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Development of a converterless energy management system for reusing automotive lithium-ion battery applied in smart-grid balancing

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A B S T R A C T

To reuse lithium-ion battery scrapped from electric vehicles in accumulating off-peak electricity at night and unstable renewable energies is regarded as an effective way of extracting the residual capacity in scrapped automotive battery pack. However, decay of life cycle in such reused lithium-ion battery is an issue. In this study, a simple converterless energy management system is developed for controlling the power flow. One physical battery of ultracapacitor is used to couple with energy management system. It functions in the supply of peak power so that to ease the deviation of voltage drop. Two types of lithium-ion batteries ($LiFePO_4$ and $LiMnNiCoO_2$) in electric vehicles are utilized and imposed US federal driving pattern for simulating random use in urban area. Assessment of energy management system is conducted through the bench test of monitoring the voltage drop of battery pack. In addition, a real-time simulator is developed for optimizing current sharing ratio between battery pack and ultracapacitor for minimizing voltage drop, and then compared with bench-test results. In conclusion, energy management system improves up to 50% reduction of voltage drop in the case of $LiMnNiCoO_2$, and much effective than passive control. A rough estimation by calculating the relative effect of elongating life cycle is up to 145% than original usage without energy management system. This study enables us to confirm the performance of converterless energy management system used in scrapped lithium-ion battery pack for reusing in smart-grid energy balancing.

1. Introduction

Now, more than 1.15 Million Electric Vehicles (EVs) on its roads today in the world (IEA, 2016). The first Lithium-ion Battery (LIB) is commercialized in 1991, and today LIB has become the most promising product growing in the application of EVs. Even they are scrapped from vehicles, but there is still available for energy balancing in thermal power plant due to their residual electrical capacity (Ahmed et al., 2014). However, life cycle of LIBs becomes short because geometrical structure of battery is possibly damaged by cycling use. This may be due to peak current harm structure of LIB and decrease its effective capacity as well (Liaw et al., 2005).

A huge amount of lithium-ion batteries that will be coming out of electric vehicles in the coming years. These LIBs can still provide energy storage services due to their significant capacity. Also, these batteries are big and heavy assets with a hazardous waste designation. Consequently, either of views on economics or environment these scrapped LIBs of EV should be reassembled (Schneider et al., 2009), reused (Andrijanovits et al., 2012; Yang et al., 2012; Diaz-Gonzalez, 2012) or recycled (Paulino et al., 2008) by suitable ways. For instance, one example is for purpose of energy balancing in smart grid (Khasawneh and Illindala, 2014; Debnath et al., 2015; Zhou et al., 2014; Murillo et al., 2014; Tabari and Yazdani, 2014). Scrapped LIBs of EV allows the generation of electricity to be decoupled from the demand. Renewable energies can be stored until it is needed in a scheme known as load shaving. In contrary to LIB, ultracapacitor is a physical battery with ultra-long life cycle, and capable of discharging and charging sudden peak power. Some studies have been conducted to combine the advantages of LIB and

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ultracapacitor (Carter et al., 2012; Faggioli et al., 1999; Cheng et al., 2006; Pay and Baghzouz, 2003; Matthew and Bill Kramer, 2002; Omar et al., 2010; Kawashima et al., 2009; Lu et al., 2007). However, how to compromise the cost and performance is an issue. The effect of life cycle extension on LIB is discussed in by the transient supply of ultracapacitor (Faggioli et al., 1999). From economic aspects it's cost-effective and reasonable in elongating life cycle of LIB (Pay and Baghzouz, 2003). For the control of energy flow between LIB and ultracapacitor, a smaller prototype of DC-DC converter and simple circuit has been proposed (Matthew and Bill Kramer, 2002; Omar et al., 2010) in replace of traditional large DC-DC converter in multi-battery pack. The scenarios of usage includes the regenerative braking, auxiliary power supply, and charging/discharging between individual LIB and ultracapacitor. Specific control strategies such as neutral network are illustrated in (Kawashima et al., 2009; Lu et al., 2007; Ortúzar et al., 2007). Some studies are focus on the design of leveling DC-DC converter (Cao and Emadi, 2012; Kasuga and Ohnuma, 1995) and a converterless multi-batteries pack for EV is introduced based on a direct use of inverter (Grbovic et al., 2010; Di Napoli et al., 2002). They imply the possibility of high efficiency and low cost of multi-battery pack. In particular, a possible solution for reusing LIB's pack be provided for extension of life cycle (Rosenkranz, 2003).

To consider energy usage of smart grid in a daily basis, there are three basic requirements, such as storage of unstable renewable energies, shaving for peak power demand, and economic control of battery discharge into grid, as shown in Fig. 1(a) and (b). Energy management system (EMS) is developed for controlling power flow of LIB in avoiding the overload and keeping effective use of renewable energies. Here, ultracapacitor is also used for supplying instantaneous demand power, and capable of accumulating of regenerative electricity of EV or leveling renewable energies in smart grid (Gee et al., 2013).

In this study, a converterless, cost-effective EMS is developed for managing power flow in scrapped LIB's pack. Deviation of voltage drop in scrapped LIB is monitored in the bench test to know the performance of applying EMS and ultracapacitor. The ratio of sharing current of ultracapacitor is selected by real-time simulator.

2. Topology of EMS

In this study, Pulse Width Modulation (PWM) with control of duty cycle is applied for selecting current sharing ratio between LIB and ultracapacitor. It's simple and cost-effective than existing cases by using DC-DC converter in reusing LIB in smart grid. Ultracapacitor is directly connected with EMS for supplying instantaneous power flow, and particularly improving life cycle of LIB.

For establishing one basic module for energy balancing in smart grid, a battery pack with rated voltage of 75 V is selected to be a basic unit for system integration. Fig. 2 shows the simple circuit of EMS applied in this study. It's developed to achieve active control by switching individual current sharing ratio (duty cycle) either LIB or ultracapacitor per unit time. If the sharing ratio per unit time of LIB is 40%, then ultracapacitor load become 60%. The optimized sharing ratio (duty cycle) is stationary, and should be chosen by a real-time simulator in advance. A prototype is shown in Fig. 3. Loading power pattern as shown in Fig. 4 is one cycle of US FTP-75 driving pattern by assuming the maximum power 15 kW by assuming the maximum demand of home use. As shown in Fig. 2, four scenarios of power flows controlled by EMS in smart grid are listed below:

1. LIB charges ultracapacitor;
2. LIB//ultracapacitor discharges under optimized duty cycle;
3. Ultracapacitor discharges;
4. Off-peak power charges LIB or ultracapacitor decided by the immediate voltage.

3. Real-time simulator for optimizing sharing ratio

Real-time simulator has been widely used in developing and verifying control strategy for EV. It becomes a powerful platform before on-board test. Total analytical modules including EMS module is employed in the simulator. More detailed topology refers to (Wu et al., 2009, 2010). In system level, the control strategy from vehicle side for the powertrain related to the Area Electric Range (AER) is validated (Wu et al., 2010). Through vehicle side, commands of torque and speed are sent out to demand side of motor simultaneously. Likewise, commands for gear shifting commands, the auxiliary system, protection signals, etc. are passed from vehicle side to other control units. It is originally developed in the environment of OPAL-RT®. An imaginary vehicle module is linked with the simulator via analog/digital I/O interface, CAN bus and RS-232. The off-line environment connected to real-time simulator provides sufficient capability for the development of EMS to select the optimized current sharing ratio between LIB and ultracapacitor. The environment and interface to model the dynamic response of EV, multi battery pack or EMS is shown in Figs. 5 and 6.

For the verification of analytical module belong to EMS in simulator, the brief control strategy is outlined below:

- LIB provides the major power when current demand is lower than 60% of rated value.
- Ultracapacitor provides the major power in the case of current demand is higher than 60% of rated value.
- Brake regenerative system has efficiency of 50% conversing mechanical energy to electrical energy. The default regenerative energy or renewable energies are stored in ultracapacitor.

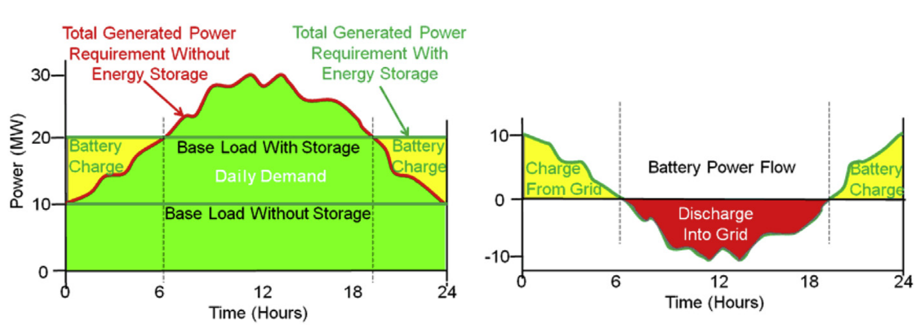

Fig. 1. (a) and (b): Load leveling of smart grid (mpoweruk).