BATTERY SYSTEM MODELING AND IDENTIFICATION FOR ELECTRIC PROPULSION VEHICLE WITH FAULT SIMULATION

Kyuhong Han

Automotive PMO, Agency for Defense Development, Republic of Korea

clickcow@gmail.com

ABSTRACT
This paper describes development process and results of a battery system model with fault simulation for electric propulsion vehicles. The developed battery system model can be used to verify control and fault diagnosis strategies of a supervisory controller in the electric propulsion vehicle. To develop this battery system model, three sub-models, including a battery model, a relay assembly model, and a BMS (Battery Management System) model, are connected together similarly to the target real battery system. Comparison results between the real battery system hardware and the battery system model show similar tendency and values. And fault injection test of the model shows real system situation. It is possible for the model to emulate battery characteristics and fault situation if it is used in the development process of the BMS or the supervisory control strategies for electric propulsion systems.

Keywords: battery, electric vehicle, fault simulation, real time model

1. INTRODUCTION

Since problems such as shortage of fossil fuels(Campbell and Laherrere 1998), global warming, and environmental pollution have been illuminated as global issues worldwide, development and usage of environmentally friendly electric propulsion systems have been increasing in automotive, marine and aircraft fields regardless of the distinction between civilian and military. Particularly in the automotive field, vehicles using hybrid or electric propulsion systems have been developed actively(Pisu, Serrao, Cantemir, and Rizzoni 2006; Hashimoto, Yamaguchi, Matsubara, Yaguchi, and Takaoka 2010). These electric propulsion systems use electric power to drive vehicles, so that energy storage devices such as batteries have an essential role in the systems.

Because a vehicle is a platform for people to be on board directly, reliability of the platform and safety of the passengers should be taken in the development phase of the system. Besides, electric propulsion vehicles require a large number of high electric power components and controllers compared to engine-based vehicles. And electric motors and high voltage batteries are necessary in the system. So, the configuration of the system has been complex and the safety of passengers for the high voltage has been more significant. Therefore, it is needed to assess the suitability of the distributed systems included in the entire system before the distributed systems are integrated in the development phase of the complex system. Suitability assessment of a sub-distributed system means to judge whether the system is properly operating in the entire system. The suitability assessment of the sub-system includes analysis to give effect to the other connected systems and analysis of operation in fault situation. Especially, the high voltage battery system is a core component in the electric propulsion system. So, the suitability assessment of the battery system is important in the development process. However, it is difficult to induce the fault to the battery system. Therefore, the test environment to assess suitability of the battery system is needed.

Control strategies of a controller are typically verified through the simulation test before applying it to the actual target system. In the case of the battery system that it is difficult to be made trouble actually, if the simulation environment is used in the suitability assessment, then it is possible to enhance efficiency of validation. There are commercial models about batteries like the CRUISE(Xie and Ding 2008; Chunhua, Jigao, and Fenglai 2011), the ADVISOR(Johnson 2002) and the AUTONOMIE(Aziz, Shafqat, Qureshi, and Ahmad 2011). And a variety of battery models, electrochemical models(Doyle, Fuller, and Newman 1993), analytical models(Linden and Reddy 2001), and electrical circuit models(Ehsani, Gao, and Emadi 2009; Jang and Yoo 2008; Kim 2012), have been consistently studied. However, these battery models are just performance models to see the operating behavior of the battery. So, additional tasks are required to connect with the BMS or the supervisory control models. Besides, it is hard to add fault models to the commercial battery models.

In this paper, a battery system model of the electric propulsion systems having similar configuration with a real battery system hardware including the battery, the relay assembly, and the BMS has been developed and it is possible to simulate fault situations in physical phenomena point of view.

The model has been developed using a complementary modeling tool, the MATLAB/Simulink, and it has a real-time character for the HILS(Hardware-In-the-Loop Simulation) environment. If this developed battery system model is used in the development process of the integrated system like electric propulsion systems, then mutual effectiveness among the sub-systems of the entire system can be discerned effectively. In order to validate accuracy of the developed model, the results for the specific power scenario are confirmed. In addition, arbitrary faults are injected through the model to evaluate the characteristics of fault simulation.

2. BATTERY SYSTEM

Target battery system in this study is a real high voltage battery system of a series hybrid electric propulsion vehicle. Nominal voltage of the one battery pack is 340V, and its capacity is at about 15Ah level. And the target system uses 4 battery packs which are configured to 2 series and 2 parallel type. So, the entire battery system has 680V nominal voltage and 30Ah capacity.

2.1. Configuration of the Battery System

Target battery system consists of a battery, a relay assembly adjusting connection between the battery and DC link, and a BMS (Battery Management System) monitoring the battery status. Figure 1 shows this configuration of the battery system.

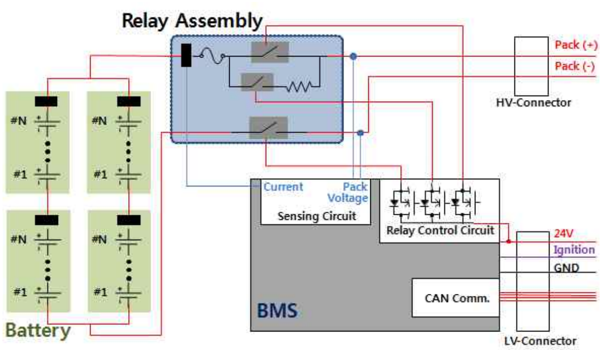

Figure 1: Configuration of the battery system

A battery module is made up of multiple unit battery cells, and the battery modules are packed in series or in parallel to make a battery pack. This package configuration of the battery pack is concluded to adjust required battery voltage. The relay assembly consists of a plus relay, a minus relay, a pre-charge relay and a pre-charge resistor. When the DC link voltage becomes the same as the battery terminal voltage, the pre-charge resistor works to give the DC link pre-charging effect. The BMS controls the three relays in the relay assembly and measures voltage and current of the battery terminal and temperature of battery cells. Also the BMS communicates with the supervisory controller to inform these values and get its command.

2.2. Modeling Requirement

In this study, the modeling of the battery system is performed to evaluate the supervisory control strategies including fault diagnosis strategies of the entire system. Therefore, three sub-model, a battery model, a relay assembly model, and a BMS model, is required to be similar with the real battery system. So, requirements of each sub-model have been derived.

First, battery cell characteristics should be shown in the battery sub-model. The main characteristic of the battery cell is the SOC (State-of-Charge) of the battery cell derived from battery cell capacity and current. And the battery sub-model should calculate loss current of the battery cell derived from heating effect. In addition, the sub-model must show change of the battery terminal voltage derived from internal resistance, internal reactance, double layer effect, and diffusion effect. From the battery package point of view, the change of voltage and current according to series or parallel connection should be shown. Change of the battery pack temperature according to the battery specification and current flow of the terminal should also be shown. Using this model to evaluate control strategies of the supervisory controller, the battery terminal through the DC-Link is connected to other electric propulsion components. Because characteristics of electrical connection are interested in the entire operation, simulating the actual battery voltage is more important than others.

Second, the requirements of the relay assembly sub-model are to have opening and closing properties of the relay itself and pre-charge resistor character. Then loss current characteristics should be shown because relay terminal is a DC link terminal.

Table 1: Battery system fault list

Fault	Detect Condition	Release Condition	BMS Behavior
Under voltage warning	V < 550V	Returns normal condition	Only alarm
Under voltage fault	V < 530V	No release	Alarm, Relay open
Over voltage warning	V > 750V	Returns normal condition	Only alarm
Over voltage fault	V > 770V	No release	Alarm, Relay open

Third, the BMS sub-model should communicate with the supervisory controller in the HILS environment. So, the communication protocol must be matched with the real hardware. Because the BMS model give various information to the supervisory controller, the application software such as SOC estimation, physical signal conditioning should be included in the BMS sub-model. And the BMS sub-model has to detect and simulate some faults like table 1. To verify these faults, fault simulation environment should also be developed in this sub-model. Using this environment, physical value variation can be induced.

3. BATTERY SYSTEM MODELING

To develop this battery system model, three sub-models, including a battery model, a relay assembly model and a BMS model, are connected together similarly as the real battery system.

3.1. Battery Model

Main function of the battery model is calculating the variation of SOC, voltage and temperature for the target battery. To develop the battery model, a RLC equivalent circuit for the battery cell(Ehsani, Gao, and Emadi 2009; Jang and Yoo 2008; Kim 2012) is used as shown below in figure 2.

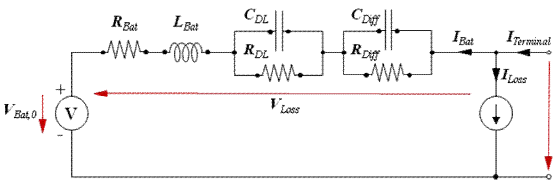

Figure 2: Battery equivalent circuit

In the battery model, SOC is first calculated using charge and discharge current of the battery cell. Because the SOC is a ratio of present energy capacity to original total capacity, the SOC is calculated using integration method which adds continuously charge and discharge current with present energy capacity based on initial SOC value as shown below in (1).

$$SOC = SOC_0 + \frac{1}{K_N}\int \left(I_{\text{Terminal}} - I_{\text{Loss}}\right) \qquad (1)$$

where K_N : nominal capacity of a battery (Ah)

After calculating the SOC, battery terminal voltage is generated from the OCV (Open Circuit Voltage) data. From this voltage value, the final terminal voltage of the battery is calculated from subtracting the loss voltages such as internal resistance (2), internal inductance (3), double layer effect (4), and diffusion effect (5).

$$I_{Bat}R_{Bat}\left(SOC, I_{Bat}, T_{Bat}\right) \qquad (2)$$

$$\frac{dI_{Bat}}{dt}L_{Bat} \qquad (3)$$

$$\frac{1}{C_{DL}}\int\left(I_{Bat} - \frac{V_{DL}}{R_{DL}}\right) \qquad (4)$$

$$\frac{1}{C_{Diff}}\int\left(I_{Bat} - \frac{V_{Diff}}{R_{Diff}}\right) \qquad (5)$$

And the parameters of the battery model are tuned in order for the characteristics to match with the real system results. Figure 3 shows the results of nominal capacity test of the one battery pack.

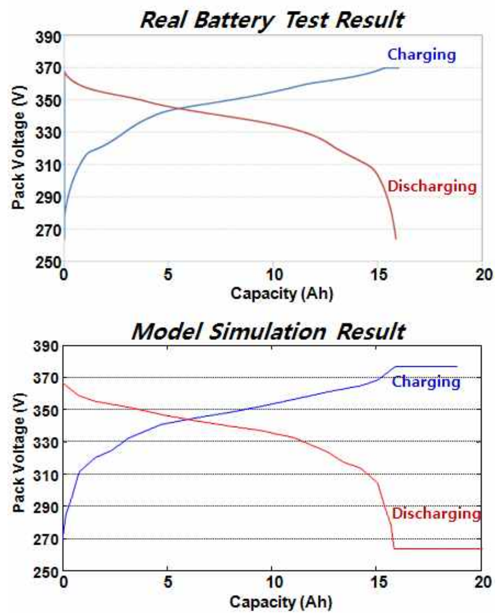

Figure 3: Battery model identification

Tested target is one of the four battery modules. As shown in figure 3, comparison results between the real battery system and the battery model show similar tendency and values.

3.2. Relay Assembly Model

The relay assembly model has a function delivering the battery terminal voltage to the DC link connected to other electric components. Because the relay assembly is designed to connect or disconnect from the battery to the DC link, the relay assembly model should be simulated as a function of connection and transient property at relay closing. The relay assembly model has been developed through rotating three sub-models using different equivalent models as below.

- Open circuit model at the relay open
- Pre-charging circuit model at the relay closing
- Short circuit model at the relay close

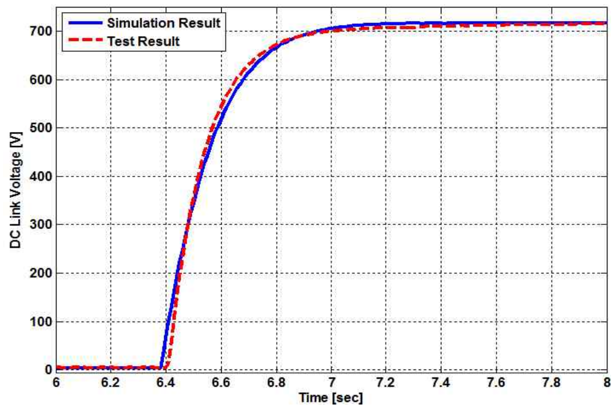

Figure 4: Relay assembly model identification

Figure 4 shows pre-charging process when the relays are closing. At the 6.4 seconds, the pre-charge and the minus relay have been closed, and then the plus relay have been also closed at about 7 seconds. As the figure 4, comparison results between the real battery system and the battery model show similar tendency and values.

3.3. BMS Model

The BMS communicates with other controllers and controls the relays in the relay assembly according to commands from the supervisory controller. And various information such as measured voltage, current, and temperature are gathered to deliver them to the supervisory controller. The developed BMS model can emulate same signals just like the real system including the control signals and the fault diagnosis signals shown in table 1.

4. PERFORMANCE EVALUATION

In order to confirm the performance of the battery system model developed in this study, a part of the characteristics of the model was confirmed based on the test results of the actual propulsion system. Then, to simulate the situation of fault occurs, fault injection simulation was performed.

4.1. System Characteristics Evaluation

In this study, to confirm the characteristics of the model, a test result of a real system's power load during the FTP-75 cycle, which has been commonly used for fuel economy test, is inserted as charged or discharged electric power to the battery system model. The FTP-75 cycle has fast and slow speed sets that is appropriate to show the loading of highly transient power, and includes resting for about 10 minutes to see the relay operation during the relay opening or closing.

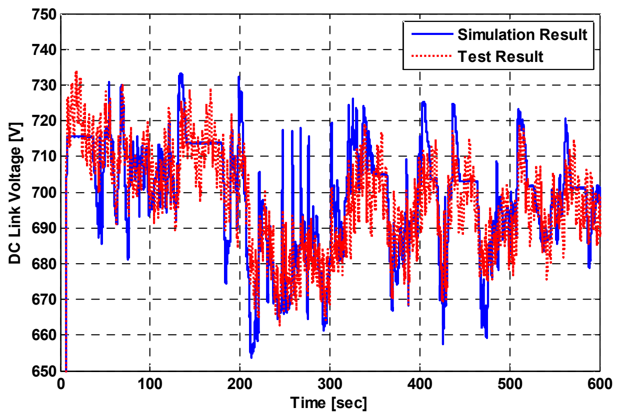

Figure 5: Battery characteristics evaluation result

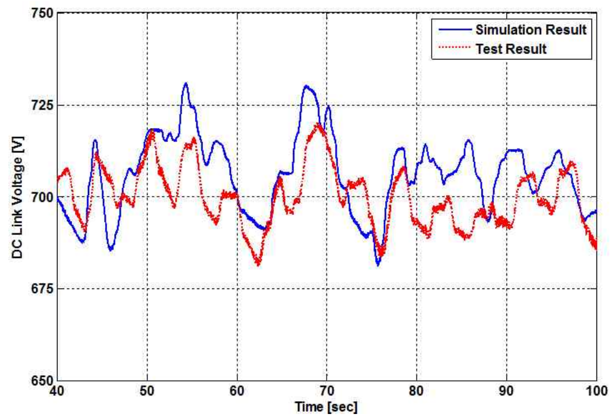

Figure 6: Battery characteristics evaluation result (part)

To confirm the battery system model, the current load has been input to the DC link terminal. And supervisory control commands such as a relay command have been input to the BMS model. In comparison with test data, the actual terminal voltage of the battery and the simulation value is generated like figure 5. And there is some part of the test data in figure 6.

The FTP-75 cycle has low and high speed region, so that battery current critically fluctuates during the cycle. Comparison results between the real battery system and the battery model show similar tendency and values. Considering the high voltage range around 700V, the result shows less than 2 percent error.

4.2. Fault Simulation

The test scenario of fault simulation that was used to confirm the performance for the fault situation is battery voltage variation for 100 seconds. The power load is applied during simulation, and the arbitrary voltage was forced at the moment of 30 seconds. With this condition, the BMS performed its own operations for fault diagnosis. Figure 7 shows the situation and results of this fault simulation.

There is a command of the supervisory controller to connect the relay at a second section, and the BMS controls the relay assembly to match this command. Therefore, it can be seen that the DC link voltage is equal to the battery voltage at this time. From the moment 30 seconds, the voltage of the battery is increased gradually. Then, a warning and a fault alarm are occurred at each conditions. Regardless to the instruction of the supervisory controller by the operation of the own behavior of the BMS, it can be seen that the relay was opened and the current flow through the battery was stopped. When a fault occurs, the DC link voltage decreases gradually, but it is possible to confirm that the battery was separated from the DC link. Through fault simulation like this, system developer can figure out how failure of a battery system can effect to other components on an electric propulsion system, and how the supervisory controller will have to go with the fault diagnosis strategy and control strategies based on the simulation results.

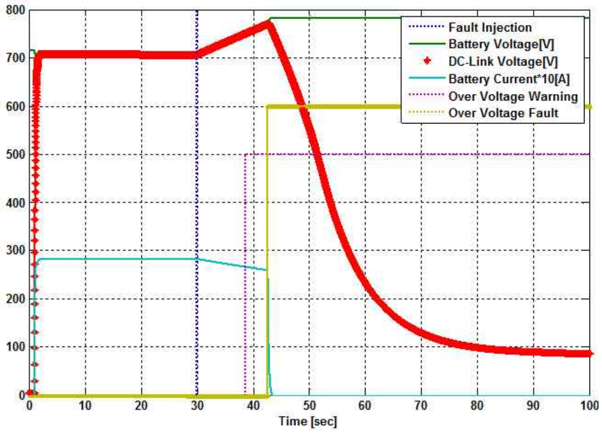

Figure 76: Fault simulation result

5. CONCLUSION

A battery system model with real-time property to evaluate control and fault diagnosis strategies has been developed. In the development process of a supervisory controller for the electric propulsion system, the developed model can be used effectively. Conclusions in this paper are as follows.

1. A detailed battery system model based on the specification and the configuration of the battery system for the electric propulsion systems with real-time properties has been implemented. Some parts in the model related to the specification of the system such as the capacity of the relay assembly element and the battery capacity have been treated with parameters for developer to change the battery system specification easily.
2. A part of the battery system model is a fault simulation model to force the physical values discretionally. Further, it has been configured to be able to accept own fault diagnosis of the BMS to behave as the actual BMS. It is possible to confirm that the fault simulation of the battery system effects the other components in the configuration of the electric propulsion system. It has purpose to reflect the design of the control strategy to the BMS or the supervisory controller.

REFERENCES

Campbell, C.J. and Laherrere, J.H, 1998. The End of Cheap Oil, *Scientific American*, March, p. 78-83.

Pisu, P., Serrao, L., Cantemir, C., and Rizzoni, G., 2006. Hybrid-Electric Powertrain Design Evaluation for Future Tactical Truck Vehicle Systems. *ASME 2006 International Mechanical Engineering Congress and Exposition*, pp. 271-278. November 5-10, Chicago (Illinois, USA).

Hashimoto, T., Yamaguchi, K., Matsubara, T., Yaguchi, H., and Takaoka, T., 2010. Development of New Hybrid System for Compact Class Vehicles. *Transactions of Society of Automotive Engineers of Japan*, 41 (1), 43-47.

Xie, H. and Ding, Y., 2008. The Study of Plug-In Hybrid Electric Vehicle Power Management Strategy Simulation. *VPPC 2008 Vehicle Power and Propulsion Conference*, pp. 1-3. September 3-5, Harbin (China).

Chunhua, X., Jigao, N., and Fenglai, P., 2011. Design and Simulation of the Power-train System for an Electric Vehicle. *AIMSEC 2011 2nd International Conference on Artificial Intelligence, Management Science and Electronic Commerce*, pp. 3868-3871. August 8-10, Zhengzhou (China).

Johnson, V.H., 2002. Battery Performance Models in ADVISOR. *Journal of Power Sources*, 110 (2), 321-329.

Aziz, A., Shafqat, M.S., Qureshi, M.A., and Ahmad, I., 2011. Performance Analysis of Power Split Hybrid Electric Vehicles using AUTONOMIE. *SCOReD 2011 IEEE Student Conference on Research and Development*, pp. 144-147. December 19-20, Putrajaya (Malaysia).

Doyle, M., Fuller, T.F., and Newman, J., 1993. Modeling of Galvanostatic Charge and Discharge of the Lithium/Polymer/Insertion Cell. *Journal of the Electrochemical Society*, 140 (6), 1526-1533.

Linden, D. and Reddy, T., 2001. *Handbook of Batteries*. 3rd ed. USA: McGraw-Hill.

Ehsani, M., Gao, I., and Emadi, A., 2009. *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design*. 2nd ed. USA: CRC Press.

Jang, J.H. and Yoo, J.Y., 2008. Impedance-Based and Circuit-Parameter-Based Battery Models for HEV Power Systems. *International Journal of Automotive Technology*, 9 (5), 615-623.

Kim, T., 2012. *A Hybrid Battery Model Capable of Capturing Dynamic Circuit Characteristics and Nonlinear Capacity Effects*. Thesis (MD). University of Nebraska.

AUTHORS BIOGRAPHY

Kyuhong Han received his BS and MS in electrical engineering (major in modeling and control of automotive propulsion systems) in 2008 and 2010, respectively, all from Hanyang University, Seoul, Korea. He joined the High Mobility Hybrid Electric Propulsion System Research Project and the Open System Integration Laboratory Project for Electric Propulsion System at Agency for Defense Development in 2010 as a research associate. Since then, he has been working in these projects on research and development of electric and hybrid electric vehicles.