteries at any time point during the charging process in the IIS, which is helpful to optimize the charging process for the dispatching control. The initial charging power $P^*(0)$ can be expressed by the relation between the forecasting load curve $P^*{}_G(t)$ and present load level $P_G(0)$ as

$$P^*(0) = P_c \cdot [2 - \frac{P_G(0) \cdot T_c / \Delta t}{\sum_{i=0}^{T_c/\Delta t} P^*{}_G(i\Delta t)}] \tag{13}$$

The optimal charging power in time interval T_c is

$$P^*(t+\Delta t) = P^*(t) - P_c \cdot \frac{[P^*{}_G(t+\Delta t) - P_G(t)](T_c / \Delta t)}{\sum_{i=0}^{T_c/\Delta t} P^*{}_G(i\Delta t)} \tag{14}$$

It is assumed that the rated charging power P_c and the optimal charging power P^* at time t are constants. The regulation factor of charging power can be calculated by the deviation of forecasting load P_G^* at $t + \Delta t$ and actual load level P_G at t. Thus, P^* in (14) can be derived.

V. EXPERIMENTAL RESULTS OF THE DISPATCHING CONTROL

The IISs are owned and operated by the electric power companies. To avoid the uncontrollable and uncertain charging of EVs, they are encouraged to exchange their EV batteries with those in the IIS. The IIS operates as electric load during valley periods and energy source during peak periods to ensure both the benefits of EV customers and distribution networks.

An IIS in Jiading district, Shanghai, China is chosen to test the above dispatching control strategy. The IIS is supported by the project 'EVs Intelligent Charging-exchanging-storage Integrated Station and Engineering Demonstration'. It is connected to the local 400V distribution network, covering an area of 2503.8 square meters and a total construction area of 4326 square meters.

TABLE II
INFORMATION OF EVS IN THE STATION

Iterm	Line 1	Line 2	Line 3
T_{im}	$T_{1m} = 8:00$	$T_{2m} = 8:30$	$T_{3m} = 24:00$
T_{in}	$T_{1n} = 21:00$	$T_{2n} = 20:30$	$T_{3n} = 6:00$
t_{sepi} (mins)	$t_{sep1} = 60$	$t_{sep2} = 45$	$t_{sep3} = 90$
T_{iD} (mins)	$T_{1D} = 150$	$T_{2D} = 135$	$T_{3D} = 120$

The IIS provides battery exchange service for 15 EVs. The driving information of these EVs is shown in Table II. The energy capacity of the EBS is ~~2MWh~~0.5MWh. The energy capacity of the CES is ~~5MWh~~3MWh, which is twice as that of the EVs. The rated charging/discharging rate of the CES is 350kW, and it is ~~150kW~~ 40kW for the EBS.

A. Load curve of Power Grid

Fig. 4 shows the load curve of the power grid for 24 hrs duration. The green area represents the load level during off peak periods (less than 80% of the maximum value), the yellow represents the load level during mid-peak periods (more than 80% and less than 95% of the maximum value) and the orange represents that of the peak periods (more than 95% of the maximum value). The typical customer load patterns show that the system load is low before 8:00, and it rises evidently after 8:00. Off peak hour load is approximated to be 60% of the peak hour load. If the charging/discharging of the batteries is done in an intelligent fashion, they can act as distributed energy sources to smoothen the load profiles by providing peak shaving and valley filling.

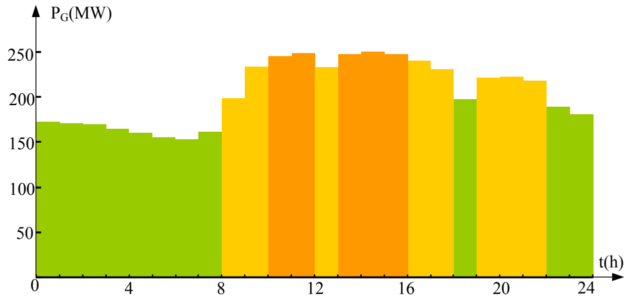


Fig.4. Grid load curve in one day

B. *Generalized energy of EVs*

Fig. 5 depicts the generalized energy of EVs in 24hrs. The discharged batteries of EVs are replaced with charged batteries in the CES from 2:00 to 5:00. For each EV, the battery is assumed to be exchanged at the same time point t_3 every day. Here we have $t_3 = 2:00$. The energy curve in Fig. 5 indicates that the energy of EVs reaches the maximum value of ~~2.5~~1.5MWh at 5:00 and decreases gradually during the operation of EVs till around ~~0.6~~0.4MWh at 24:00.

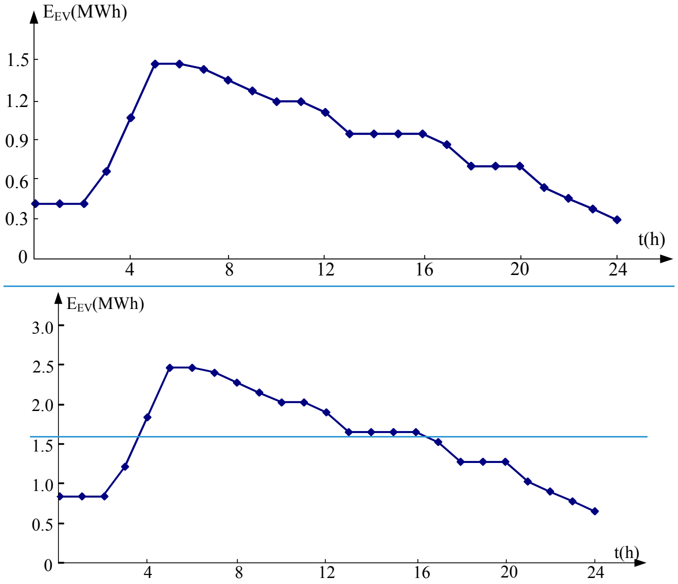
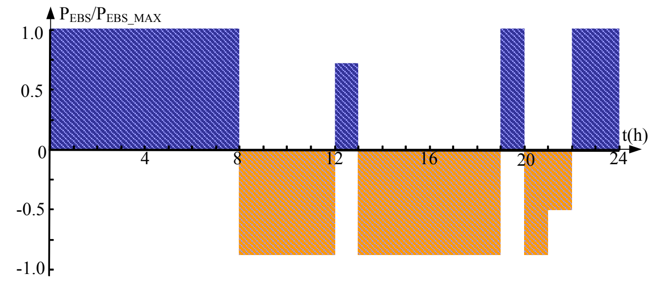


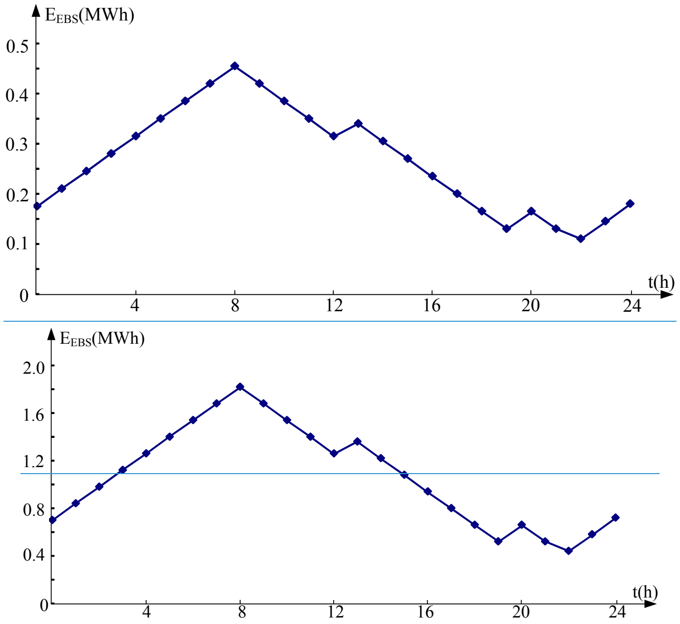
Fig. 5. Generalized energy of EVs

C. *Generalized energy of EBS*

Based on the proposed control strategy, we can plan the charging/discharging of the EBS according to the load curve and batteries exchanging requests, shown in Fig. 6. The daily periodic behaviour is clear. It is because that the control algorithm fully recharged batteries in the EBS valley load periods and discharges them at periods of peak load. Blue areas indicate that the grid delivers power to the EBS during valley hours, and orange areas represent time slots that are allocated for the EBS to support the grid during peak hours.



(a) Charging/discharging power curve of EBS



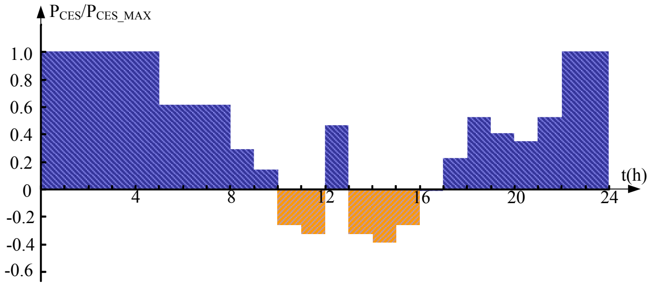
(b) Generalized energy curve of EBS

Fig. 6. Charging/discharging power and generalized energy of EBS

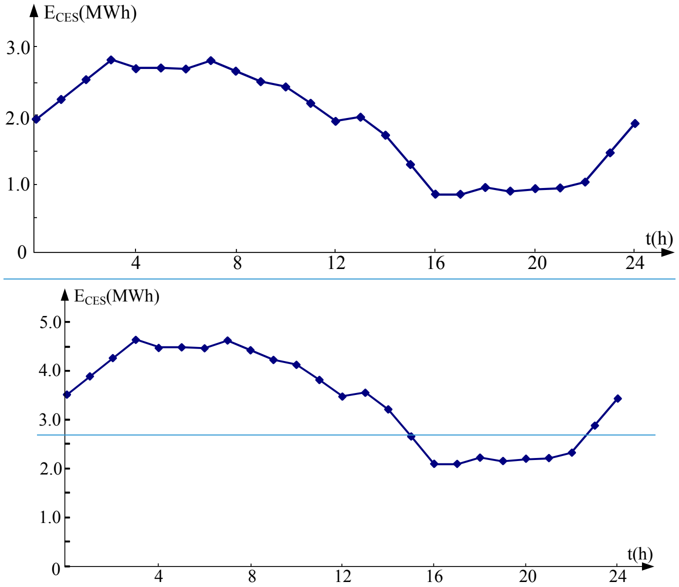
As shown in Fig. 6(b), the initial value of the generalized energy of EBS is ~~1.8~~0.46MWh at time 8:00. The EBS charges from the power grid at rated charging power and the energy capacity increases from 0:00 to 8:00 and from 22:00 to 24:00 when the grid operates at valley periods. On the contrary, it discharges from 8:00 to 12:00 and from 13:00 to 19:00 to support the power grid. In order to maintain the energy level of the EBS to be no less than 20% of the initial value, the EBS is required to charge from the grid at a reasonable charging rate during time intervals from 12:00 to 13:00 and from 19:00 to 20:00 when the power grid operates in mid-peak periods. The energy capacity of the EBS drops to the minimum value of ~~0.4~~0.1MWh at the time 22:00 due to its peak load shifting for the power grid.

D. *Generalized energy of CES*

The planned charging/discharging power and generalized energy of the CES are presented in Fig. 7. In Fig. 7(a), the blue area represents the charging power of CES and the orange means the discharging one. As shown in Fig. 7(b), the initial value of the generalized energy of the CES is ~~4.5~~2.8MWh at time 5:00. The CES charges from the grid in rated charging power during valley periods in the night and discharges to the grid during peak periods in time intervals 10 to 12 and 13 to 16. The energy capacity of the CES drops to the minimum value of ~~2.2~~1.0MWh at the time 16:00.



(a) Charging/discharging power curve of CES



(b) Generalized energy curve of CES

Fig. 7. Charging/discharging power and generalized energy of CES

E. Optimal charging of batteries replaced

Study is further carried out on using the charging of discharged batteries replaced from EVs to optimize the charging rate from the grid's perspective. Here three charging scenarios are considered: fast charging, slow charging and the optimal charging analyzed in Section IV.

The experimental results of the charging power in the three scenarios are depicted in Fig. 8, which illustrates that:

- The short dash line in red depicts the charging rate in fast charging scenario. Here, the charging scheduling of replaced batteries is performed from the customers' perspective and batteries are charged at rated charging rate of ~~155Kw~~80kW. Since the EV batteries are replaced with charged batteries from 2:00 am to 5:00 am, the charging takes about 16 hours at rated charging rate until all discharged batteries are fully charged. Therefore, much of the charging load coincides with normal residential load peak, which could have adverse impact on the distribution grid.
- The long dash line in red depicts the charging rate in slow charging scenario. The charging request of batteries is calculated according to the number of replaced batteries. The batteries are charged at constant rate, which is ~~110Kw~~55kW, and the charging load is thus a constant load.
- The solid line in green depicts the charging rate in the optimal charging scenario. The approach considers the load curve as well as EV charging requests. The batteries are charged minimally or even stop charging during peak periods, such as the time intervals from 10:00 to 12:00 and 13:00 to 16:00. On the contrary, the batteries are charged in rated charging rate of ~~155MW~~ 80kW during off-peak periods, such as the time interval from 18:00 to 19:00 and in the night valley periods. During the mid-peak periods, the batteries are charged at a lower rate of ~~110kW~~55kW, such as the time interval from 19:00 to 22:00.

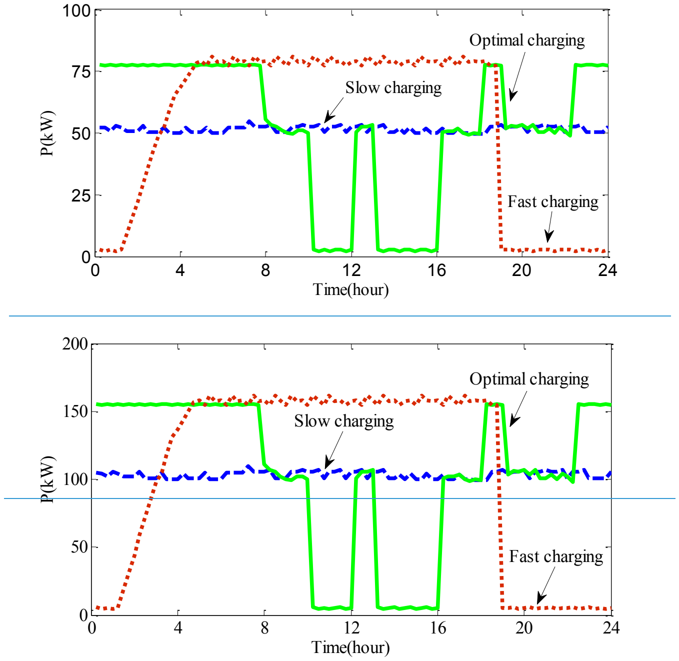


Fig. 8. Operating results of an IIS based on different charging modes

TABLE III
OPERATING RESULTS OF THE OPTIMAL CHARGING PROCESS

Time interval	Load level	Average charging power (kW)	Charging energy (MWh)	Energy deviation (MWh)
0:00-8:00	Off-peak load	~~155~~80	~~1.24~~0.64	~~0.36~~0.2
8:00-10:00	Mid-peak load	~~110~~55	~~0.54~~0.11	0
10:00-12:00	Peak load	~~10~~0	~~0.02~~0	-~~0.2~~0.11
12:00-13:00	Mid-peak load	~~110~~55	~~0.11~~0.055	0
13:00-16:00	Peak load	~~10~~0	~~0.03~~0	-~~0.3~~0.165
16:00-18:00	Mid-peak load	~~110~~55	~~0.22~~0.11	0
18:00-19:00	Off-peak load	~~155~~ 80	~~0.155~~0.08	~~0.045~~0.025
19:00-22:00	Mid-peak load	~~110~~ 55	~~0.33~~0.165	0
22:00-24:00	Off-peak load	~~155~~80	~~0.31~~0.16	~~0.09~~0.05

We study the charging energy in different time intervals considering both slow charging and optimal charging scenarios, as shown in Table III. One typical day is divided into nine time intervals according to the load level of the grid. The third column shows the average charging rate in each time interval. The last column shows the energy contribution for peak load shifting of the optimal charge approach compared with the constant charging rate ~~110kW~~ 55kW in slow charge scenario. The positive value represents the amount of the valley to be filled and the negative value represents the amount of peak to be shaved, which illustrates that:

- During off-peak periods, i.e., the time intervals 0:00-8:00, 18:00-19:00 and 22:00-24:00, the batteries are charged in rated charging rate of ~~155kW~~80kW, and the charging energy deviation is about ~~0.5~~0.275MWh compared with the slow charging scenario of ~~110kW~~55kW.

- During peak periods, i.e., the time intervals 10:00-12:00 and 13:00-16:00, the batteries ~~are minimally charged in~~stop charging, i.e., the charging rate ~~of 10~~is 0kW, and the charging energy deviation is about ~~0.5~~0.275MWh compared with the slow charging scenario of ~~110kW~~55kW.

Therefore, when the batteries are charged in the optimal approach, the energy absorbs from the power grid is ~~0.5~~0.275MWh more during off-peak periods and ~~0.5~~0.275MWh less during peak periods in one day compared with the slow charging scenario. It suggests that the optimal charging approach can offer peak load shifting when meeting EVs' batteries charging requests.

VI. CONCLUSION

This paper proposes a novel model of EV station -IIS and a new method for optimal operation of IISs to offer efficient batteries charging and exchange, with minimum negative impacts on power systems. It is designed according to load curves, EVs batteries exchanging request, and charging strategies of the charge exchange system and echelon battery system in the station. The generalized energy concept and a novel control strategy of batteries are proposed as well. The experimental results indicate that

- the IIS can operate in optimal charging and discharging process in the long run. Particularly,
- the charge exchange system charges from the power grid at rated rate during valley periods and at lower charging rate during mid-peak periods, and even discharges to the grid during peak periods;
- the echelon battery system works as an energy storage system by charging from the grid during valley periods and discharges to the grid during peak periods.
- Compared with normal charge modes, the optimal charging mode for batteries is capable of shaving peak and filling valley of the power grid.

The work is extremely useful for the development of smart dispatching strategies for EVs, as well as for the management of next-generation charging stations with smart grid systems.

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VIII. BIOGRAPHIES

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