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An Innovative DOSBAS® Battery System for Electric Vehicles Based upon Lithium Iron Phosphates Chemistry

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Abstract

In the development process of electric vehicles, the design of battery systems has long been the most challenging problem due to high energy density and high power density requirements. To date, the problem has been alleviated in hybrid electric vehicles because the employment of internal combustion engines replenishes the energy deficiency of batteries available in today's market. However, the advent of lithium ion chemistry may circumvent the difficulties in design of battery systems for electric vehicles. The safety issues of lithium ion chemistry still concern the public in the past few years due to reported accidents either in the lab or on the road. In this paper, a fault-tolerant battery system consisting of small-format cylindrical cells based upon lithium iron phosphates chemistry is investigated with design details and experimental verifications.

Keywords: Lithium Battery, Safety, Battery Management, Secondary Battery.

1 Introduction

Since more than half a century ago, electric drive technologies have gradually gained significant attention from both government and industry because of the forecast for shortage in oil-production and global weather warming. Along with Toyota promoting her HEV, namely Prius, to the market, many auto manufacturers are showing their future cars based upon FCEV, HEV, or EV platform. However, the key decision for mass production of these future cars has yet to be made due to a lack of availability of mature energy storage technologies. Since secondary batteries are essential for both HEV and EV development, many types of chemistry have been proposed and tested in the past decades. Not until recently, lithium ion battery technology has been carefully investigated because of its characteristics include [1]:

- High gravimetric and volumetric energy densities
- Ambient temperature operation
- Long life cycle
- Good pulse power density

Although there are many "high voltage" cathode materials being tested continuously in the past years, $LiCoO_2$, $LiNiO_2$ and $LiMn_2O_4$ are the most commonly reported potential chemistries [2]. Among the various chemistries, Zaghib *et al* [3] recently reported that C-$LiFePO_4$ is one of the most promising technologies because its charge and discharge properties at high operating temperature could circumvent the problems of thermal runaway. Table 1 shows comparisons of the general characteristics among C-$LiFePO_4$, $LiMn_2O_4$ and $LiCoO_2$ available for the market today. Nonetheless, when battery cells are packed into battery systems, Performance Safety and Abuse Test must be conducted on the systems to characterize the responses of integrated battery system to expected and worse-case accidents and abuse situations. Under no circumstance, the battery systems under test should burst into flames or combustible fumes. Table 2 compares the mechanisms of decomposition between $LiCoO_2$ and C-$LiFePO_4$ chemistry which indicate potential hazards still existent due to internal short-circuit situations. Hence, it is noted that safety protection devices must be installed in the battery systems if higher safety standard is adopted for the battery systems in HEV or EV applications.

In this paper, a patented DOSBAS® safe battery system is introduced and investigated for illustration of protection mechanisms on thermal runaway or fire hazard [4]. The DOSBAS was named as DOnald Safe BAttery Systems first studied in 2005 and then proposed for EV battery packs by Dr. Wu in 2007. The main feature of the system is to protect each cell in the system individually by a serially connected quick-blown fuse with or without a LED indicator. The protected cells are then connected in serial or parallel configuration or encapsulated the parallel or serial battery cells by a prismatic plastics box or together with a voltage balancing circuit. The proposed system can further enhance the inherent safety of the C-$LiFePO_4$ chemistry or different battery chemistries to a road-worthy level. In addition to the robustness in safety of the DOSBAS® battery system, the total cost of system is significantly reduced by replacing the isolated malfunction-cells in the battery system during maintenance services. As compared to the battery systems packed with large format cells, standard format cells, such as 18650 or 26650 cells, or even lithium polymer cells can be employed in the system for reducing costs and enhancing reliability. The DOSBAS® safe battery system is devised as a trade-off of performance, safety, reliability and costs in the battery systems for EV or HEV applications.

2 Cell Performance

In the development history of lithium ion battery cells, both cylindrical and prismatic cells are mass produced for commercial applications in camcorders, cellular phones and notebook computers. More recently, many pilot projects have been launched for the tests of large format lithium ion cells in HEV and EV applications. Nevertheless, there has been no official report for the inauguration of commercial implementation of technology up to date. The rationale may be the concerns for the safety and reliability of large format cells are still needed to be completely studied and verified before any decision can be made for the technology. On the contrary, the production technology for the standard 18650 cells has been widely accepted as the mature technology for small format implementation. In the mean time, standard 18650 cells based upon C-$LiFePO_4$ chemistry have been successfully mass produced by a handful of manufacturers in the world.

For example, Fig. 1 illustrates the remained capacity versus cycle number on standard 18650 cells mass-produced by PHET Co. in Taiwan; and, the test data were measured under 2C charge and 10C discharge conditions. It is noted that the standard 18650 cells can survive more than 1,100 cycles even under high rate of discharge conditions. Under standard battery test requirements, nail-penetration test was adopted for benchmark of the standard 18650 cells in $LiCoO_2$ chemistry. The results are shown in Fig. 2 with heavy smoke and flame after the test. On the contrary, the same test conducted on the C-$LiFePO_4$ cells shows that little smoke and no flame was observed as shown in Fig. 3.

3 Battery Packs for HEV/EV

As descried in the introductory section, the DOSBAS® battery system could isolate any over-heated cell(s) caused by internal short-circuiting via a fuse device, and, it certainly would help salvaging the normal cells from thermal runaway of the system. Figure 4 shows the photographic picture of an example of DOSBAS® battery system with outer casing removed. In the picture, the red circle illustrates a fast-blown fuse with a LED indicator being connected to a standard cell inside the system. The system could not only prolong the cycle life of the battery pack also prevent injury to the occupants by blocking damaged cells due to external impact accidents. Because of the simplicity in structure, the DOSBAS® battery system has been proven to be able to withstand vibration and weather conditions by putting the system without casing through 150 hours in a salt mist chamber. For benchmark comparisons shown in Fig. 5, a battery pack was put to short-circuiting test with final thermal runaway temperature reaching at 309 degree C. The results would be devastating if large number of cells were assembled into a battery system. However, a DOSBAS® battery pack safely passed the short-circuiting test with no temperature increase and cell damage as shown in Fig. 6. As a further step, a DOSBAS® battery pack was drop-tested to simulate external impact forces as shown in Fig. 7. In this case, no thermal runaway was noted with fuses blown by the damaged cells and low residual pack voltage.

Ultimately, a fleet of twenty-three electric vehicles has been road-tested with an average mileage of 9,868 km in Asia and Europe from August, 2007 to January, 2009. Figure 7 shows one of the EV being road-tested in Taiwan. The EVs have been assessed under various weather conditions for road performance, life expectancy, and safety reliability. It should be further noted that by installing a voltage balance board (VBB) between the positive and negative terminals of each battery pack for overcharge prevention, a battery management system (BMS) for charging and discharging status management is redundant. Hence, none of the twenty-three EVs in the fleet has been equipped with the BMS. Up to date, the test results have comprehensively proven that all the battery packs successfully retraced the expected retained capacity compared to the testing-conditions in the laboratory. The above results are obtained by periodically sampling standard 18650 cells from the test fleet for laboratory analysis.

As a further step, on one of the vehicles with accumulated mileage over 15,000 km, a handful of standard 18650 cells, parallel connected inside different battery packs, from the battery packs were purposely replaced with new cells typically with lower impedance. The preliminary results have shown that the new cells blended into the existing battery packs without noticeable change in the autonomy per charge on the vehicle even though the new cells are lower in impedances. It is evident that the above treatment could be very challenging for battery packs consisting of large-format cells without protection device on the cells. Helped by the DOSBAS$^{®}$ battery system, replacement of battery cells damaged by internal short-circuiting or depleted in early cycle-life could be practically accomplished. It is still debatable that with the help of today's most advanced BMS, battery systems consisting of large-format cells would require cumbersome services for cell replacement. After going through available tests in the factory, the DOSBAS$^{®}$ battery system has been proven to be one of the most promising battery systems for electric vehicles today.

4 Discussions and Conclusions

In conclusions, the development of lithium ion batteries for HEV and EV applications may not have come to the final stage; however, safety design and protection devices must be carefully evaluated since both the energy and power density of the batteries could lead to potential hazards under abnormal operating conditions. The proposed DOSBAS$^{®}$ battery system provides not only a cost effective solution for meeting the current regulations but also a feasible engineering design for mass production in the relevant applications. Up to date, the DOSBAS$^{®}$ battery systems have been pre-configured into various specifications in voltage and amp-hours with embedded battery balance boards as shown in Fig. 8. Moreover, the battery systems have been installed on a fleet of EVs for the purposes of evaluation on performance, endurance, and safety issues. Based upon the collected data from various sources, the preliminary test results are very satisfactory and promising because significant improvements on safety and reliability have been achieved on all kinds of power-train platforms. The proposed DOSBAS$^{®}$ battery systems could serve as one of the promising battery systems for the current and future HEV and EV applications.

Table1: Comparisons of basic characteristics among various lithium ion chemistries

Lithium ion chemistry	Volumetric energy density (Wh/l)	Gravimetric energy density (Wh/kg)	Cycle Life	Storage Temperature (C)
C-$LiFePO_4$	181	90	2,000	60
$LiMn_2O_4$	232	101	300	50
$LiCoO_2$	310	124	500	50

Table 2 : Comparisons of decomposition mechanism between $LiCoO_2$ and C-$LiFePO_4$ chemistry

Temperature (C)	90-250	170-230	250-300	> 300
$LiCoO_2$	SEI decomposition LiC_6/EC/DMC reaction	Oxide decomposition	LiC_6/PVDF reaction	Combustion in flame
C-$LiFePO_4$	SEI decomposition LiC_6/EC/DMC reaction	No	LiC_6/PVDF reaction	No

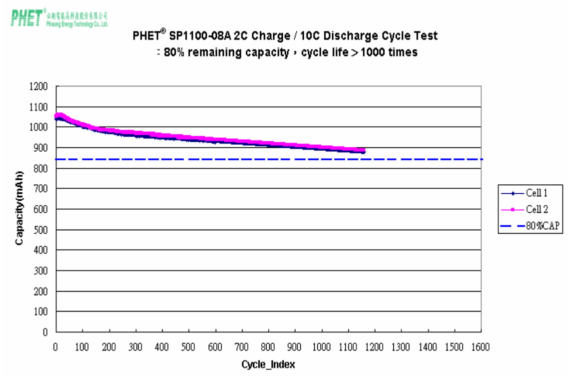

Figure 1 Cycle test results on the lab bench for standard 18650 format cells conducted under 2C charge/10C discharge conditions; the blue dotted line is the 80 % SOC line.

Figure 2 Photographic picture of nail-penetration test on a standard 18650 cell made of $LiCoO_2$, $LiMn_2O_4$ chemistry; heavy smoke and flames being observed.

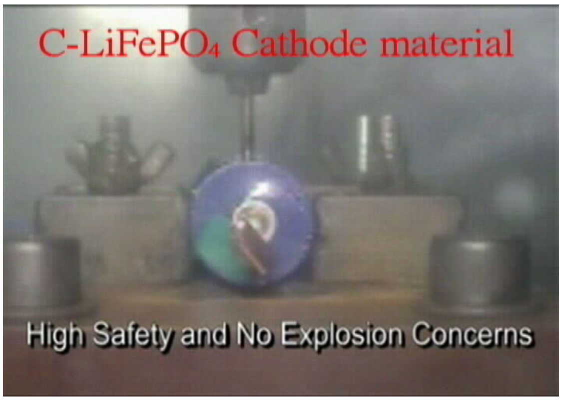

Figure 3 Photographic picture of nail-penetration test on a standard 18650 cell made of C-$LiFePO_4$ chemistry; little smoke and no flame being observed.

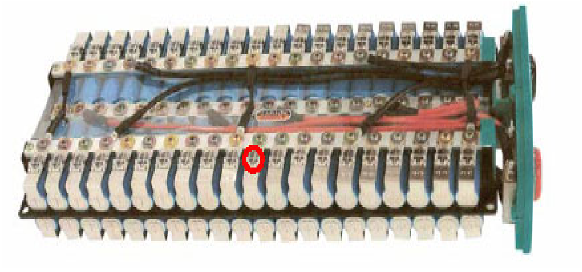

Figure 4 Photographic picture of a typical battery system with casing removed for showing a protection device in series with each cell; the device being indicted by a red circle.

Figure 5 Photographic picture of a battery pack assembled with 10 cells in C-$LiFePO_4$ chemistry being short-circuit tested with thermal runaway results; the final cell temperature being at 309 C as indicated on the thermometer.

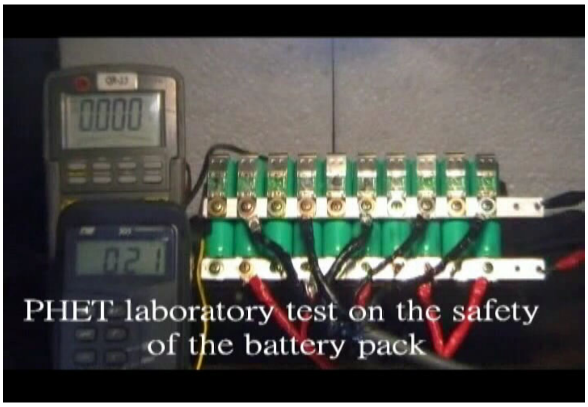

Figure 6 Photographic picture of a DOSBAS® battery system assembled with cells in C-$LiFePO_4$ chemistry being short-circuit tested with no increase in cell temperature and visible cell damage except the blown fuses.

Figure 7 Photographic picture a DOSBAS® battery pack safely passed the drop-test for simulating external impact forces; 0.426 volt of residual voltage being measured on the pack.

Figure 7 Photographic picture of an electric car powered by the DOSBAS® battery system configured for 72V and 120AH under the hood.

Figure 8 Photographic picture of two battery packs assembled for 12V and 24V applications embedded with the DOSBAS® system and voltage balancing boards on top of the packs.

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Dr. Donald P.H. Wu has been an inventor, engineer and company founder in Taiwan. He is currently the president of Pihsiang Machinery Manufacture Co., the world largest medical electric-scooter manufacturer, and the chief executive officer of PHET Co., the largest battery manufacturer using the World Pat. C-LiFePO$_4$ cathode materials.