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Article

The Concept of EV's Intelligent Integrated Station and Its Energy Flow

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Abstract: The increasing number of electric vehicles (EVs) connected to existing distribution networks as time-variant loads cause significant distortions in line current and voltage. A novel EV's intelligent integrated station (IIS) making full use of retired batteries is introduced in this paper to offer a potential solution for accommodating the charging demand of EVs. It proposes the concept of generalized energy in IIS, based on the energy/power flow between IIS and EVs, and between IIS and the power grid, to systematically evaluate the energy capacity of IIS. In order to derive a unique and satisfactory operation mode, information from both the grid (in terms of load level) and IIS (in terms of its energy capacity and batteries charging/exchanging requests) is merged. Then, based on the generalized energy of different systems, a novel charging/discharging control strategy is presented and whereby the operating status of the grid, the batteries exchanging requests and energy capacity of IIS are monitored timely to make reasonable operation plans for IIS. Simulation results suggest that the proposed IIS offers peak load shifting when satisfies EVs' batteries charging/exchanging requests compared to existing charging stations.

Keywords: Charging/discharging strategy; electric vehicle; energy flow; generalized energy; intelligent integrated station; load level; peak load shifting.

1. Introduction

Due to issues such as air pollution and global warming, and concerns of fossil energy reserves and energy prices, electric vehicles (EVs) are gaining increasing attention to reduce dependency on fossil fuels as well as environmental pollution. In China, considerable amount of work, such as technical research and plan of EV development, has been done by the government, academic institutes and the automobile industry [1]. However, issues such as high initial cost, short driving range, and long charging time constrains EV development [2-3].

As EVs rely on the electricity from the power grid, they could bring serve negative impacts on power generation, transmission, and distribution installations, if their charging and schedules are not properly managed [4-5]. Smart grid operation to reduce both cost and emission simultaneously is a very complex task considering intelligent charging/discharging of EVs in distributed networks and load environment [6]. The work in [7] developed a detailed model of the performance, energy use, manufacturing cost, retail cost, and lifecycle cost of EVs to address the issue of cost. Moreover, with the increasing penetration of EVs, the distributed feature of EV plug-in/off time has more significant effect on the aggregation load characteristics [8-9]. Since a sizable EV load can introduce a new peak in the early off-peak period, in [10] the optimization of the EV charging during the low cost off peak period is formulated to minimize the cost of EV charging in Singapore system. The work in [11] investigates a tradeoff between the user satisfaction fairness and the total cost of electricity for charging. The work in [12] proposes the use of EVs as responsive demand to complement network stress relief by allowing EVs to absorb excessive renewable generation when they cause network pressure.

The performance of EVs is influenced by the energy capacity of the onboard energy storage system, i.e., the battery pack [13]. Several factors such as deep depth-of-discharge, high or low temperature, extreme state-of-charge (SOC) levels, etc., are generally acknowledged to promote capacity fade [14-16]. A significant number of researches have focused on the design and optimization of energy management control strategies for EVs [17-18]. In addition, a great deal of attention has been paid towards the influence of charging patterns on battery life for plug-in EV applications [19-20]. In [21], the proposed strategy not only seeks to minimize fuel consumption while maintaining the SOC of the battery within reasonable bounds but also to minimize wear of the battery by penalizing the instantaneous battery usage with respect to its relative impact on battery life.

Although EV advocates have spent decades on tackling all kinds of challenges, EV charging control strategies which can affect the impacts and benefits significantly are still under discussion [22-24]. EVs still have relatively long and frequent charging cycles. Obviously, EVs will introduce additional load to the power system, and consequently, they can challenge power quality and reliability of power systems if their charging is not coordinated properly [25-27]. The impact of EVs on distribution networks can be determined according to their following aspects: driving patterns, charging characteristics, charge timing, and vehicle penetration, etc [28-30]. Moreover, charging resources are typically limited and must therefore be used efficiently [31]. In one study, it presents an integrated rapid-charging navigation strategy that considers both the traffic condition and the status of the power grid [32]. Other studies propose solutions for charging autonomous EVs in parking places and efficiently using scarce charging resources, thus simplifying the life of customers and increasing the feasibility of the EVs [33-34]. Another study proposes a multi-objective EV charging station planning method, which can ensure charging service while reducing power losses and voltage deviations of distribution systems [35]. Also, many studies focus on the charging scheduling of EVs at a charging station equipped with renewable energy generation devices, considering the uncertain arrival of EVs, the intermittence of renewable energy, and the variations of electricity price [36-37].

In recent years, vehicle-to-grid (V2G) technology has drawn research attention to improve the performance of the electricity grid in areas such as efficiency, stability, and reliability [38-40]. The V2G facilitates a large pool of EV batteries to store the energy during off-peak hours and inject it back to the grid during peak hours thus achieving valley filling and peak shaving [41-42].

A number of studies have investigated V2G technologies. The work in [43] presents a strategy for grid power peak shaving and valley filling by using V2G systems, and the influences of the number of connected EVs and the average value of the target curve are analyzed. Other researches make use of the distributed power of EVs to produce the desired grid-scale power to: i) participate in primary frequency control considering charging demands from EV customers [44-45]; or ii) to provide local voltage support, thereby reducing the need for voltage regulation at distribution nodes [46]. Another study analyses impacts of EVs on power grid planning, transmission/distribution networks and important aspects of utilization [47]. Also, many studies focus on the economic analysis for the integration of EVs to the grid [48-49].

Most of the previous research focused on developing charging strategies, but one major challenge still remains. EV customers expect a short charging time just like refuelling their current vehicles. Although rapid charging stations provide a solution, it is very difficult to implement centralized charging control since much of the EV charging load coincides with normal residential load peaks. Therefore, there is a need to investigate EVs batteries charging/exchanging stations and battery management of EVs. Moreover, little effort has been paid to the construction of charging stations with batteries exchanging service or the use of retired batteries, not to mention the optimal operation of charging station considering local load profiles and EVs batteries exchanging requests.

Most cities in China, however, do not have public charging infrastructure networks to support EVs. This lack of infrastructure is one of the major barriers to mass household adoption of EVs. The EVs charge-discharge-storage intelligent integrated station project, funded by China’s Ministry of Science and Technology, started in 2011 and aimed to resolve these problems by combining the concept of optimal fusion of energy storage systems and public transportation with the convenience of autonomous parking and coordinated batteries exchanging strategies. Its objective is to develop an EV’s intelligent integrated station (IIS) that offers batteries charging/exchanging services. The proposed IIS is composed of multi-purpose converter devices, a dispatching center, a charge exchange system, and an echelon battery system. Compared with the existing charging stations, the proposed IIS provides batteries exchanging service as well as EVs charging service. The retired batteries are abandoned in most charging stations, in IIS, however, they serve as an energy storage system in the echelon battery system. Furthermore, by properly controlling the IIS, it can provide grid-support services, such as reactive power support, primary frequency control, and peak shifting and valley filling, which is essential for smart network planning and operation [50-52].

In this paper, we introduced the framework of IIS and analyzed the information flow as well as power flow in IIS. In addition, we researched the energy flow inside and outside the station and proposed the concept of generalized energy to systematically investigate the energy distribution. Moreover, in order to analyze the energy in batteries independently, we separate the energy into three parts, i.e., energy in the charge exchange system, energy in the echelon battery system and energy in EVs batteries on-board. The generalized energies of the charge exchange system and load level of the power grid are important factors in determining the charging/discharging of IIS. According to the load level and the energy capacity of the charge exchange system, we proposed a novel control strategy to optimize the charging and discharging management of batteries. The echelon battery system serving as an energy storage system charges from the grid during off-peak periods and discharges to the grid during peak periods. Moreover, when the charge exchange system operates in charging mode during peak load periods, it is optimal to charge from the echelon battery system other than the grid if the energy capacity of the echelon battery system is high enough. In this way, batteries charging behavior is optimized to minimize charging costs and to achieve optimal power balancing. The simulation results show the effectiveness of the strategy.

The rest of the paper is organized as follows: Section 2 introduces the framework of the proposed integrated station by introducing power flow and information flow in it. Section III discusses the dispatching center and its function, the intelligent dispatch platform, and control strategy of energy/power flow in IIS. In addition, the charging/discharging state of the multi-purpose converter device and operating modes of the charge exchange system and the echelon battery system are talked in detail in this Section. Section IV introduces the generalized energy based on the energy/power flow between the IIS and EVs as well as the IIS and the power grid. In Section V, the dispatching control strategy for batteries charging/discharging is discussed under different conditions. Section VI presents the simulation results of batteries charging/discharging in the IIS during two periods. Finally, conclusions are drawn in Section VII.

2. The Proposed Intelligent Integrated Station

2.1. Overall Structure -Hardware

Most operation models in the field of EV charging stations are in decentralized fashions. Constrained by the factors such as short of plant area, expensive price of batteries and restrict integration standards of the power grid, most research on charging stations focuses on avoiding charging during critical peak periods to prevent the failure of the grid due to over-demand. Therefore, the development of EV charging stations is constrained by cost and service quality.

Here, a novel EV’s charge-exchange-storage intelligent integrated station is proposed. An IIS is an electric system cluster composed of a charge exchange system (CES), an echelon battery system (EBS), multi-purpose converter devices and a dispatching center, shown in Fig. 1. As the heart of an IIS, the main function of the dispatching center is to utilize the input signals, i.e., operating information of the IIS, EVs, and the grid, to make optimal operating decisions that enable the IIS to provide good services to customers and cooperate with the power grid. The CES can provide charging and exchanging services for EVs. The EBS is composed of batteries retired from the CES or EVs, i.e., batteries with energy capacity less than 80% of the initial value after a number of charge/discharge cycles. The CES and EBS can exchange electric power with the power grid through two sets of parallel converters, i.e., the multi-purpose converter devices. The multi-purpose converter device can be controlled to work in rectifier or inverter mode to realize the charging or discharging of batteries in IIS.

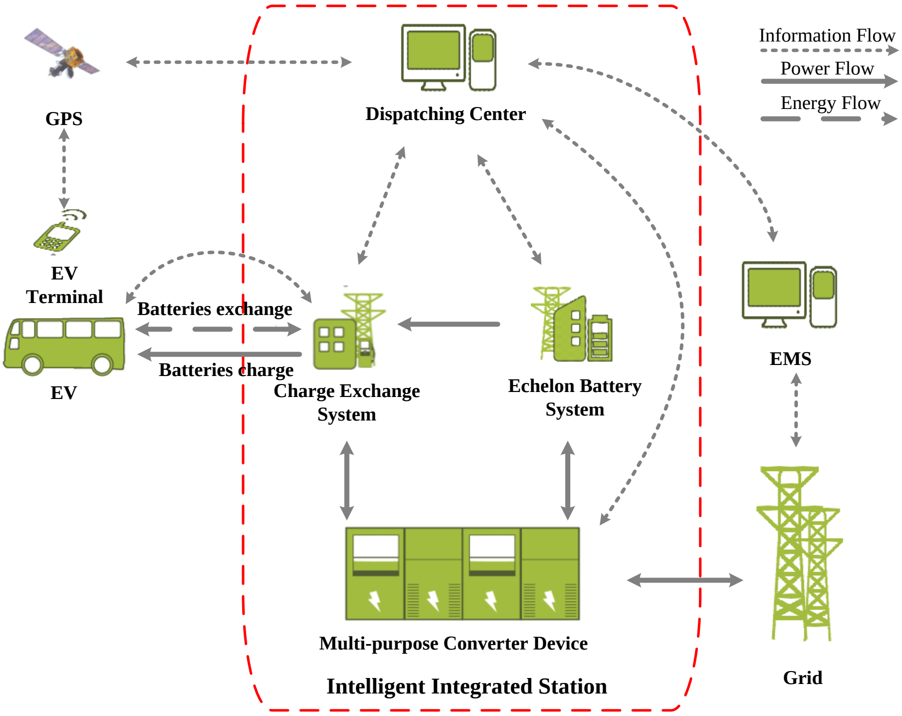


Figure 1. Power flow and information flow in IIS

Moreover, the EBS allows for delivering electric power to the CES through DC/DC converters to maintain the energy capacity of the CES during peak periods. Compared to traditional EV batteries charging and exchanging systems, the IIS proposed in this paper has many significant advantages in terms of utilization of batteries, efficient battery exchanging process, coordination with the power grid, and optimal allocation of energy. The EBS makes full use of retired batteries to utilize batteries out of service. The CES can provide efficient batteries exchanging service for customers except for batteries charging in fast-charge and slow-charge modes. Moreover, the EBS and CES work as energy storage systems to coordinate with the power grid and optimize power flow between the grid and IIS.

2.2. Information/energy Flow -Software

The heart of an IIS is the dispatching center, which collects information inside and outside the IIS and coordinates the power exchanging processes, considering the operating states of the power grid, battery exchanging requests and energy capacity of IIS. The EV terminal installed in a vehicle is able to record the position of the vehicle and exchange information with the dispatching center based on the technology of GPS.

The dispatching center plays a fundamental role in battery management. It is a natural platform for the implementation of battery exchanging strategy because it is capable of predicting battery exchanging requests based on the information from the EV terminal and monitoring energy capacity of the CES. Furthermore, the dispatching center provides additional services, such as the possibility of coordinating IIS and the power grid to store surplus grid energy at a given instance and to inject it into the grid when required. In particular, the multi-purpose converters are the key components, because they allow the power grid to exchange electricity with CES or EBS, permitting both batteries charging during valley periods and batteries discharging during peak periods.

In order to coordinate battery exchanging requests of EVs and interact with the power grid, the availability of information flow plays an important role in battery management and operation of the IIS. As shown in Table I, the term information flow in the IIS covers many parameters: i) SOC of batteries, which indicates energy capacity of batteries in the CES and EBS, and batteries onboard of EVs outside the IIS; ii) operating parameters of converters, which indicate the direction as well as value of power flow between the IIS and the power grid; iii) the information of batteries onboard through GPS technology; and iv) information of the power grid through energy management system (EMS) of the grid.

Table 1. Information Flow in IIS

Information sender	Information receiver	Information flow	Information code
EV terminal	CES	Information of battery uninstalled	I1
	GPS	Information of EV	I2
CES	EV terminal	Information of battery installed	I3
	Dispatching center	SOC of CES	I4
	Dispatching center	Power flow between CES and grid	I5
	Dispatching center	Power flow between CES and EBS	I6
EBS	Dispatching center	SOC of EBS	I7
	Dispatching center	Power flow between EBS and grid	I8
	Dispatching center	Power flow between EBS and CES	I9
Converters of CES	Dispatching center	Power flow between CES and grid	I10
Converters of EBS	Dispatching center	Power flow between EBS and grid	I11
DC/DC converter	Dispatching center	Power flow between EBS and CES	I12
EMS of grid	Dispatching center	Information of grid	I13
	Dispatching center	Power flow between CES and grid	I14
	Dispatching center	Power flow between EBS and grid	I15
GPS	Dispatching center	Information of EV	I16
	EV terminal	Battery exchanging suggestion	I17
Dispatching center	EMS of grid	IIS information	I18
	Converters	Power flow control	I19
	CES	Battery exchanging demands	I20
	EBS	Battery disposal	I21
	GPS	Battery exchanging suggestion	I22

3. Structure of the IIS

3.1. Dispatching Center

The dispatching center in the IIS is in charge of information collection/processing, condition monitoring, and operation control. It is capable of controlling the power flow between the grid and IIS based on the present and predicted information of EVs operation, the grid dispatching, and the operation of IIS.

There exists information flow between the dispatching center and EVs, the IIS, and the grid. By collecting information from these systems, a dispatching center needs to forecast their changing trends and propose control strategies for the sustainable and optimal operation of IIS. The dispatching center is able to obtain the EV's location according to the EV terminal and calculate onboard battery capacity. Based on the information above, the dispatching center can forecast EVs capacity curves, adjust the charging process of IIS and issue dispatching orders of EVs' management. In the meantime, the dispatching center can acquire the operating information of the grid through EMS and adjust batteries charging plans to avoid peak hours. Therefore, by storing electric power during off-peak hours with low price, IIS is able to send the energy back to the grid when needed.

(1) *Intelligent dispatch platform*

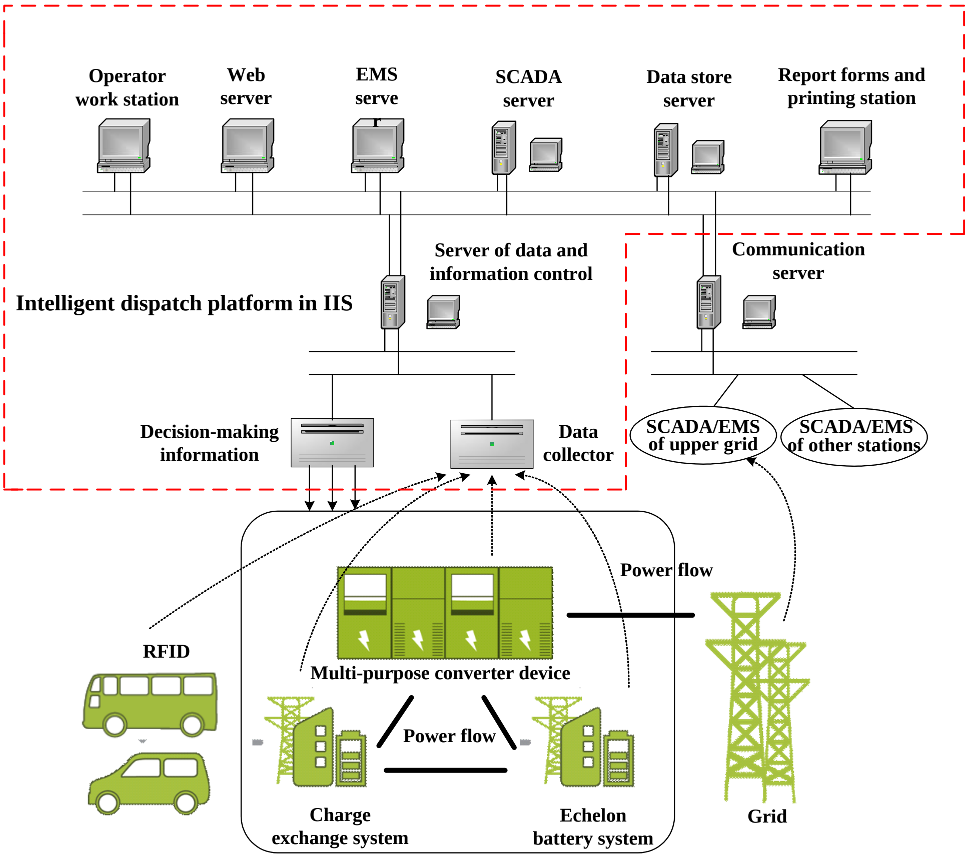


Figure 2. Intelligent dispatching of IIS

To realize the fusion of multi-source information from the grid, EVs and IIS, a dispatch platform is needed to cooperate with supervisory control and data acquisition (SCADA) system, EMS and internet of things (IoT) system. The intelligent dispatch platform in IIS is circled by the red dotted square, as presented in Fig. 2.

The data collector in the dispatch platform is in charge of collecting operating information of the IIS and EVs for the operator work station. The operator work station also collects the grid operating information through the SCADA and EMS.

By combining the information above, the operator work station is able to make optimal operation decision for the IIS and send the decision-making information to the IIS. It includes the following key servers:

- The web server is able to obtain and upload information through internet.
- The EMS server is used to manage energy flow in IIS and make smart dispatching strategies.
- The SCADA server in IIS is employed to acquire the scene information and send the decision-making information to corresponding systems.
- The data store server is capable of storing large number of data during the operation of IIS, which is of great value for making dispatching strategy by analyzing and forecasting the changing trend. For example, by monitoring the information of EVs in operation, we can analyze and forecast batteries exchanging requests and send this message to the CES.
- The communication server is used to communicate with SCADA/EMS of the upper systems to receive the operating information of the grid and other stations, which provides reference for the smart dispatching of IIS to reach optimal operation.

(2) *Control strategy of energy/power flow in IIS*

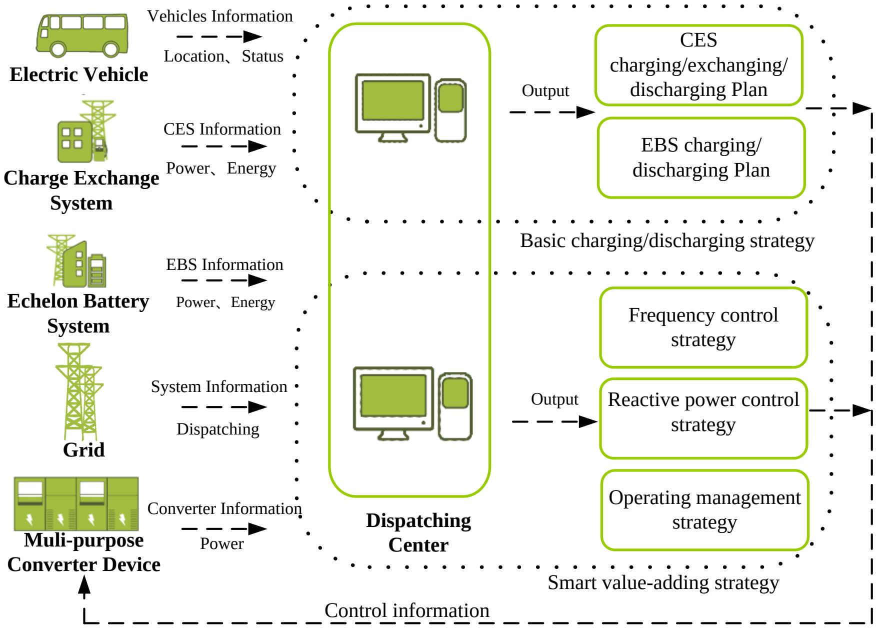


Figure 3. The control strategy of the energy/power flow in IIS

As shown in Fig. 3, the dispatching center is able to collect all kinds of information, such as the location and operation status of EVs, the energy capacity and charging/discharging power of CES/EBS, the dispatching order and operating status of the grid, and the information of power flow in each converter. Based on the information above, the control strategy of energy/power flow in IIS shown in Fig.3 can achieve the optimality of peak load shifting to the grid.

The basic charging/discharging strategy aims to satisfy EVs batteries charging/exchanging requests and optimize charging/discharging process of IIS to achieve peak load shifting, which will be talked in detail later.

Furthermore, according to the operating status of the grid and energy capacity of IIS, IIS can provide auxiliary services to the power grid such as frequency control and reactive power control, by controlling the power flow between the power grid and IIS, called smart value-adding strategy. The frequency control strategy is applied to IIS when the deviation of frequency Δf is in a setting range. If $\Delta f > 0$, IIS charges from the grid in rated power. Otherwise, IIS does not charge or even discharges to the grid. Moreover, IIS can operate as a static var generator to compensate reactive power for the distribution grid [50]. The smart value-adding strategy is not the emphasis of this paper.

3.2. Multi-purpose Converter Device

Essentially, the multi-purpose converter device is a combination of voltage source converter, monitoring sensor, system controller and transformer. The charging/discharging of batteries in IIS are closely related to the direction and value of the power flow between the power grid and IIS through the multi-purpose converter device.

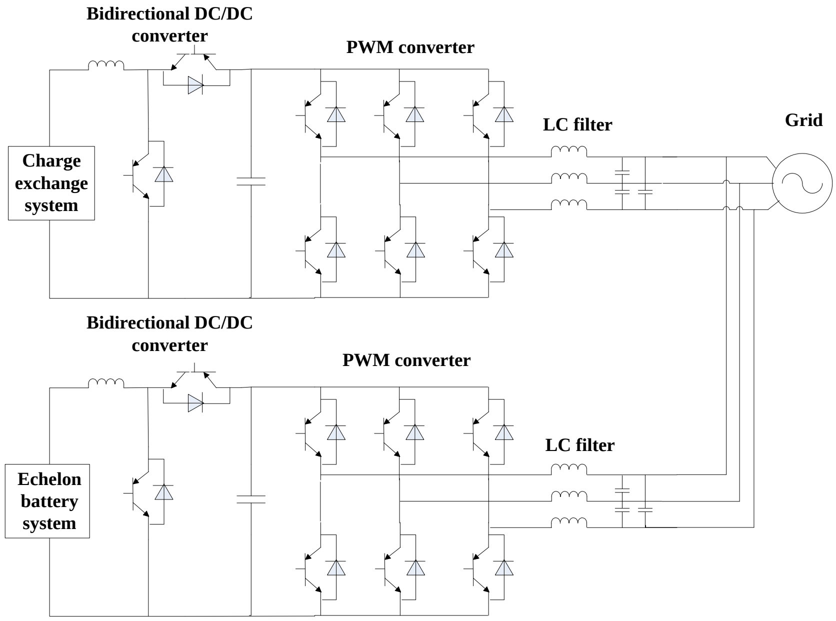


Figure 4. Multi-purpose converter device

To manage the charging and discharging of batteries in CES and EBS, we adopt a simple but practical converter device, which includes DC/DC and DC/AC circuits [53], shown in Fig. 4.

It shows the basic structure of the multi-purpose converter device which consists of two sets of parallel converters connecting to CES and EBS. The DC/DC part is a Buck-Boost circuit which avoids the use of an AC/AC transformer to obtain suitable voltage for the charging and discharging of batteries. The DC/AC part employs PWM converter which works in rectifier or inverter mode. This structure has widespread applicability to control the charging and discharging of two sets of batteries independently. Unavoidably, the conversion efficiency decreases due to the existence of the DC/DC part.

The multi-purpose converter device in CES works in two stages.

- Charging stage. In this stage, the power grid delivers electric power to batteries in CES to maintain the energy capacity of IIS. The DC/AC part works in rectifier state and the DC/DC part works in Buck mode. It serves as a high power charger. Generally, the charging process is done during valley periods to provide valley filling service to the grid.

- Discharging stage. The CES can be used to provide peak shaving service to the grid when the energy capacity of CES is high enough. Batteries discharge to the grid to alleviate the over-demand condition of the grid. In this condition, the DC/AC part works in inverter mode and the DC/DC part works in Boost mode.

Similarly, the multi-purpose converter device in EBS can be controlled to operate in charging or discharging mode accordingly.

3.3 Charge Exchange System

To satisfy EVs batteries charging demand, the CES proposed in this paper can provide fast-charging and slow-charging services. Moreover, the CES is expected to provide full-capacity batteries for EVs in batteries exchanging mode. Therefore, EV batteries can be replaced in a short time and the batteries in CES can be charged during off-peak periods. The CES consists of EVs batteries exchanging room and charging room, control room, maintenance center, and switching room, as shown in Fig. 5.

- The switching room is used to supply electric power for IIS operation. It provides electric power for the charging machine, the batteries exchanging robots, and the control devices.
- The control room is in charge of monitoring and controlling the operation of the CES.
- The maintenance room provides charging, maintenance and storage service for batteries in the CES.
- EVs' batteries exchanging/charging room provides batteries exchanging/charging service for EVs.

Therefore, the CES is supposed to provide maintenance service for batteries and batteries exchanging/charging service for EVs.

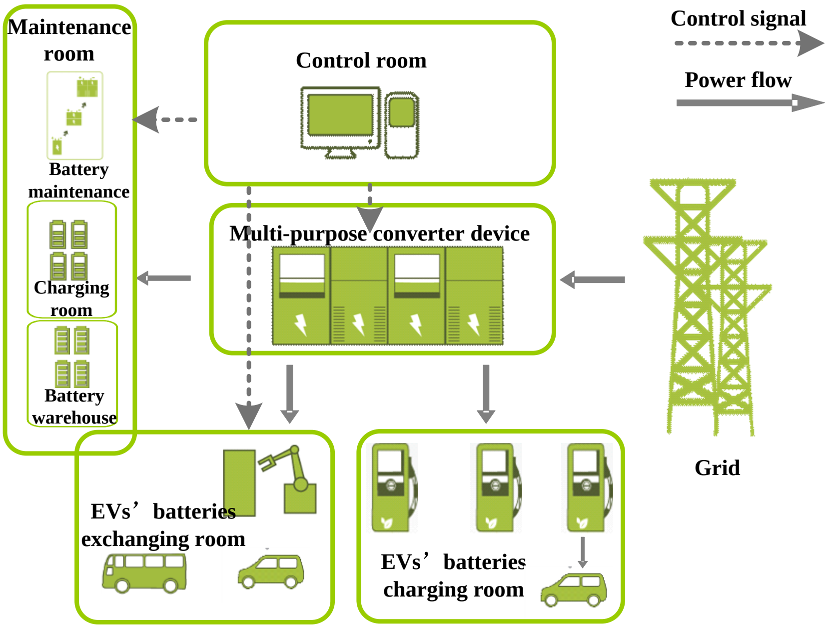


Figure 5. Layout of charge exchange system

Aiming to overcome severe exchanging demand of batteries caused by a large level of EV penetration, IoT and GPS technologies are used to monitor EVs' operation in order to obtain batteries exchanging forecast information.

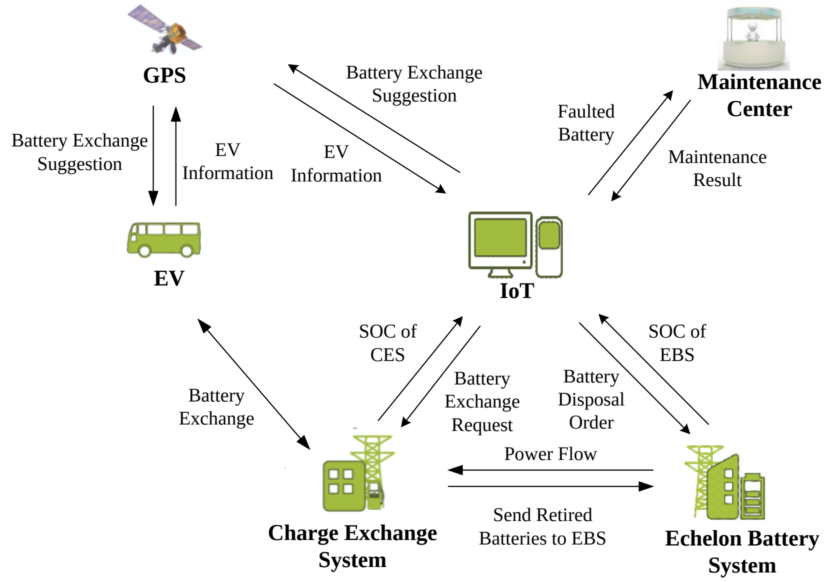


Figure 6. Battery management in IIS

As shown in Fig. 6, GPS technology is used to monitor EV locations and collect driving information. IoT needs to estimate the energy capacity of batteries installed in EVs according to their driving information. Based on the energy capacity of EVs, IoT will provide batteries exchanging suggestions to EVs and send the messages of batteries exchanging request to CES. Based on EVs' driving information received from GPS, IoT provides additional important services, such as diagnosing EV's operating states and sending message to maintenance center when an EV is in trouble. Moreover, IoT is able to obtain information from CES/EBS, such as energy capacity of CES and operating state of each battery. By detecting the operating status of batteries in CES/EBS, IoT gives dispatching orders, such as sending retired batteries to EBS and transporting faulted batteries to the maintenance center.

3.4 Echelon Battery System

In this paper, we adopted a throughput-based capacity fade model to make full use of retired batteries. The capacity fade model is based on the assumption that, under constant operating conditions, a battery can withstand a certain number of charge/discharge cycles, before reaching its end-of-life.

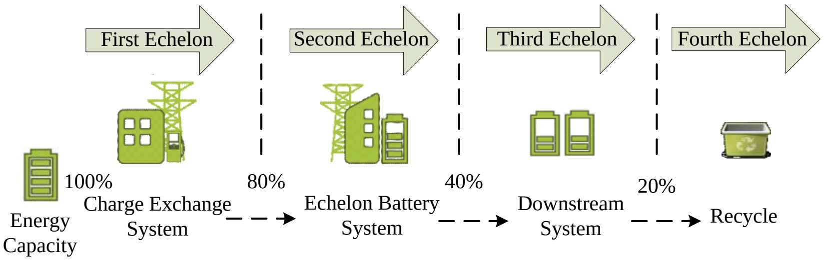


Figure 7. Echelon exploit of batteries

As shown in Fig. 7, according to the energy capacity of a battery, the capacity fade model divides batteries into four echelons:

- 1) first echelon: batteries with energy throughout no less than 80% of the initial energy capacity. To improve the operating condition of EVs, the energy capacity of batteries replaced from CES should be no less than 80% of the initial value.
- 2) second echelon: batteries with energy throughout less than 80% but more than 40% of the initial energy capacity. This echelon is the collection of retired batteries from CES whose energy capacity is less than the service limit. These retired batteries can be used as energy storing device to support for the grid as well as CES.
- 3) third echelon: batteries with energy throughout less than 40% but more than 20% of the initial energy capacity. Batteries in this echelon are not suitable for frequent charging/discharging due to their low energy capacity. They can be used in downstream system which has no strict demand for battery capacity.
- 4) fourth echelon: batteries with energy throughout less than 20% of the initial energy capacity. Since the battery is not suitable for discharging over 20% of its initial capacity, batteries in this echelon should be recycled.

Here we mainly consider batteries of the first two echelons in IIS. EBS is expected to provide backup energy supply for CES by delivering electric power to CES through DC/DC converters during high-demand exchanging periods. Clearly, as the EV penetration increases, high concentrations of charging requests over a restricted time period will inevitably cause a sharp drop in energy capacity of CES. In order to alleviate such severe situation, IoT is employed to monitor the energy capacity of each parts in IIS so as to deliver electric power to CES from EBS when needed.

4. Generalized Energy of the IIS

The batteries in IIS exchange electrical power with the power grid in charging/discharging mode. Smart strategies have to be scheduled to control the charging/discharging so as to optimally distribute energy location and power flow. However, direct analysis of energy in IIS is difficult due to the complexity and multi-attributes of energy/power flow in it. In this study, the concept of generalized energy is introduced to analyze power/energy flow in an IIS.

4.1. Energy Distribution in IIS

The energy in IIS can be divided into three parts: 1) energy of all batteries inside and outside IIS; 2) exchanged energy between IIS and the grid; 3) energy consumption of on-board EV batteries.

1) Energy of all batteries inside and outside an IIS

The energy of batteries includes three parts: energy of batteries in CES, energy of EVs on-board batteries and energy of batteries in EBS. The total energy of all batteries at time t_0 is written as:

$$E_1(t_0) = \sum_{i=1}^{n_{CES}} e_{CES\_i}\Big|_{t=t_0} + \sum_{j=1}^{n_{EV}} e_{EV\_j}\Big|_{t=t_0} + \sum_{k=1}^{n_{EBS}} e_{EBS\_k}\Big|_{t=t_0} \tag{1}$$

where, n_{CES} is the number of batteries in CES, e_{CES_i} is the energy of the ith battery in CES; n_{EV} is the number of batteries on-board outside the IIS; e_{EV_j} is the energy of the jth battery on-board; n_{EBS} is the number of batteries in EBS, e_{EBS_k} is the energy of the kth battery in EBS.

2) Exchanged energy between IIS and the grid

The energy exchanged between IIS and the grid from time t_0 to t is written as:

$$E_2(t)=\sum_{i=1}^{m}\int_{t_0}^{t}P_i(t)dt=\sum_{j=1}^{m_{CES}}\int_{t_0}^{t}P_{CES\_j}(t)dt+\sum_{k=1}^{m_{EBS}}\int_{t_0}^{t}P_{EBS\_k}(t)dt \tag{2}$$

where m is the number of converters connecting IIS and the grid; m_{CES} is the number of converters in CES; m_{EBS} is the number of converters in EBS, and we have $m=m_{CES}+m_{EBS}$; $P_i(t)$ is the power flow through the ith converter, $P_{CES\_j}(t)$ is the power exchanged between CES and the grid through the jth converter, and $P_{EBS\_k}(t)$ is the power exchanged between EBS and the grid through the kth converter. Negative power implies that energy is transferred to the grid from CES/EBS while positive power implies that energy is drawn from the grid to charge the batteries in CES/EBS.

3) Energy consumption of on-board EV batteries

The energy consumption of EVs on-board batteries is:

$$E_3(t)=-\sum_{i=1}^{p_{EV}}\int_{t_0}^{t}W_{EV\_i}(t)dt \tag{3}$$

where p_{EV} is the number of EVs, $W_{EV\_i}(t)$ is the electric power consumption of the ith EV.

4) Total energy in IIS

By combining three kinds of energy above, the total energy in IIS at the time t can be written as:

$$\begin{aligned}E(t)&=E_1(t_0)+E_2(t)+E_3(t)\\&=\sum_{i=1}^{n_{CES}}e_{CES\_i}\Big|_{t=t_0}+\sum_{j=1}^{n_{EV}}e_{EV\_j}\Big|_{t=t_0}+\sum_{k=1}^{n_{EBS}}e_{EBS\_k}\Big|_{t=t_0}+\sum_{l=1}^{m_{CES}}\int_{t_0}^{t}P_{CES\_l}(t)dt\\&\quad+\sum_{m=1}^{m_{EBS}}\int_{t_0}^{t}P_{EBS\_m}(t)dt-\sum_{n=1}^{p_{EV}}\int_{t_0}^{t}W_{EV\_n}(t)dt\end{aligned} \tag{4}$$

The total energy in IIS can be analyzed through centralized and decentralized approaches. One common centralized approach divides it into three parts according to the belonging of batteries to optimize the operation of IIS and the dispatching of EVs. Thus, the state equation (4) becomes:

$$\begin{aligned}E(t)&=\left[\sum_{i=1}^{n_{CES}}e_{CES\_i}\Big|_{t=t_0}+\sum_{l=1}^{m_{CES}}\int_{t_0}^{t}P_{CES\_l}(t)dt\right]+\left[\sum_{k=1}^{n_{EBS}}e_{EBS\_k}\Big|_{t=t_0}+\sum_{m=1}^{m_{EBS}}\int_{t_0}^{t}P_{EBS\_m}(t)dt\right]\\&\quad+\left[\sum_{j=1}^{n_{EV}}e_{EV\_j}\Big|_{t=t_0}-\sum_{n=1}^{p_{EV}}\int_{t_0}^{t}W_{EV\_n}(t)dt\right]\\&=E_{CES}(t)+E_{EBS}(t)+E_{EV}(t)\end{aligned} \tag{5}$$

where $E_{CES}(t)$ is the energy of CES at the time t, respectively, $E_{EBS}(t)$ and $E_{EV}(t)$ are the energy of EBS and EVs batteries on-board at the time t.

It should be noted that EVs batteries exchanging requests and load level of the grid are almost the same every day. Therefore, in order to make the IIS operate in steady state on the long run, the generalized energy in each system should be periodic, i.e., the increasing energy and decreasing energy are equal on a 24-hour cycle.

4.2. Generalized Energy

The normal concept of energy is defined as the integral of power flow in a certain time interval. Here we consider the abrupt change of energy in IIS and EVs in the batteries exchanging process. The concept of generalized energy proposed in this paper is defined as the combination of all types of electrical energies in IIS and EVs, including energy consumption of EVs, the integral of power flow in IIS and abrupt change of energy during batteries exchanging process.

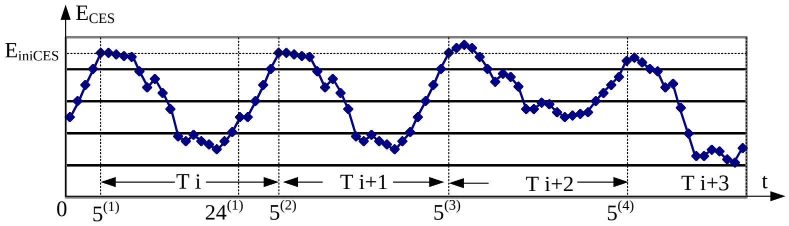
In order to analyze the energy flow systematically and make optimal dispatch order, we distribute the generalized energy in IIS into three parts: energy in CES, energy in EBS and that of batteries in EVs on-board. We consider the energy/power flow in one cycle (24 hours), which can be divided into 24 time periods, with the time interval of one hour. Here T_j is the jth time interval, T_{j0} is the initial time of the time interval T_j, T_{jEND} is the end point of the time interval T_j. $E_{CES}^{(T_j)}(t)$ is the generalized energy of CES at the time t in the time interval T_j, respectively; $E_{EBS}^{(T_j)}(t)$ and $E_{EV}^{(T_j)}(t)$ are the generalized energy of EBS and EVs on-board batteries.

1) Generalized energy of the charge exchange system

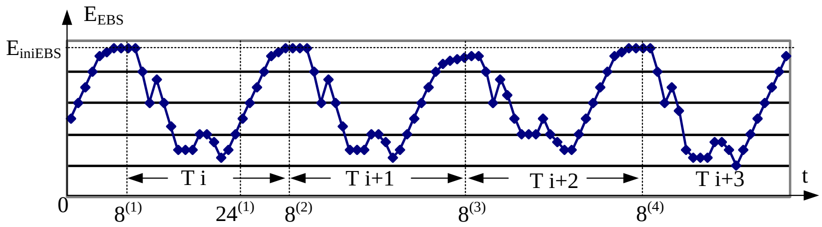
The generalized energy of CES is related to the current time t and the time interval T_j written as:

$$\begin{aligned} E_{CES}^{(T_j)}(t) &= E_{CES}^{(T_j)}(t)\Big|_{t=T_{j0}} - \sum_{i=1}^{n_{CES}^{(T_j)}} e_{CES\_i}^{(T_j)} + \sum_{k=1}^{n_{CES}^{(T_j)}} e_{EV\_k}^{(T_j)} + \sum_{l=1}^{m_{CES}} \int_{T_{j0}}^{t} P_{CES\_l}(t)dt \\ &= E_{CES}^{(T_{j-1})}(t)\Big|_{t=T_{(j-1)END}} - \sum_{i=1}^{n_{CES}^{(T_j)}} e_{CES\_i}^{(T_j)} + \sum_{k=1}^{n_{CES}^{(T_j)}} e_{EV\_k}^{(T_j)} + \sum_{l=1}^{m_{CES}} \int_{T_{j0}}^{t} P_{CES\_l}(t)dt \end{aligned} \tag{6}$$

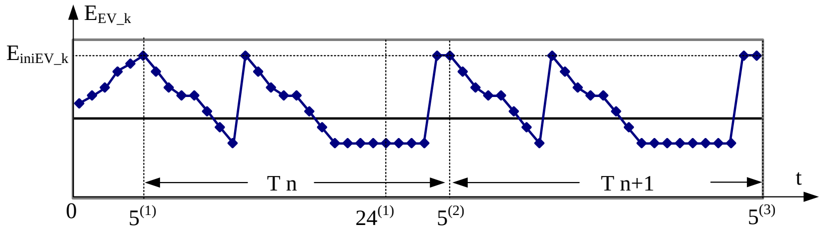
where $n_{CES}^{T_j}$ is the number of batteries installed on-board from CES in the time interval T_j, and $e_{CES\_i}^{(T_j)}$ is the energy of the ith one; $e_{EV\_k}^{(T_j)}$ is the energy of the kth battery uninstalled from EVs; m_{CES} is the number of converters in CES, $P_{CES\_l}(t)$ is the power exchanged between CES and the grid through the lth converter. Negative power implies that energy is transferred to the grid from CES while positive power implies that energy is drawn from the grid to charge the batteries in CES.



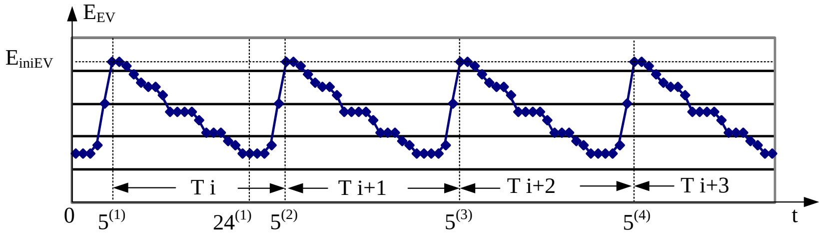
(a) Generalized energy curve of CES



(b) Generalized energy curve of EBS



(c) Generalized energy curve of single EV



(d) Generalized energy curve of EVs

Figure 8. Typical operation curve of generalized energy

Fig 8 shows the typical steady operation of CES, EBS and EVs in China according to people's travelling habits. The unit for the horizontal axis is hour. The vertical axis is the energy capacity of different systems and the peak value is the initial energy capacity of one period. It reveals the driving rule of the drivers and the changing trends of energy in CES and EBS in two or three cycles. The profiles of generalized energy in different cycles are not exactly the same, but some important time points must be controlled in the same energy level. For instance, if the generalized energy in the time point 5:00 is assumed to be the initial value of the day, named E_{iniCES}, it should be equal in different cycles.

The energy capacity of CES is directly related to the normal operation of IIS, and the following aspects should be considered: 1) the initial generalized energy of CES E_{iniCES} should satisfy EVs batteries exchanging requests even without the support of the grid; 2) CES is able to coordinate with the grid to provide auxiliary services such as peak shaving and valley filling; 3) E_{iniCES} is less than the maximum capacity of CES. Therefore, E_{iniCES} should satisfy the following inequalities.

$$\begin{cases} E_{iniCES} - \sum_{j=0}^{23}\sum_{i=1}^{n_{CES}^{(T_j)}} e_{CES\_i}^{(T_j)} + \sum_{j=0}^{23}\sum_{k=1}^{n_{CES}^{(T_j)}} e_{EV\_k}^{(T_j)} \ge E_{CES\min} \\ E_{iniCES} - \sum_{j=0}^{23}\sum_{i=1}^{n_{CES}^{(T_j)}} e_{CES\_i}^{(T_j)} + \sum_{j=0}^{23}\sum_{k=1}^{n_{CES}^{(T_j)}} e_{EV\_k}^{(T_j)} + \sum_{l=1}^{m_{CES}} \int_{t_0}^{t_1} P_{CES\_l}(t)dt \ge E_{CES\min} \\ E_{iniCES} \le E_{CES\max} \end{cases} \tag{7}$$

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

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

$$E_{iniCES} = E_{CES\max} \cdot (90\% + \varepsilon_{CES}) \tag{8}$$

In (8), ε_{CES} is a variable set by operators according to the load level and EVs batteries exchanging requests, where generally, $-5\% < \varepsilon_{CES} < 5\%$.

2) Generalized energy of the echelon battery system

The generalized energy of EBS is related to the current time t and the time interval T_j written as:

$$\begin{aligned} E_{EBS}^{(T_j)}(t) &= E_{EBS}^{(T_j)}(t)\Big|_{t=T_{j0}} + \sum_{l=1}^{m_{EBS}} \int_{T_{j0}}^{t} P_{EBS\_l}(t)dt \\ &= E_{EBS}^{(T_{j-1})}(t)\Big|_{t=T_{(j-1)END}} + \sum_{l=1}^{m_{EBS}} \int_{T_{j0}}^{t} P_{EBS\_l}(t)dt \end{aligned} \tag{9}$$

where m_{EBS} is the number of converters in EBS, P_{EBS_l} is the power exchanged between EBS and the grid through the lth converter. Negative power implies that energy is transferred to the grid from EBS while positive power implies that energy is drawn from the grid to charge the batteries in EBS.

It is important to remember that EBS can be controlled to work as energy storing device and provide auxiliary services to the power grid. According to the load profile of the grid, strategies are made for batteries in EBS to charge from the power grid before 8:00, and discharge to the grid according to the dispatching order after 8:00. Fig 8(b) shows the typical generalized energy profile of EBS.

In accordance with CES, the full discharge of batteries in EBS is not recommended. The initial value of generalized energy in EBS E_{iniEBS} is about 90% of $E_{EBS\max}$:

$$E_{iniEBS} = E_{EBS\max} \cdot (90\% + \varepsilon_{EBS}) \tag{10}$$

In (10), ε_{EBS} is a variable set by operators according to the load level, generally $-5\% < \varepsilon_{EBS} < 5\%$.

3) Generalized energy of EVs batteries on-board

The generalized energy of batteries on-board in time interval T_j can be written as:

$$\begin{aligned} E_{EV}^{(T_j)}(t) &= E_{EV}^{(T_j)}(t)\Big|_{t=T_{j0}} + \sum_{i=1}^{n_{CES}^{(T_j)}} e_{CES\_i}^{(T_j)} - \sum_{k=1}^{n_{CES}^{(T_j)}} e_{EV\_k}^{(T_j)} - \sum_{n=1}^{p_{EV}} \int_{t_0}^{t} W_{EV\_n}(t)dt \\ &= E_{EV}^{(T_{j-1})}(t)\Big|_{t=T_{(j-1)END}} + \sum_{i=1}^{n_{CES}^{(T_j)}} e_{CES\_i}^{(T_j)} - \sum_{k=1}^{n_{CES}^{(T_j)}} e_{EV\_k}^{(T_j)} - \sum_{n=1}^{p_{EV}} \int_{t_0}^{t} W_{EV\_n}(t)dt \end{aligned} \tag{11}$$

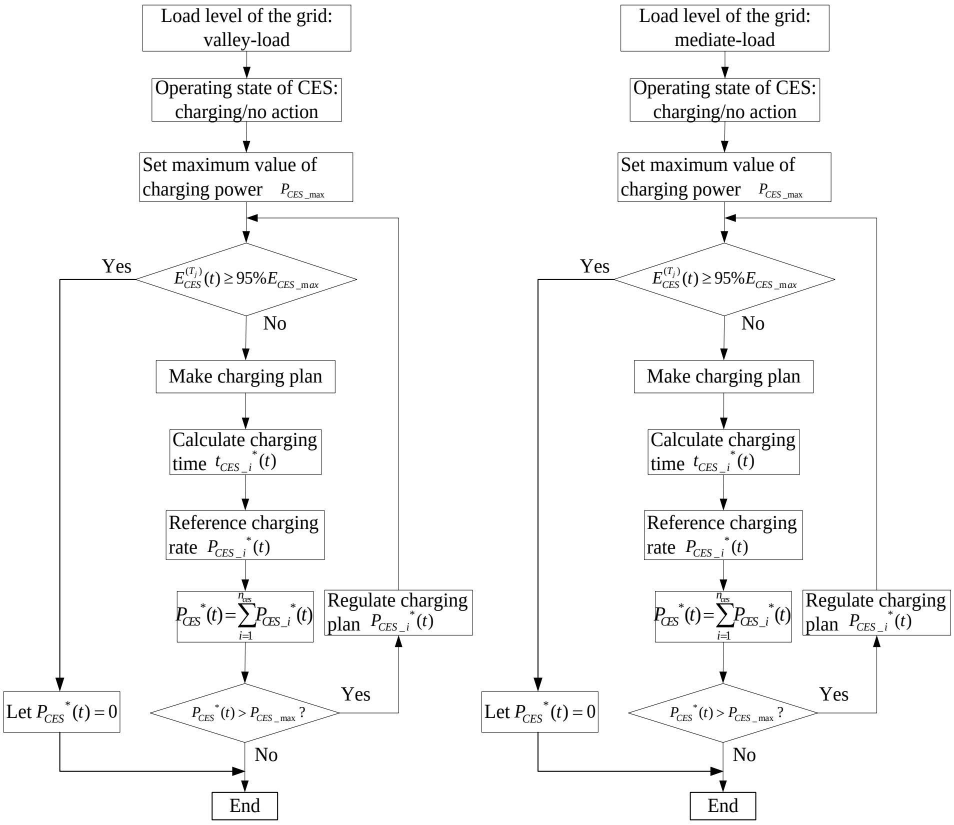
where, $n_{CES}^{(T_j)}$ is the number of batteries exchanged from CES in time interval T_j, $e_{CES\_i}^{(T_j)}$ is the energy of the ith battery exchanged from CES, $e_{EV\_k}^{(T_j)}$ is the energy of the kth battery replaced from EVs, p_{EV} is the number of EVs, $W_{EV\_n}(t)$ is the power consumed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

Fig. 8(c) shows the generalized energy curve of one single EV in which the battery is exchanged at 5:00 in every cycle. Suppose that all EVs batteries are exchanged at 5:00 every day, we can obtain the generalized energy of all EVs, as shown in Fig. 8(d).

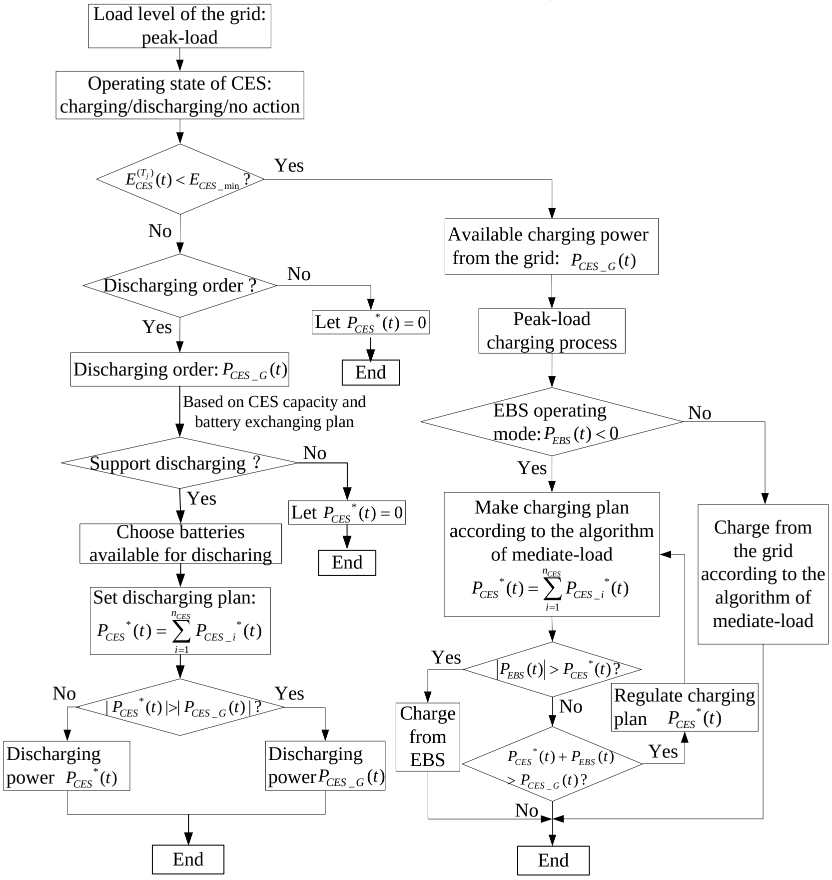
5. Dispatching Control of IIS

The energy capacity of IIS is directly related to the charging/discharging rate, i.e., the power required/available to charge/discharge the batteries in IIS. In scheduling the power exchange between IIS and the grid, cost minimization and service quality improvement are two conflicting aspects. On one hand, batteries charging behavior is optimized to minimize charging costs and to achieve satisfactory energy levels and optimal power balancing. Thus, batteries scheduling problem is formulated to fill/cut the electric load valley/peak as an optimal control problem. On the other hand, in order to improve the efficiency of batteries exchange and minimize the waiting time of EVs, batteries exchange requests forecasting for EVs is important for IIS to maintain satisfactory energy level.

It should be emphasized that the charging/discharging rate varies during the charging/discharging process depending on the SOC of batteries and price, except for the factors of grid condition and energy capacity of the IIS.



(a) During valley load periods (b) During mediate load periods



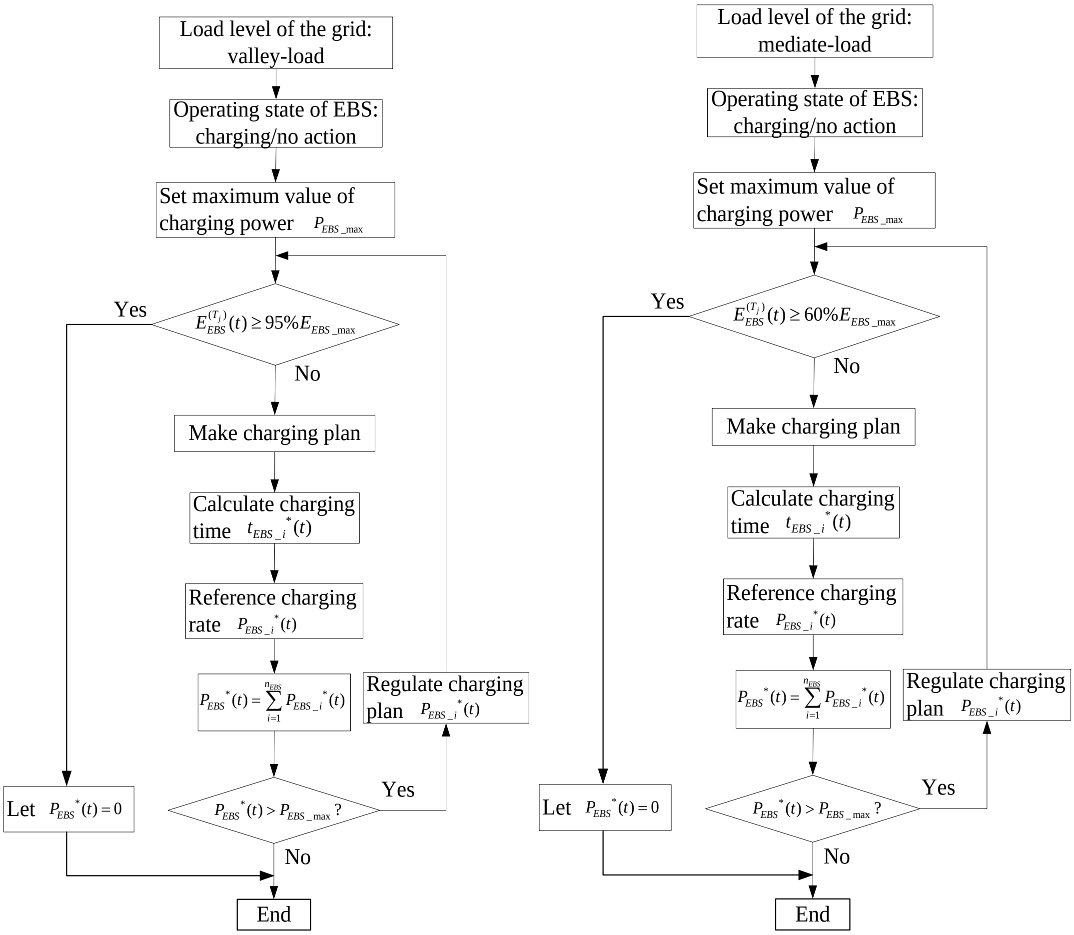
(c) During peak load period

Figure 9. Charging discharging algorithm of CES at different load status

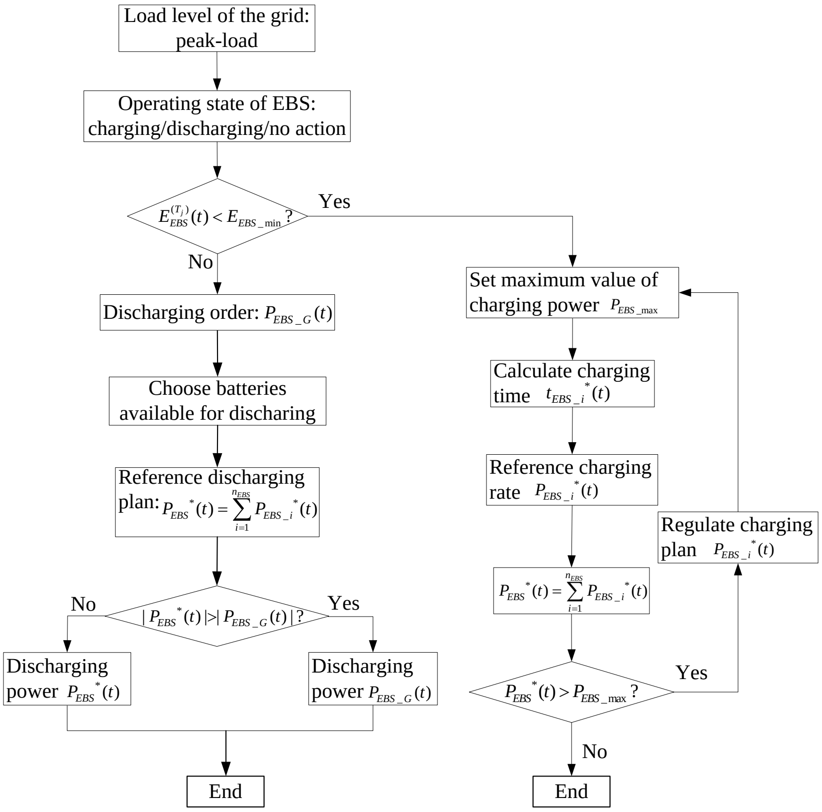
Therefore, a novel dispatching strategy is proposed considering both load curves and EV batteries exchanging demand to optimize the operation of IIS. Based on the current load level and operating mode of CES, Fig. 9 shows the charging/discharging algorithm flows of CES under different load conditions.

The energy capacity of CES and load level of the power grid are important factors in determining the charging/discharging of CES. Furthermore, the charging/discharging rate is closely related to EVs batteries exchanging requests. Fig. 9(a) shows the charging/discharging flowchart of CES during valley load periods. In this case, we will allocate as much power as possible from the grid to realize valley filling to the grid. This is because the power from the grid is free. Fig. 9(a) shows the charging/discharging flowchart of CES during mediate load periods. Under this condition, energy is drawn from the grid to charge the batteries in CES in limited power until all the batteries are in full capacity. During peak load periods, CES is able to discharge to the grid according to the dispatching order if the energy capacity is high enough, as shown in Fig 9(c). However, when CES operates in charging mode during peak load periods to satisfy batteries exchanging requests, it is optimal to charge from EBS other than the grid to maintain the normal operation of the gird. When the energy capacity of EBS is low enough, CES charges from the power grid in a reasonable charging rate, which is similar to the mediate load level condition.

Similarly, Fig. 10 shows the charging/discharging chart flow of EBS under different load conditions. EBS charges from the grid in different charging rate during valley periods or mediate periods. Moreover, the batteries in EBS are discharged during peak periods for shaving peak unless the energy capacity of EBS is poorly low.



(a) During valley load periods (b) During mediate load periods



(c) During peak load period

Figure 10. Charging discharging algorithm of EBS at different load status

Therefore, we can obtain the charging/discharging flowchart of IIS overall, as shown in Fig. 11.

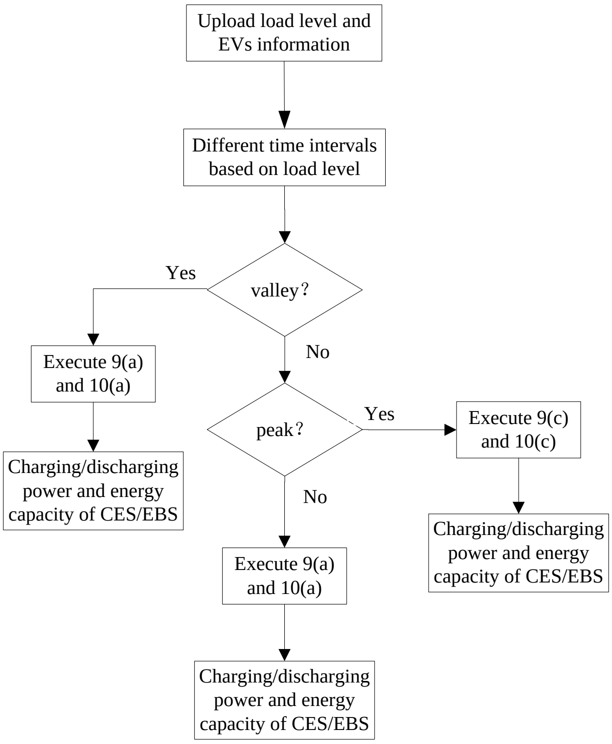


Figure 11. Charging discharging algorithm of IIS

Due to the high cost of electricity power during peak hours, batteries charging scheduling should avoid critical peak periods. Therefore, a prediction-based charging scheme is proposed. It predicts the load level based on information from the grid, thus able to control the charging rate according to the load level. The initial charging power $P^*(0)$ can be expressed by the relationship between the forecasting load curve $P^*_{\mathrm{G}}(t)$ and present load level $P_{\mathrm{G}}(0)$ written as:

$$P^*(0) = P_{\mathrm{c}} \cdot [2 - \frac{P_{\mathrm{G}}(0) \cdot T_{\mathrm{c}} / \Delta t}{\sum_{i=0}^{T_{\mathrm{c}}/\Delta t} P^*_{\mathrm{G}}(i\Delta t)}] \tag{12}$$

where, Δt is the time interval in dynamic forecasting, T_{c} is the available charging time, P_{c} is the rated charging power.

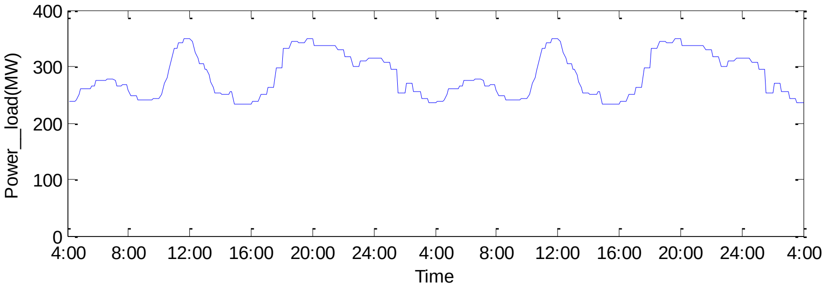
Based on the initial charging power $P^*(0)$ and the actual load level P_{G} at the time t, $t \in [0, T_c]$, the optimal charging power in time interval T_c can be obtained:

$$P^*(t+\Delta t) = P^*(t) - P_{\mathrm{c}} \cdot \frac{[P^*_{\mathrm{G}}(t+\Delta t) - P_{\mathrm{G}}(t)](T_{\mathrm{c}} / \Delta t)}{\sum_{i=0}^{T_{\mathrm{c}}/\Delta t} P^*_{\mathrm{G}}(i\Delta t)} \tag{13}$$

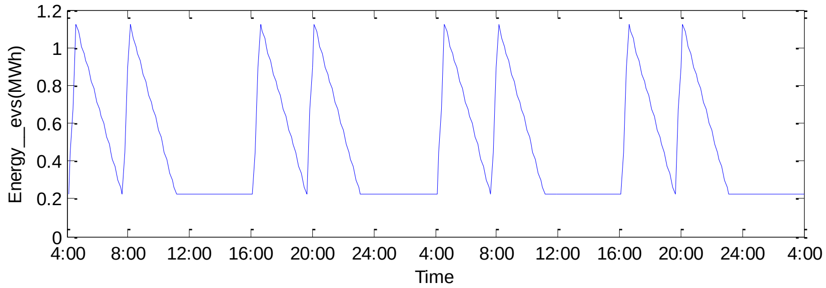
It is assumed that P_{c} and P^* are constants at time t. The regulation factor of charging power can be calculated by the deviation of forecasting load P^*_{G} at $t + \Delta t$ and actual load level P_{G} at t. Therefore, P^* in (13) can be derived.

6. Simulation Results of the Charging/discharging Strategy

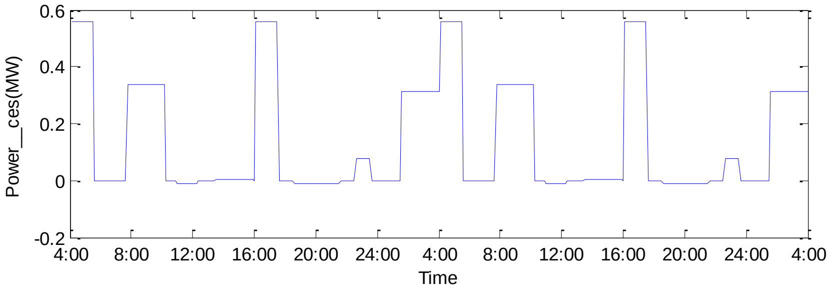
To check the effectiveness of the proposed charging/discharging strategy, dynamic load profile in two cycles is shown in Fig. 12(a) for simulation. 10 EVs were divided into two sets, each with 5 EVs. The first set exchanged batteries twice in one cycle: one was at 4:00, another was at 7:00. Similarly, the second set exchanged batteries at 16:00 19:00. Respectively, the EVs energy capacity is shown in Fig. 12(b).



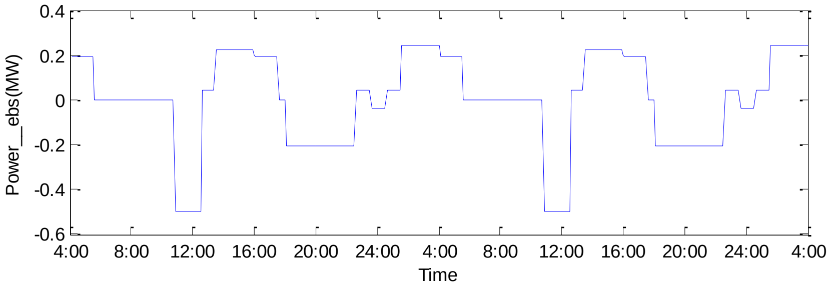
(a) load curve



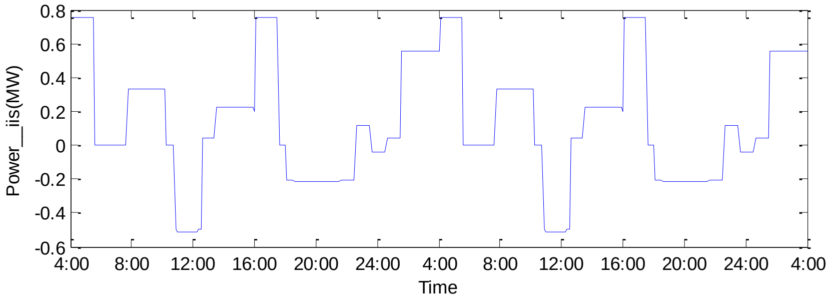
(b) energy curve of EVs



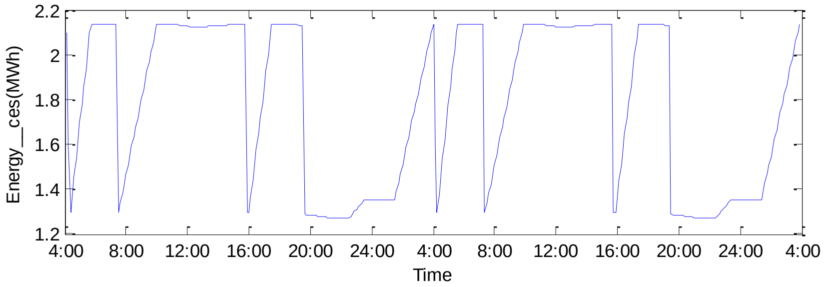
(c) charging/discharging power of CES



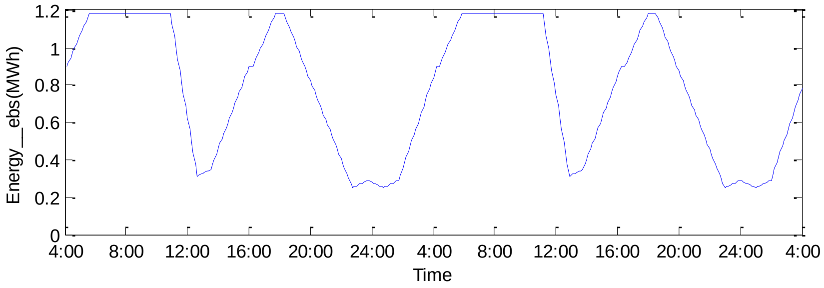
(d) charging/discharging power of EBS



(e) charging/discharging power of IIS



(f) energy capacity of CES



(g) energy capacity of EBS

Figure 12. Simulation results of the proposed charging/discharging strategy

The aim of this simulation was to evaluate the behavior of the IIS applied the proposed charging/discharging strategy, regarding battery exchanging requests and load level of the power grid.

Fig. 12(c) presents the operating results of charging/discharging flow in CES. Positive power implies that energy is drawn from the grid to charge the batteries in CES while negative power implies that energy is transferred to the grid from CES. Accordingly, the energy capacity of CES is shown in Fig. 12(f).

Operating results show that CES is able to satisfy batteries exchanging request, and at the same time it is capable of charging from the power grid during valley load periods to sustain its normal operation. We take the first time of batteries exchanging process for example. Due to EVs batteries exchanging request around 4:00, energy capacity of CES drops sharply, as shown in Fig. 12(f). In the meantime, the power grid operates at valley load period, CES charges from the power grid to get ready for the next batteries exchanging process.

Fig. 12(d) presents the operating results of power flow in the echelon battery system side. And the energy capacity of EBS is shown in Fig. 12(g). It suggests that EBS discharges to the grid from 11:00 to 13:00 and from 18:00 to 22:00 when the grid operates in peak load periods. In order to maintain the energy level of EBS no less than 20% of the initial value, EBS is required to charge from the grid during time intervals from 13:30 to 16:00 and from 2:00 to 5:00. Moreover, it charges from the grid in the maximum charging rate during the valley periods. Operating results show that the echelon battery system is capable of discharging to the power grid during peak periods, and at the same time it is able to charge from the grid during valley load periods to maintain its energy capacity.

Fig. 12(e) shows the power flow between the grid and IIS, it suggests that IIS can act as distributed energy sources to smoothen the load profiles by providing peak shaving and valley filling.

7. Conclusion

A novel EV’s intelligent integrated station has been presented in this paper. The most outstanding feature of this station is that EV batteries can be replaced within a short time and the batteries in IIS can be charged during off-peak periods. We analyzed the generalized energy in IIS to obtain the accurate information of energy capacity in EVs and IIS. Based on the load level of the grid and energy capacity of IIS, a novel charging/discharging strategy is introduced to make reasonable operation plans for IIS.

Based on the proposed control strategy, the simulation results indicate that the station operates in optimal charging and discharging process in the long run: (i) the charge exchange system charges from the power grid in rated charging power during valley periods, it charges in lower power during mid-peak periods or even discharges to the grid during peak periods, (ii) the echelon battery system works as an energy storage system by charging from the grid during valley periods and discharging to the grid during peak periods. Simulation results show that IIS can act as distributed energy sources to smoothen the load profiles by providing peak shaving and valley filling. The proposed charging/discharging strategy gives useful guidelines for the development of EVs energy supply, as well as the next-generation EVs charging station and smart grid management systems.

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