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Verification of Ultra capacitor-Battery Cross breed Energy Storage Systems Connected in Electric Vehicle Based on Real-time Simulations

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Abstract-In this study, a paralleling Ultracapacitor-Lithium-Ion-Battery(UC-LIB) Hybrid Energy Storage System(HESS) with rated voltage 75V is established for pure electric vehicle(EV). An Energy Management Unit (EMU, e.g. DC-DC converter) is applied to control power flow of HESS. Two types of LIB packs($LiFePO_4$ and $LiMnNiCoO_2$) are individually utilized in this study. The main propose of this study is to investigate the effect of LIB in Discharge Of Depth (DOD) distribution of HESS with/without control (active/passive control in the article). A real-time Hardware-In-the-Loop (HIL) simulator embedded with analytical module of HESS with EMU has been developed for verifying control strategy, and here the measured results of DOD are compared with bench-test results of UC-LIB HESS. First of all, the accuracy of a real-time HIL simulator is verified. Results of simulation shows good agreement with bench-test results in the case of passive control without considering the linear assumption of OCV. Besides, DOD distributions of HESS by comparing two types of LIB packs($LiFePO_4$ and $LiMnNiCoO_2$) that run in US FTP-75 driving pattern are measured. In the case of high Internal Resistance(IR) of $LiFePO_4$ compared to UC, the active control with 60% duty cycle setting of LIB pack doesn't acquire DOD reduction than passive control. However, a passive control is effective in reducing the range of DOD. It also found that active control of setting duty cycle causes the impulse peak variation of DOD. For the other case of $LiMnNiCoO_2$, HESS with active duty control improve 50% reduction of DOD much effect than passive control. Consequently, IR of LIB and UC are key factor in considering the control strategy otherwise UC may not function effectively in improving DOD.

Keywords **- Hybrid Energy Storage System (HESS), Lithium-Ion Battery (LIB), Ultracapacitor (UC), control strategy, life cycle, pure EV.**

I. INTRODUCTION

Life cycle of LIB is still a concern for EV, especially for pure Electric-Vehicle (EV) users. Generally, peak current harms life cycle of LIB and decrease its effective capacity as well. In contrast with LIB, physical battery of UC is capable of absorbing and delivering peak power and have extremely long life cycle. It's realized that using UC to cover the peak current in a system with LIB might be an effective way of keeping, even elongating the life cycle of LIB. There are at least three demerit of pure single LIB. Response of charging/discharging is slow due to battery stores energy with chemical reactions. The second one is that battery energy density is lower than that of combustion engine. In addition, the lifetime is short because geometrical structure of battery is damaged by charge and discharge [1-5].

For the proposal of reducing the peak current in LIB pack, UC is employed in HESS effectively, but range extension is still limited in the case study of [1]. The effect of life cycle extension is discussed in [6] by the transient supply of UC. Due to the traditional large DC/DC converter in ESS, [7,8] propose a smaller prototype of DC-DC and simple circuit to keep the battery pack isolate, not to harvest energy from random peak power. The scenarios of usage have cover the regenerative braking, assist power supply, and charging/discharging between individual battery and UC. Some studies are focus on the design of levering DC-DC converter [9,10], but [11,12] introduces a converterless HESS in EV based on a direct use of inverter. It implies the possibility of high efficiency and low cost of HESS. Specific control strategies including neutral networks are illustrated in [13-15]. The economic analysis shows that the higher price of ESS gain higher benefits in elongating life cycle. Real-time simulator becomes a powerful platform before on-board test [15].

A typical flow chart in traction or regeneration mode of EV along with HESS (ESS+AES) is illustrated in Figure 1. In general, ESS (e.g. LIB) is a domestic energy storage unit provides/absorbs the nominal traction/regeneration power. In Figure 1, a power and energy management unit (e.g. EMU) is used to control power flow in DC-link to avoid the intense loading of LIB. For example, the high-power need might occur while climbing a steep slope so that the resulting peak power will deepen DOD of LIB. One possible way of easing the LIB loading is to add an auxiliary energy system such as UC as discussed. The role of auxiliary energy source is to supply additional demand power, and capable of increasing regeneration efficiency, narrowing DOD to elongate the life cycle of LIB. In particular, the relationship between life cycle and average DOD in lifespan is nonlinear, like an exponential curve, implying that LIB can earn more usable energy if narrowing average DOD [17].

In this study, a paralleling UC-LIB HESS with rated voltage 75V is established for EV. An EMU is applied to control power flow of HESS. Two types of LIB packs (LiFePO4 and LiMnNiCoO2) are individually utilized in the study. A real-time HIL simulator embedded with HESS module and EMU is applied for simulating the response of EV. First of all, results of simulation and bench test of DOD will be compared for verification of HIL. Then, $LiFePO_4$ and $LiMnNiCoO_2$ LIB packs are built and employed to be measured DOD in one cycle of US FTP-75 driving pattern. Here, 60% working duty of LIB in HESS are regarded as a representative case of active control compared to passive control and single LIB pack. The resulting DOD distributions of these three cases under the utilization of $LiFePO_4$ and $LiMnNiCoO_2$ LIB packs will be discussed in this study.

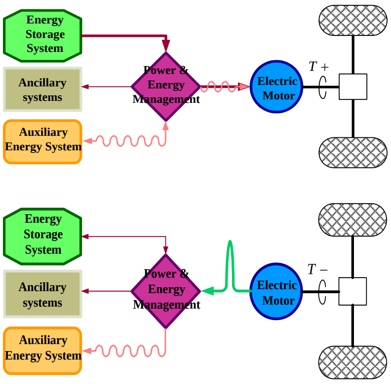

Fig 1: Flow chart in traction and regenerative modes of EV

II. REAL-TIME HIL SIMULATION

A HIL simulator has been widely used in developing and verifying a control system for EV. A HESS module for the HIL is established for simulation. The detailed topology is refer to [15]. In system integration level, the control strategy of Vehicle Control Unit(VCU) for the powertrain related to the Area Electric Range(AER) is validated [15]. HESS models of LIB and UC controlled by EMU are developed and established in simulator.

VCU accepts signals from imaginary driver and deliver commands to other control units. Analog input signals of VCU include: key on, pedal position, and brake position. Digital input signals are gear position, status of control units delivered via CAN bus or RS232. Analog response from other control units are ON/Off command of the relays. Through DSP's calculation of VCU, commands of torque and speed are sent out to motor control unit(MCU) simultaneously. Likewise, commands for gear shifting commands, the auxiliary system, protection signals, etc. are included in the processing from VCU to other control units as Figure 2 shown. Our HIL simulator is originally developed by OPAL-RT®. In-house VCU is linked with the simulator via analog/digital I/O interface, CAN bus and RS-232. The offline environment connected to HIL simulator provides sufficient capability for the VCU development.

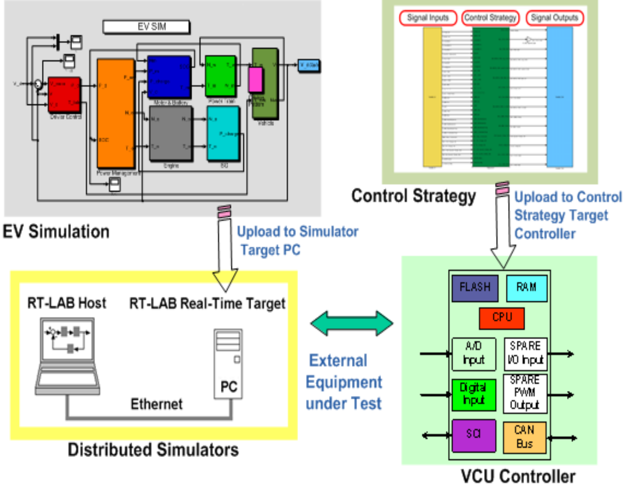

Fig 2: Real-time simulator and VCU

EV model is depicted in Figure 3. The input is driving pattern, and the response of EV is vehicle speed.

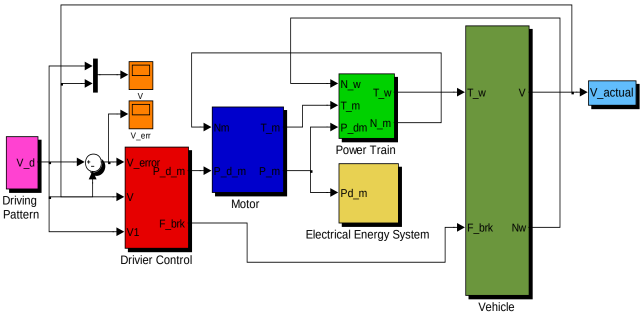

Fig 3: EV model embeded in HIL

HIL provides users the environment and interface to model the dynamic response of motor, power Train, Electrical Energy System, and Vehicle as shown in Figure 3. HESS of UC-LIB stack with EMU embedded in Electrical Energy System of Figure 3 is listed in Figure 4.

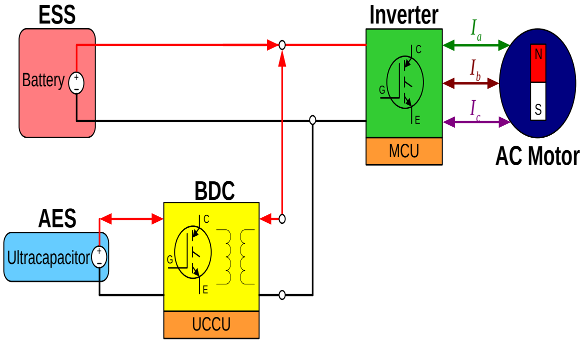

Fig 4: HESS of UC-LIB stack with EMU (UCCU in the figure)

The control strategy in BDC(i.g. EMU) is outlined below:

- LIB provides the major power when current demand is lower than 60% of rated value.
- UC 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 is stored in UC; if UC is full charged, the regeneration energy will be stored to LIB.

Flow chart of power control is listed in Figure 5.

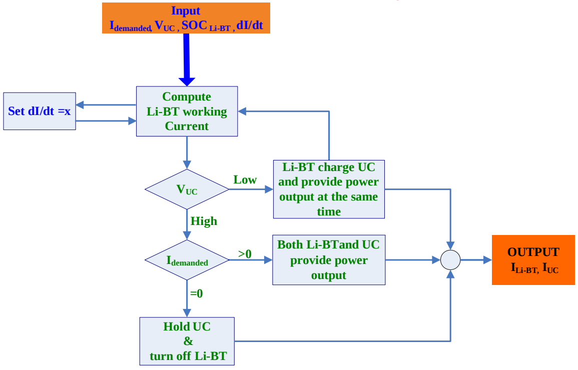

Fig 5: Flow chart of power control

III. TOPOLOGY OF PARALLELING HESS

Due to our target product of Light EV, the rated voltage of HESS is set to 75V. Figure 7 shows a basic parallel-connection case. EMU here is to achieve active control by switching 60% discharging ratio of LIB and 40% of UC at unit time. Specification of EMU is listed in Table 1. It is modified from a traction motor controller. Maximum efficiency of the EMU is about 92%. Maximum allowable regenerative power is 15kW. Loading power pattern as shown in Figure 12 is one cycle of US FTP-75 driving pattern of Light EV. Circuit of EMU as shown in Figure 8 is disposed as a connection interface between LIB and DC-link. The control strategy is to keep the switch periodically close and open by predetermined duty cycle, i.e. 60% selected tentatively here. Then, EMU generates a PWM signal to control the on/off time of lower arm of the IGBT module while the upper arm of the IGBT is always open. As red solid loops shown, four scenarios included:

1. LIB charges UC
2. LIB//UC discharges
3. UC discharges
4. Regenerative power charges LIB or UC

As blue solid loop shown, two scenarios included:

1. Only UC discharges
2. Regenerative power charges UC

Table 1: Specification of EMU

Item	Component
Control Unit	PMSM motor control board
Switching Power IC	IGBT
DC/DC module	SCW3A-15、SCW5A-15
DC current sensor	HAS 110-S

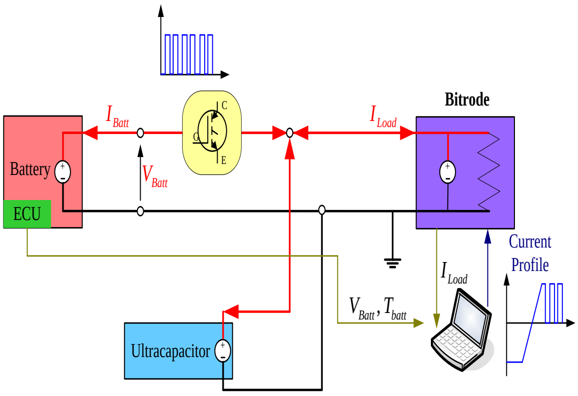

Fig 7: HESS in parallel connection (Bit rode is one automated pack-test machine)

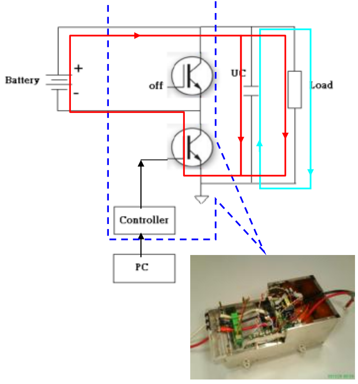

Fig 8: Architecture of EMU

IV. BENCH-TEST SET UP AND PROCEDURE

The setup of bench test is shown in Figure 9. Two types of LIB cells with large difference in IR are employed in this study and the specifications are listed in Table 2. An automated pack-test machine with rated voltage and current, 500V/450A is utilized for the test. The initial voltage of HESS is 70V. A power pattern converted from the FTP-75 driving cycle is programmed into the machine for discharge/charge operation. The duty cycle, current and voltage of the LIB terminal are monitored by the EMU, and the voltage of UC is monitored by pack-test machine. 21 cells of $LiFePO_4$ LIB and 3 modules of $LiMnNiCoO_2$ LIB are modularized into two individual packs.

Table 2: Specification of UC and LIB

Item	Unit	Energy Density (Wh/kg)	IR(mΩ)	
			Pack	**Total***
Maxwell UC Module 75V BMOD0094 E075	1 pack	2.5	3.08	
$LiFePO_4$ LIB Pishuang Cell 38.4Ah 3.2V 400013201	21 cells	60	58.05	76.82
$LiMnNiCoO_2$ LIB Kokam 6S1P Module 40Ah 22.2V SLPB100216216	3 modules	134	9.37	10.22

*Total IR is composed of internal resistance + harness resistance + fixture resistance

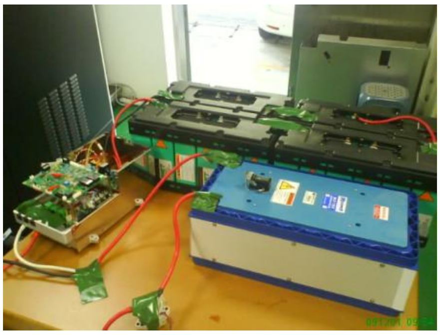

Fig 9: Implementation of HESS (EMU is left, central is $LiFePO_4$ LIB pack and right is UC pack)

Discharge curves of LIB cells and UC pack are shown in Figure 10. $LiFePO_4$ and $LiMnNiCoO_2$ LIB cell show a flat and steep curve within 90%~10% capacity respectively. In contrast, UC has linear response subjected to constant C-rate as shown in Figure 11. As listed in Table 1, the energy density of $LiMnNiCoO_2$ LIB is much higher than the $LiFePO_4$ LIB. However, the life cycle of LiMnNiCoO2 LIB (600-800cycles) is rather shorter than LiFePO4 LIB (1000-1200cycles). If energy density is the major requirement for EV application, HESS is expected for overcoming the life-cycle issue of LIB.

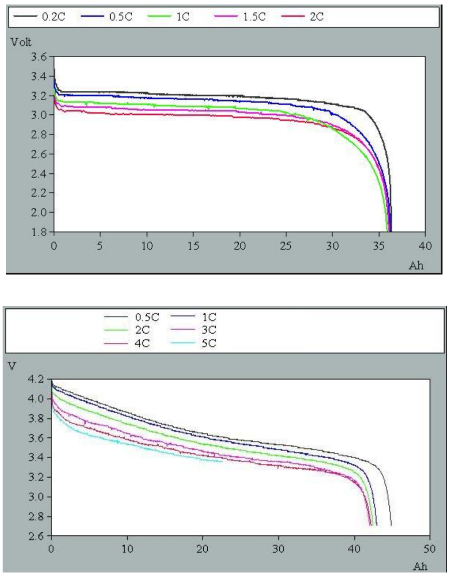

Fig 10: Discharge curves of Pishuang (upper) and Kokam LIBs (lower)

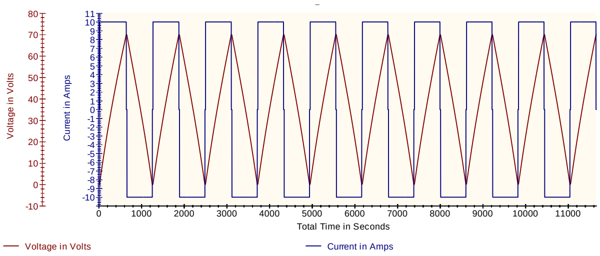

Fig 11: Charge/Discharge curves of UC

V. VERIFICATION OF PARALLELING HESS BASED ON HIL SIMULATIONS

To consider the real case of Light EV with 35kW PMSM motor, the current draw of FTP-75 driving cycle listed in Figure 12 is imposed on the HESS. In Figure 13, the accuracy of HIL simulator with HESS analytical module is examined by comparing to the measured results. It is shown that the simulator with assumed linear Open Circuit Voltage (OCV) yields the deviation from the measured voltage curve. Otherwise, the simulator accurately predict the response of LIB.

For examining the effect of LIB’s type under various control strategies, two types of LIB cells ($LiFePO_4$ and $LiMnNiCoO_2$) are individually utilized in this study. By setting a tentative loading of LIB(60%), DOD with respect to each LIB pack in the HESS for one FTP-75 driving cycle is measured in the cases with active control and without control(e.g. passive control) of EMU. In Figure 14, the energy efficiency resulted by the passive HESS ($LiFePO_4$ LIB, red line) is better than the single LIB pack (blue line). It states that better energy-saving effect can be obtained by employing UC with proper control strategy. Meanwhile, as the DOD results shown in Figure 15, the effectiveness of UC application in comparison with single $LiFePO_4$ LIB could be realized in this case. In detailed, HESS with passive control shows the most limited range of DOD than single LIB pack, even better than HESS with active control. To compare with the other case of $LiMnNiCoO_2$ LIB pack, Figure 16 shows the DOD of the HESS in comparison with single $LiMnNiCoO_2$ LIB pack. HESS in active control shows the most limited DOD than single LIB pack and passive HESS. However, there is no obvious difference by comparing single pack and HESS in passive control. It’s known that IR of LIB pack plays essential role in the distribution of DOD. As listed in Table 1, IR of $LiFePO_4$ LIB pack about 58mΩ is much higher than 9 mΩ of $LiMnNiCoO_2$ LIB pack and 3 mΩ of UC by excluding the harness resistance and fixture resistance. The load current that UC pack could share depends on each IR in parallel connection relative to LIB pack, i.e. the lower IR of the UC, the higher current it can share. On the other hand, the less discrepancy of IR between $LiMnNiCoO_2$ LIB and UC results in almost identical DOD curve by comparing the single pack and HESS in passive control. However, HESS with active control of setting duty cycle 60% of LIB pack shows 50% DOD improvement comparing with other two cases. It might be realized the active control is effective in the parallel connection between LIB pack and UC with close IR.

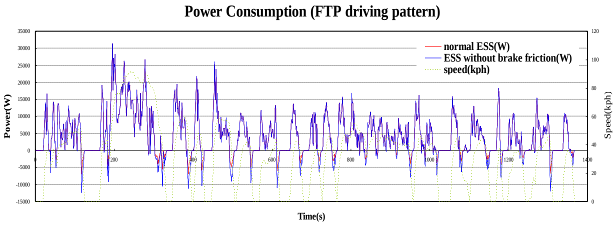

Fig 12: Required power of EV for FTP-75 driving pattern

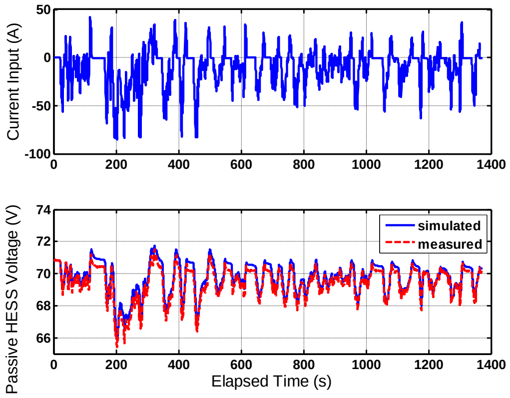

Fig 13: Comparison of simulation and measured results (upper:current, down:voltage)

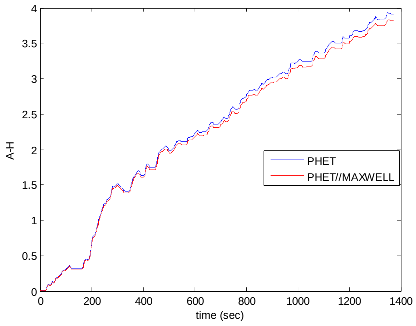

Fig 14: Energy expenditure of Pishuang LIB and HESS for imposing FTP-75 driving cycle

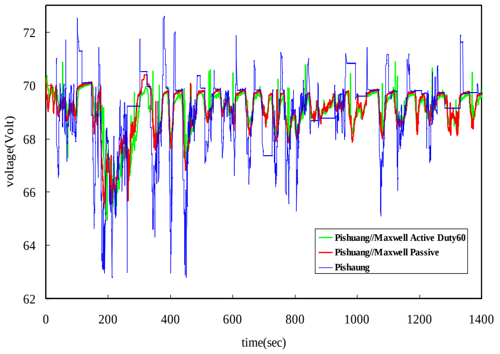

Fig 15: Comparison of DOD in single $LiFePO_4$ LIB pack and HESS with active/passive control

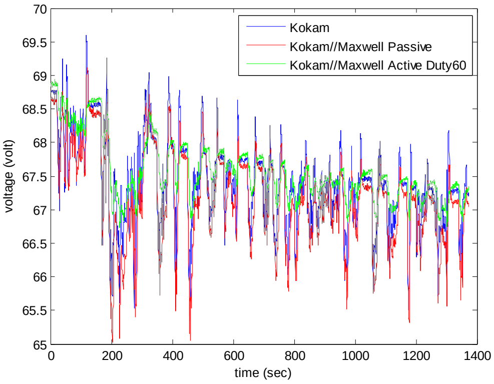

Fig 16: Comparison of DOD in single $LiMnNiCoO_2$ LIB pack and HESS with active/passive control

VI. CONCLUSION

First of all, the accuracy of a real-time HIL simulator is verified. Results of simulation shows good agreement with bench-test results in the case of passive control without considering the linear assumption of OCV. Besides, DOD distributions of HESS by comparing two types of LIB packs ($LiFePO_4$ and $LiMnNiCoO_2$) that run in US FTP-75 driving pattern are measured. In the case of high Internal Resistance (IR) of $LiFePO_4$ compared to UC, the active control with 60% duty cycle setting of LIB pack doesn't acquire DOD reduction than passive control. However, a passive control is effective in reducing the range of DOD. It also found that active control of setting duty cycle causes the impulse peak variation of DOD. For the other case of $LiMnNiCoO_2$, HESS with active duty control improve 50% reduction of DOD much effect than passive control. Consequently, IR of LIB and UC are key factor in considering the control strategy otherwise UC may not function effectively in improving DOD.

REFERENCES

[1] R. Carter, A. Cruden, and P. J. Hall, “Optimizing for Efficiency or Battery Life in a Battery/Super capacitor Electric Vehicle,” IEEE Transactions on Vehicular Technology, Vol.61 No.4 May 2012.

[2] Pay, S. and Baghzouz, Y. (2003) Effectiveness of Battery-Super capacitor Combination in Electric Vehicles. 2003, IEEE Power Tech Conference, Bologna, 23-26 June 2003.

[3] Cheng, Y., Van Mierlo, J., Van den Bossche, P. and Lataire, P. (2006) Super Capacitor Based Energy Storage as Peak Power Unit in the Applications of Hybrid Electric Vehicles. 3rd IET International Conference on Power Electronics, Machines and Drives, Dublin, 4-6 April 2006, 404-408.

[4] E. Faggioli, P. Rena, V. Danel, X. Andrieu, R. Mallant, and H. Kahlen, “Super capacitors for the energy management of electric vehicles,” Journal of Power Sources, Vol. 84, pp.261-269, 1999.

[5] Matthew D. Zolot, Bill Kramer, “Hybrid Energy Storage Studies Using Batteries and Ultra capacitors”, 2th International Seminar on Double Layer Capacitors and Similar Energy Storage Devices, Deerfield Beach, FL, December 9-11th, 2002.

[6] Omar, N., Van Mierlo, J., Verbrugge, B. and Van den Bossche, P. (2010) Power and Life Enhancement of Battery-Electrical Double Layer Capacitor for Hybrid Electric and Charge-Depleting Plug-In Vehicle Applications. Electrochemical Acta, 55, 7524-7531.

[7] J. Cao and A. Emadi, “A New Battery/Ultra Capacitor Hybrid Energy Storage System for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles,” IEEE Transactions on Power Electronics, Vol. 27, No. 1, pp. 122–132, Jan, 2012.

[8] Nobuyuki Kasuga，Nobuhito Ohnuma, “Ultra-Capacitor and Battery Hybrid EV with High Efficiency Battery Load Leveling System”，EVS15，1995.

[9] P. J. Grbovic, P. Delarue, P. L. Moigne, and P. Bartholomeus et. al., “A Bidirectional Three–level DC–DC Converter for the Ultracapacitor Applications,” IEEE Transactions on Industrial Electronics, Vol. 57, pp.3415–3430, Oct, 2010.

[10] A. Di Napoli, F. Crescimbini, L. Solero, F. Caricchi, and F. G. Capponi, “Multiple-input DC-DC power converter for power-flow management in hybrid vehicles,” IEEE International Conference on Industrial Applications: the 37th annual meeting, Vol. 3, pp. 1578-1585, 2002.

[11] K. Kawashima, T. Uchida, and Y. Hori, “Development of a Novel Ultracapacitor Electric Vehicle and Methods to Cope with Voltage Variation,” in IEEE Vehicle Power and Propulsion Conference 2009, Sept, 2009.

[12] S. Lu, K. A. Corzine, and M. Ferdowsi, “A new battery/ultracapacitor energy storage system design and its motor drive integration for hybrid electric vehicles,” IEEE Transactions on Vehicular Technology, Vol. 56, No. 4, pp. 1516-1523, 2007.

[13] Micah Ortúzar, Jorge Moreno, and Juan Dixon, “Ultracapacitor-Based Auxiliary Energy System for an Electric Vehicle: Implementation and Evaluation”, IEEE Transactions on Industrial Electronics, Vol. 54, No. 4, August 2007.

[14] Chien-Hsun Wu, Yi-Hsuan Hung, Wu-Yang Sean, “Development of a Real-time Simulator for Electric Vehicle with Dual Energy Storage System, Li-ion Battery and Ultracapacitor”, 2009 workshop on Power Electronics and Intelligent Transportation System, PEITS 2009.

[15] Chien-Hsun Wu, Yi-Hsien Chiang, Wu-Yang Sean, Shih-Ming Lo, Jia-Cheng Ke, Yi-Hsuan Hung, Optimal Designs and Experimental Verification for a Hybrid Energy Storage System, IEEE Program Committee of 3CA May 2010.

[16] http://www.nrel.gov/vehiclesandfuels/energystorage/model_simulation.html.

[17] http://www.ukpower.com