The applications of echelon use batteries from electric vehicles to distributed energy storage systems

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Abstract. Echelon use batteries from electric vehicles will bring not only the cost reduction of energy storage but also the social benefits of circular using of resource, energy conservation and emission reduction. It is an important echelon use orientation that retired batteries from electric vehicles are rebuilt into distributed energy storage systems. The article introduces 8 cases of distributed energy storage systems containing echelon use batteries, whose application scenarios include load shifting, renewable energy storage, frequency modulation of power system, and capacity charge management. In summary, the reconstruction of echelon use batteries is based on battery packs or modules in order to reduce the cost of their secondary development as much as possible because the advantage of echelon use batteries is low cost after all. Echelon use batteries should be used under the regime of low rate and/or shallow charge-discharge for the sake of their cycle life and safety. Besides, a set of distributed energy storage system containing retired batteries from ROEWE e50 electric vehicles was developed by us and its application effects in a distributed PV generation station was introduced. Ten 3P3S retired batteries modules with similar capacities are rebuilt a 5 kWh energy storage system with 50 V rated voltage, whose energy transition efficiency is about 88%. Energy storage applications of retired batteries from electric vehicles in distributed PV generation not only supply electrical loads with stable power, but also achieve peak shaving of solar electric power.

1. Introduction

Electric vehicle sales in China are continuing to increase substantially in recent years, due to the ongoing electric-car technology and the myriad incentives on offer in the country. Figure 1 shows electric vehicle sales in China between 2013 and 2017, displaying that electric vehicle sales have a growth rate of 53.25% in 2017 compared with 2016. China has become the number one electric vehicle population in the world.

Battery system is one of the core components of EVs and its cost accounts for about half of the total cost of an EV. With the repeated charging and discharging of the power battery of the electric vehicle, its battery capacity will continue to decline [1]. Generally, after 5-8 years of service of an electric vehicle, its battery capacity may decay to less than 80% [2], and the decrease in battery
capacity will result in more frequent charging and shorter travel distance [3]. In this case, it is necessary to replace with a new power battery to meet the normal driving requirements. Although the decommissioned power battery has declined in its capacity, it still has great value in other uses, such as serving as backup supply or renewable energy storage system [4,5]. The reuse of such decommissioned power batteries for energy storage will significantly reduce the cost of energy storage, and bring considerable economic benefits to energy storage users and good benefits to society [6]. On April 22, 2015, the Ministry of Finance and other three ministries and commissions in China jointly issued the Notice on Financial Support Policy for Promotion and Application of New-Energy Automobiles in 2016-2020 (the Ministries of Finance and Construction [2015] No. 134). The Notice specifies that automobile manufacturers and power battery manufacturers should undertake the main responsibility for recycling of retired batteries so as to make the recycling more orderly. From this it can be seen that it is urgent to research and reuse the retired EV batteries.

Figure 1. Electric vehicle sales in China between 2013 and 2017.

Figure 2 shows the life course of the power battery of electric vehicle. Generally, it is believed that when the state of health (SOH) of the power battery is 100%-80%, it shall be used as power supply for the electric vehicle; when SOH is 80%-40%, it shall be used in echelon, such as serving as mains lighting supply, communication power module and electric power storage; when SOH of the battery is reduced to less than 40%, it can only be disassembled into materials for recycling.

Figure 2. The life course of electric vehicle batteries.

This paper introduces several power battery system structures of electric vehicles and echelon use cases. On this basis, this paper introduces the distributed energy storage system (DESS) developed by us based on decommissioned battery of Roewe e50. Based on the coordinative application of DESS and roof-mounted PV power system, this paper analyzes the operation effect of the light storage system.
2. Typical cases of echelon use

2.1. Mitsubishi echelon use project

More than 100,000 Mitsubishi i-Miev electric vehicles have been sold worldwide since its launch in 2009. The battery pack of 2012 version i-Miev has a total capacity of 16 kWh and total voltage of 325.6 V, which is composed of 22 sets of modules. The modules have two kinds of specifications, of which one is composed of 8 cells, a total of 10 sets, and the other consists of 4 cells, 2 sets in total. The whole PACK has 88 cells (figure 3(a)). The cell of i-Miev is a square steel shell provided by GS Yuasa, with rated capacity of 50 Ah, rated voltage of 3.7 V, minimum voltage of 2.75 V and maximum voltage of 4.1 V.

Mitsubishi electric auto has cooperated with Tokyo Institute of Technology, etc. to carry out research on battery recycle. They built a 20 kW photovoltaic power generation system on the roof of a parking garage, and the energy storage system adopted is 5 sets of 16 kWh recycled batteries (discharge power of each battery is 3 kW) from i-Miev electric vehicles and five 16 kWh electric vehicles (discharge power of each vehicle is 3 kW) with charging and discharging functions (vehicle to grid) (figure 3(b)), aiming to use the electric vehicle batteries to reduce the peak electrical load of commercial building [7].

1. Ten modules, in which one is comprised of eight cells in series; 2. Two modules, in which one is comprised of four cells in series.

Figure 3. Battery pack of Mitsubishi i-Miev electric vehicle and its echelon use project.

2.2. Nissan echelon use project

More than 300,000 Nissan Leaf electric vehicles have been sold worldwide. The battery pack es (figure 4(a)). Each battery module is composed of two cells connected in parallel and two cells connected in series. The cell of Leaf is layered lithium ion battery which is provided by AESC automotive energy company, a joint venture of Nissan and NEC, with rated capacity of 33 Ah and rated voltage of 3.75 V. Each cell has energy density of 140 Wh/kg and power density of 2.5 kW/kg.

Figure 4. Battery pack of Nissan Leaf electric vehicle and its echelon use project.

Nissan and Sumitomo built a joint venture company to explore the recycling of decommissioned
power battery. In February 2014, the joint venture company developed decommissioned power batteries of 16 Nissan Leaf electric vehicles into a large-scale battery system for reuse, with a capacity of 600 kW/400 kWh to verify the smoothing effect of photovoltaic power output (figure 4(b)).

2.3. GM echelon use project
GM Chevrolet Volt extended-range electric car is the plug-in hybrid power vehicle that realized cumulative sales of more than 140,000 units. Chevrolet Volt extended-range electric car adopts the cylindrical lithium manganate battery of the company Compact Power Incorporated (CPI), with battery capacity of 15 Ah, voltage of 3.7 V, energy density of 150-200 Wh/kg and power density of 3-4 kW/kg. It consists of 288 cells that are integrated with temperature sensors and cooling elements in four main battery modules to form a 16 kWh battery pack with total voltage of 386.6 V (figure 5(a)). In order to maintain the service life of the battery, according to GM’s design, the lithium battery is set to charge up to 85% on the coulombmeter (SOC). When the battery is lower than the warning value (<25%), the internal combustion engine will start to charge the battery and keep the battery level at about 30% SOC, so the actual efficacy of the battery is about 8.8 kWh (16kWh × 55%).

Through cooperation with ABB, GM re-integrated five used batteries from the Chevrolet Volt extended-range electric vehicle into a 25 kW/50 kWh modular energy storage system that can supply power to 3-5 American ordinary families for 2h [8] (figure 5(b)). The system can store electric power from the grid at low-demand period to meet peak demand for electricity, thus saving costs for individual users and public institutions. The battery pack can also be used as a backup power source during power cuts and brownouts, and to store renewable energy sources such as wind and solar power.

2.4. BMW echelon use project
The global sales of BMW i3 battery electric vehicles are about 100,000 units. i3’s battery system had a total electricity of 22 kWh before 2016 and was upgraded to 33 kWh after 2016. Its energy density also increased by 50%, but the volume and structure of the battery pack remained unchanged. i3 battery pack is composed of 8 modules in series, and each module consists of 12 cells in series (figure 6(a)). The cells used by BMW are square Ni-Co lithium manganate batteries with aluminum shell provided by Samsung SDI, with rated voltage of 3.7 V and voltage limit range of 2.8-4.1 V. The cell capacity was 60 Ah before 2016 and is 94 Ah after 2016.

BMW and Beck Automation jointly developed the i3 EV used battery household energy storage system [9] (figure 6(b)), which is compatible with new battery packs and used battery packs that cannot serve as power battery for vehicles. Compared with other energy storage systems, this system has more value in increasing the use of renewable energy and thus reducing the purchase of electricity from the grid, such as saving the energy of solar panels for home use. In addition, this energy storage system will integrate with charging stations that users may use in garages to charge BMW i3 by using
stored solar energy. BMW i-series lithium ion batteries have two capacities including 22 kWh and 33 kWh, which can meet the electricity demand of the average American family for up to 24 hours.

![Figure 6. Battery pack of BMW i3 electric vehicle and its echelon use project.](image)

2.5. **Toyota echelon use project**

Toyota has sold more than 10 million Prius hybrid electric vehicles worldwide, most of which are non-plug-in hybrid electric vehicles. The battery used has a small capacity. One of its functions is to recover part of the energy under the deceleration and braking conditions of the vehicle. The other function is to supplement the power output of the engine itself by using the motor to drive the wheels when the vehicle is accelerating or under a heavy load.

Every battery pack from Camry hybrid electric vehicles is composed of 70 lithium ion batteries in series, with total electricity of 1.036 kWh (figure 7(a)). Each lithium ion battery has a capacity of 4Ah and a rated voltage of 3.7 V. In 2015, Toyota used the decommissioned battery packs for energy storage of PV power in USA Yellowstone National Park (figure 7(b)) and re-designed the energy storage battery management system [10]. 208 Camry battery packs can store 85 kWh of power, equivalent to 0.4087 kWh for each Camry battery pack, which extends the battery’s service life to three times. Assuming that the capacity of decommissioned battery has reduced to 80%, then, the decommissioned battery can store energy of 0.8288 kWh. Considering the performance degradation of decommissioned batteries, the depth of discharge (DOD) of the energy storage system is controlled in 50% (0.8288 kWh × 50% = 0.4144 kWh, approximate to 0.4087 kWh).

![Figure 7. Energy storage application of retired battery modules from Toyota Camry hybrid vehicle at PV generation station in USA Yellowstone National Park.](image)

3. **Roewe e50 echelon use project**

3.1. *The configuration of energy storage system of retired batteries from Roewe e50*

Roewe e50 electric vehicles adopted A123 Systems nanoscale lithium iron phosphate as cell material with high power performance before 2016. The battery system has total electricity of 18 kWh, total
voltage of 300 V and total capacity of 60 Ah (figure 8(a)). It is composed of 7 modules, of which three large modules adopt 3 cells connected in parallel and 27 in series (5.184 kWh), and 4 small modules adopt 3 cells connected in parallel and 3 in series (0.576 kWh), that is, 279 cells in total with 3 in parallel and 93 in series. Every cell capacity is 20 Ah, with rated voltage of 3.3V and energy density of 135 Wh/kg.

This energy storage system based on echelon use batteries adopts 3P3S decommissioned batteries from Roewe e50. After capacity recalibration, 10 modules with similar capacity are selected. Every 5 modules were connected in series to form 1 PACK, and then the two PACKs were connected in parallel to form a battery pack with rated voltage of 50 V, rated capacity of 100Ah and total electricity of 5 kWh (figure 8(b)). The battery management system (BMS) hardware is mainly composed of battery module management unit (BMU), battery cluster management unit (BCMS), local monitoring unit (HMI) and DC monitoring unit (DMU). BMS adopts the two-level management mode. The first-level management unit is BMU responsible for collecting and managing the voltage, current and temperature information of cells and uploading such information to BCMS, as well as managing cells in the module to realize the real-time monitoring of cells. The second-level management unit is BCMS (Battery cluster management unit) responsible for collecting the voltage, current, temperature and other information of all batteries in the battery cluster and uploading such information to HMI, as well as managing batteries in the battery cluster. The bi-directional inverter is controlled by a 3.7 kW inverter control all-in-one machine. On the one hand, the inverter control all-in-one machine can charge the battery by directly using the photovoltaic DC input through the controller, then convert direct current of the battery into alternating current (220 V, 50 Hz) for the load; on the other hand, the inverter control all-in-one machine can directly convert the photovoltaic DC input into alternating current for the load. If the photovoltaic system fails to generate electricity, the energy storage system can be connected to the electricity grid to charge the batteries. The inverter control all-in-one machine can realize automatic switch over between grid-connection and grid-disconnection.

3.2. The cooperation of the photovoltaic-energy storage system of retired batteries

Figure 9 shows the power curve of the photovoltaic-energy storage system under charging and then discharging conditions. The test was conducted on a sunny day and the photovoltaic system on the inverter was set in self-generation and self-use mode. The initial SOC of the energy storage system of decommissioned batteries was 0. First, the photovoltaic system charged the energy storage system, and after being fully charged, the energy storage system, together with the photovoltaic system, supplied power for 1 kW load. On this day, the gross generation of the photovoltaic system was 6.73 kWh, the total power consumption of the load was 4.55 kWh, the energy supply volume of the electric grid was 0.04 kWh, and the conversion efficiency of the energy storage system was 67.01%. Therefore, the battery got 4.76 kWh from photovoltaic system and discharged 4.20 kWh, the conversion efficiency of the energy storage system was 88.24%. Through compatibility with the photovoltaic power station,
stable power supply can be provided for the load.

Figure 9. Power diagrams of a hybrid system containing PV and retired batteries in the pattern of charging firstly and discharging secondly.

Figure 10. Power diagrams of a hybrid system containing PV and retired batteries in the pattern of peak shift.

Figure 10 shows the power curve of the photovoltaic-energy storage system in peak load shifting mode. The test was conducted on a day with abundant sunlight and the photovoltaic system on the inverter was set in self-generation and self-use mode. The initial SOC of the energy storage system of decommissioned batteries was 40%, with 2 kWh electricity. From 6:00 and 8:00, photovoltaic power was all used to charge the battery; from 8:00 to 14:20, 1kW electricity load was connected, and at this time, the photovoltaic power supplied power to the load and the rest photovoltaic power was stored in the energy storage system; from 14:20 to 18:17, as the light intensity decreased, the photovoltaic system and the energy storage system were automatically adjusted to supply power to the load simultaneously to maintain 1 kW using electric power. On this day, the gross generation of the photovoltaic system was 8.42 kWh, the total power consumption of the load was 9.24 kWh, the energy supply volume of the electric grid was 0.48 kWh, and the gross efficiency of the photovoltaic-energy storage system was 84.07 %. Thereinto, the photovoltaic system charged the battery by 2.81 kWh, so in addition to the original 2 kWh, the energy storage system stored electricity of 4.81 kWh in total. The battery discharged 4.26 kWh, so the conversion efficiency of the energy storage system was 88.57%. The energy storage system, through compatibility with the photovoltaic power station, not only can supply stable electricity supply for the load but also can realize the shifting for utilization of photovoltaic power at low demand hours to peak hours.

The cycle life of retired batteries is a concern. In general, retired batteries have a cycle life of more than 5 years if the charge/discharge rates are smaller than 1/3 C and the depth of discharge is less than 80%.

4. Conclusions

- Electric vehicle decommissioned batteries with a residual capacity of about 80% still have great echelon use value. Decommissioned batteries can be reintegrated into a distributed energy storage system to extend their service life. This can reduce the cost of electric vehicle batteries on the one hand, and reduce the cost of power energy storage one the other hand.
- Ten of 3P3S decommissioned battery modules from Roewe e50 with similar capacity were reintegrated into a decommissioned battery energy storage system with rated voltage of 50 V, total electricity of 5 kWh and conversion efficiency of about 88%. The energy storage system, through compatibility with the photovoltaic power station, not only can supply stable power for the load but also can realize the shifting for utilization of photovoltaic power at low demand hours to peak hours.
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