Article

Battery System Modeling for a Military Electric Propulsion Vehicle with a Fault Simulation

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

Keywords: battery; electric vehicle; military vehicle; fault simulation; real time model

1. Introduction

Since problems such as the shortage of fossil fuels [1], global warming, and environmental pollution have become global issues, the development and usage of environmentally friendly electric propulsion systems have been increasing in automotive, marine and aircraft technology in both civilian and military designs. Particularly in the automotive field, vehicles using hybrid or electric propulsion systems have been actively developed [2,3]. These electric propulsion systems use electric power to drive the vehicles, so energy storage devices such as batteries have an essential role in these systems.

Compared to engine-based conventional vehicles electric propulsion vehicles require a large number of high electric power components and controllers, so the configuration of the overall system is more complex, making the safety of the passengers more significant due to the high voltage. Therefore, the suitability of sub-distributed systems must be assessed before integrating the system in the development phase of the complex and integrated system. Especially, since the high voltage battery system is a core component in the electric propulsion system from the point of view that the battery system supplies the power to the various electric components, the suitability assessment of the battery system is more important in the development process. A suitability assessment of the sub-distributed system must judge whether a system operates properly or not by linking with other sub-distributed systems in the entire system. A suitability assessment of the sub-distributed system also includes an analysis of the effect on the other connected systems and influence on failure occurrence and the fault management strategy for the entire system. However, because a high voltage failure is very dangerous and can be critical to other important components in a vehicle, it is difficult to conduct a failure test of the battery systems. Therefore, a test environment that can simulate a failure situation is needed to assess the suitability of the battery system.
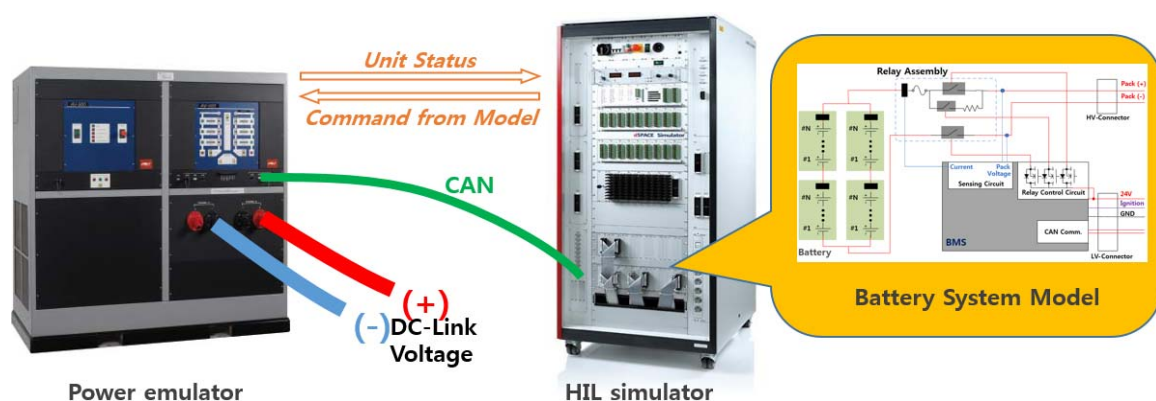
Research on battery models has been ongoing in automotive field for the last two decades. From these literature surveys, there are typically three types of battery models: analytical [4], electrochemical [5,6] and electrical circuit based [7–10] models. Most of this research has been on battery statement estimation, for instance, state of charge (SOC), state of health, internal resistance, *etc.* In addition there have been some papers that use commercial software packages that simulate vehicles equipped with an electric propulsion system including batteries, such as AVL CRUISE [11,12], the National Renewable Energy Laboratory's ADVISOR [13] and the AUTONOMIE package [14] of the Argonne National Laboratory. However, these works only identify the performance and the operating behavior of the vehicle and battery, so additional tasks are required to validate the correlation performance connected with a battery management system (BMS) and a supervisory controller. Furthermore, it is hard to add fault models to the battery models of commercial packages.

In this paper, a lithium-ion polymer battery system model of electric propulsion systems with a similar configuration as a real battery system hardware, including the battery, the relay assembly, and the BMS has been developed, and it is possible to simulate the fault situations from the physical phenomena point of view. Each sub-system, the battery, the relay assembly and the BMS, is modularized and integrated into a whole battery system model. Using this battery system model, the battery performance can be predicted by simulation and the behavior of the system according to failures inserted in the same part as a real battery system for analysis. Furthermore, the proposed model is developed so that it is possible to simulate the communication error by designing a controller

area network (CAN) structure that is the same as in an actual vehicle. If the proposed battery system model is used in the development process of an integrated system such as a hybrid electric vehicle (HEV) system, the mutual effectiveness among the sub-systems can be effectively discerned. Especially, if the proposed battery system model is applied to hardware-in-the-loop simulation (HILS) environment including a power emulator as shown in Figure 1, it can obtain more reliable performance and fault management strategy evaluation results of a hybrid control unit (HCU) which must monitor the power consumption state, since the power emulator can simulate the DC Link voltage close to real values.

The model has been developed using a complementary modeling tool, the Matlab/Simulink, and the real-time characteristic is assigned for a HILS environment (Figure 1). The battery model is based on an electrical circuit and re-arranged in accordance with the actual hardware structure. To simulate the operation of the actual BMS controller hardware, the BMS algorithm processes battery sensor information and includes the control strategy for the relay assembly control. The feasibility of the developed model is validated by a comparison between the simulation results and the vehicle test results acquired using a well-known driving cycles, for example FTP-72, and internal developed driving cycle related to military tactics. In addition, the arbitrary faults signals are injected through the model to evaluate the characteristics of the fault simulation.

Figure 1. HILS environment.
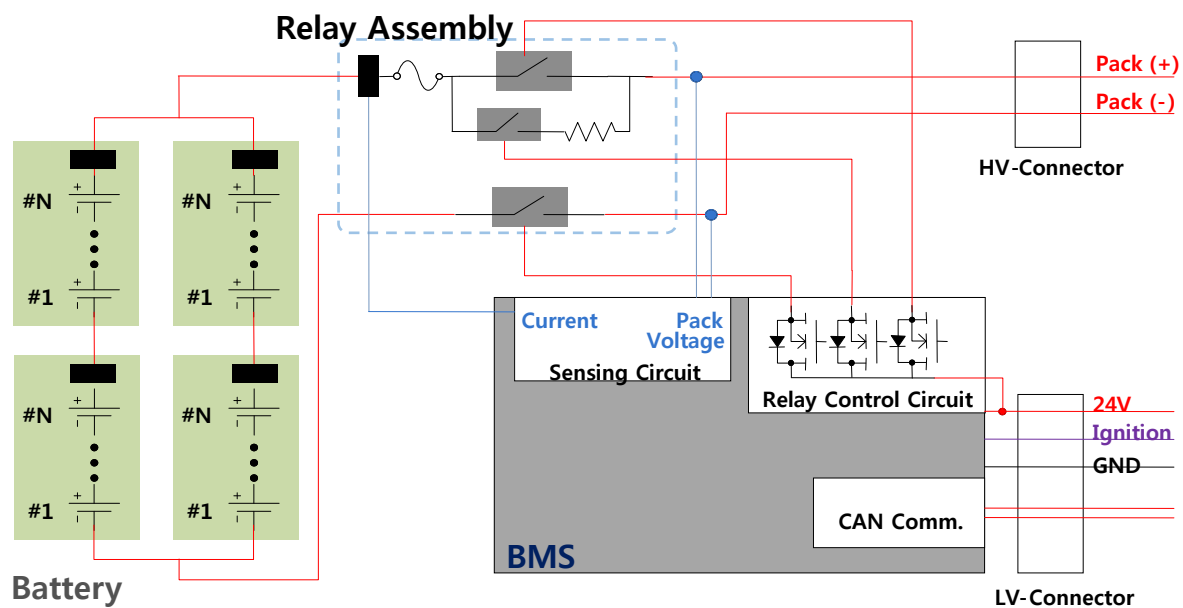
2. System Outline

As mentioned previously, the HEV system that has a complex configuration requires a strategy and capability with respect to the failure situation. Integrated with electronic sensors, actuators, electric control units, and bus communications, HEVs have a more complicated control strategy than that of conventional vehicles and thus face a great challenge for safety and reliability [15]. Therefore, the necessity of a fault tolerant algorithm is more important because the ranges of the battery voltage and current for military HEVs are broader than for commercial HEVs. Like the preceding, the target battery system in this study is a real high voltage battery system of a military series hybrid electric propulsion vehicle. The nominal voltage of one battery pack is 340 V, and its capacity is at about 15 Ah level. The target system uses four battery packs which are configured to two series and two parallel types, so the entire battery system has a 680 V nominal voltage and 30 Ah capacity. Configuration of the battery system and analysis of the modeling requirement will be presented in the next section.

2.1. Configuration of the Battery System

The target battery system consists of a battery, a relay assembly adjusting the connection between the battery and the DC link, and the BMS monitoring the battery status and controlling the relay assembly. Figure 2 shows this configuration of the battery system.

Figure 2. 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 to the 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 a pre-charging effect. The BMS controls the three relays in the relay assembly and measures the voltage and current of the battery terminal and the temperature of the battery cells. In addition, the BMS communicates with the supervisory controller to inform these values and receive its command.

2.2. Modeling Requirement

In this study, the modeling of the battery system is performed to evaluate the supervisory control strategies including the fault diagnosis strategies of the entire system. Therefore, three sub-models, the battery model, the relay assembly model and the BMS algorithm, are required to be similar to the real system, so the requirements of each sub-model have been derived as follows:

First, the battery cell characteristics should be shown in the battery sub-model. The main characteristic of the battery cell is the SOC of the battery cell derived from the battery cell capacity and current. The battery sub-model should also be able to calculate current loss of the battery cell derived from the heating effect. In addition, the battery sub-model must show a change of the battery terminal voltage derived from the internal resistance, internal reactance, double layer effect, and diffusion effect.

From the battery package point of view, a change of voltage and current according to the series or parallel connection should be shown. A change of the battery pack temperature according to the battery specification and current flow of the terminal should also be shown. When the supervisory control algorithm is evaluated using this model, the main focus is the overall electrical characteristics operating by connecting the battery and the other electric system through the DC Link. Therefore simulating the actual battery voltage is the most important requirement.

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

Third, the BMS algorithm sub-model should communicate with the supervisory controller in a HILS environment. Therefore, the communication protocol must be matched with the real hardware. Because the BMS algorithm provides various information items to the supervisory controller, the application functions such as SOC estimation and physical signal conditioning should be included. Furthermore, the BMS sub-model has to detect and simulate some faults as shown in Table 1. To verify these faults, a fault simulation environment should also be developed in this sub-model. Using this environment, the physical value variation can be induced.

Table 1. Battery system fault list.

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

3. Battery System Modeling

To develop this battery system model, three sub-models: a battery, a relay assembly and a BMS algorithm, are connected together to match a real battery system. The model is implemented by Matlab/Simulink and guarantees a real-time characteristic of a 1 millisecond (1×10^{-3} s) step size.

3.1. Battery Sub-Model
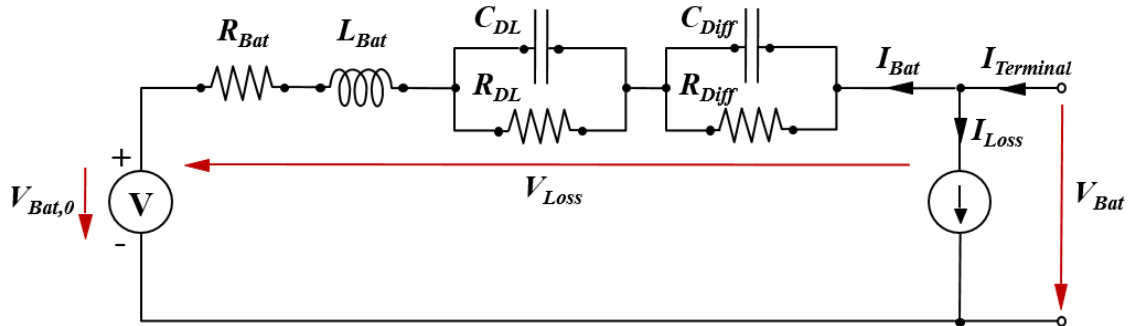
The main function of the battery sub-model is calculating the variation of the SOC, voltage and temperature of the target battery. To develop the battery sub-model, an RLC equivalent circuit for the battery cell [16–18] is used as shown below in Figure 3.

In the battery sub-model, the SOC is first calculated using the charge and discharge current of the battery cell. Because the SOC is the ratio of the present energy capacity to the original total capacity, the SOC is calculated using an integration method that continuously adds the charge and discharge current with the present energy capacity based on the initial SOC value as shown below in Equation (1) [16]:

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

(1)

where SOC_o: Initial SOC; K_N: Nominal capacity of (a) battery (Ah); $I_{Terminal}$: Terminal current; I_{Loss}: Loss current.

Figure 3. Battery equivalent circuit.

When the SOC is calculated by charge/discharge current, the loss current indicated in Figure 3 must be considered as the following Equation (2):

$$I_{Loss} = I_0 e^{\left(\frac{V_{Bat}-V_N}{K_1}+K_2\frac{T_{Bat}-T_N}{T_{Bat}T_N}\right)}$$

(2)

where I_o: Sum of loss currents at nominal conditions; V_{Bat}: Battery cell voltage; V_N: Nominal cell voltage; T_{Bat}: Battery temperature; T_N: Nominal temperature; K_1: Constant, shows dependence on clamp voltage; K_2: Constant, shows dependence on temperature.

After calculating the SOC, the battery terminal voltage is generated from the open circuit voltage data. From this voltage value, the final terminal voltage of the battery is calculated by subtracting the loss voltages such as internal resistance V_{L_res}, internal inductance V_{L_ind}, double layer effect V_{DL}, and diffusion effect V_{DFF}. The loss voltage V_{Loss} is yielded from summation of these loss terms:

$$V_{Loss} = V_{L\_res} + V_{L\_ind} + V_{DL} + V_{DFF}$$

(3)

$$V_{L\_res} = I_{Bat} R_{Bat}(SOC, I_{Bat}\, T_{Bat})$$

(4)

$$V_{L\_ind} = \frac{dI_{Bat}}{dt} L_{Bat}$$

(5)

$$V_{DL} = \frac{1}{C_{DL}} \int \left(I_{Bat} - \frac{V_{C\_DL}}{R_{DL}} \right)$$

(6)

$$V_{DFF} = \frac{1}{C_{DFF}} \int \left(I_{Bat} - \frac{V_{C\_DFF}}{R_{DFF}} \right)$$

(7)

where I_{Bat}: Battery current; R_{Bat}: Battery resistance; L_{Bat}: Battery inductance; C_{DL}: Double layer capacitance; R_{DL}: Double layer resistance; V_{C_DL}: Loss voltage double layer capacitance; C_{DFF}: Diffusion capacitance; R_{DFF}: Diffusion resistance; V_{C_DFF}: Loss voltage diffusion capacitance.

Battery parameters of Table 2 and Figure 4 are used to simulate the battery voltage. To compensate for the nominal capacity, the internal resistance is properly adjusted as shown in Figure 4. Figure 5

shows the results of nominal capacity test of the one battery pack. The comparison results between the real battery system and the battery model show a nearly perfect matching tendency and values.

Table 2. Battery parameters.

Parameter	Value	Parameter	Value
L_{Bat} (H)	5.28×10^{-9}	R_{Bat} (Ohm)	Figure 4
C_{DL} (F)	0.6	C_{DFF} (F)	0.1
R_{DL} (Ohm)	1.67×10^{-3}	R_{DFF} (Ohm)	0.001

Figure 4. Curve of Battery resistance *vs.* SOC.
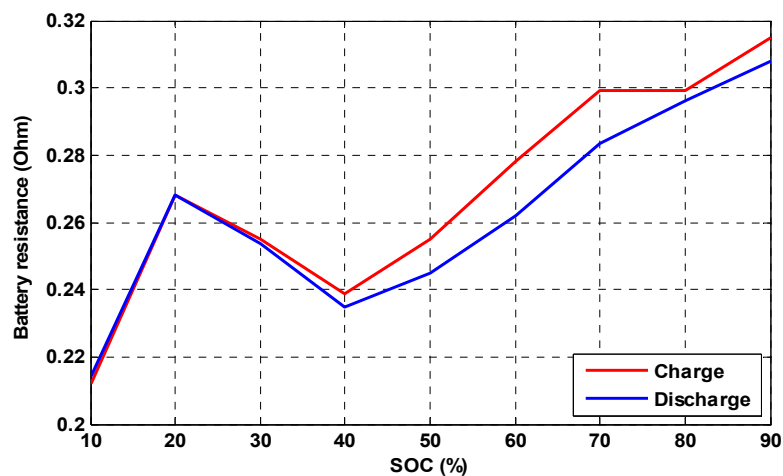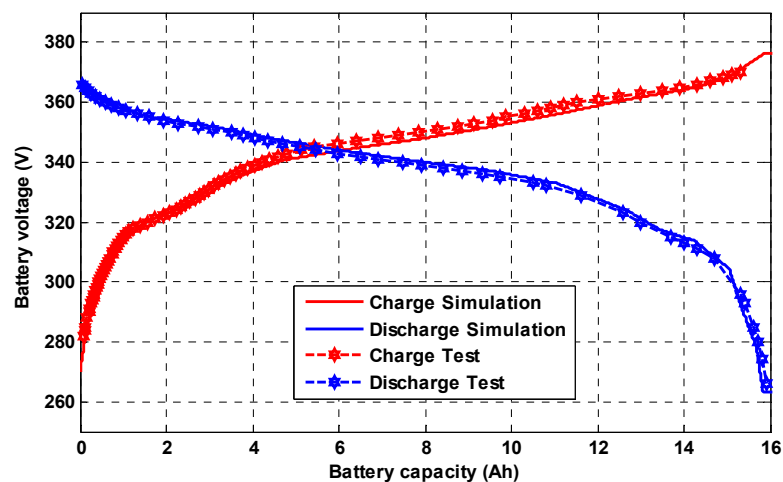
Figure 5. Battery model identification.

3.2. Relay Assembly Sub-Model

The relay assembly sub-model has a function delivering the battery terminal voltage to the DC-Link connected to the other electric components. Because the relay assembly is designed to connect or disconnect from the battery to the DC-Link, the relay assembly sub-model should be simulated as a function of the connection and transient property at the relay closing. The relay assembly sub-model has been developed by sequentially converting the three sub-models using different equivalent circuits as shown in Figure 6.

- Open circuit model at the relay opening;
- Pre-charging circuit model at the relay closing;
- Short circuit model at the relay close.

**Figure 6.** Equivalent circuits of relay assembly model. (**a**) Relay open; (**b**) Pre-charging; (**c**) Relay close.

(**a**)   (**b**)   (**c**)
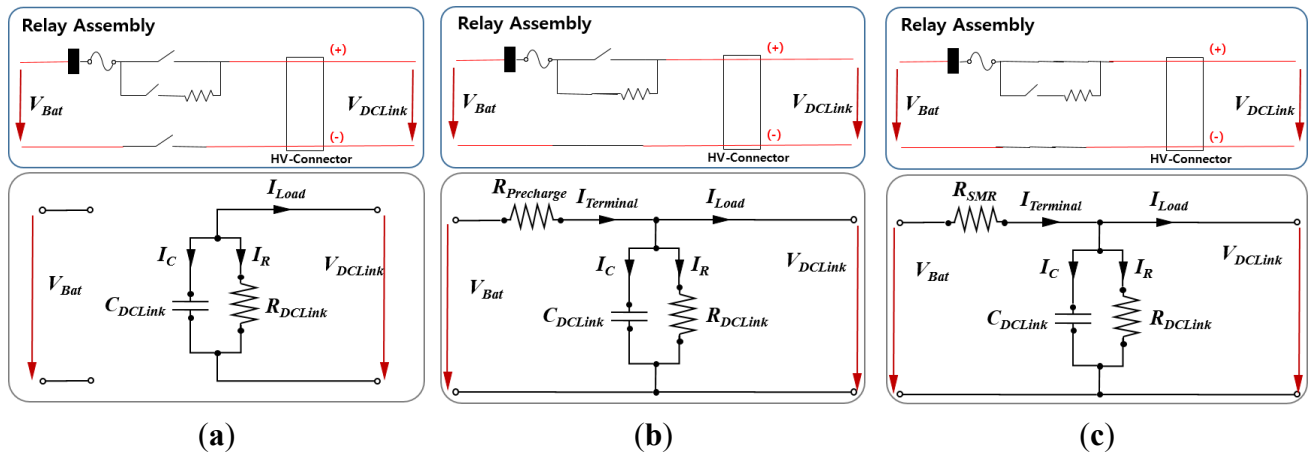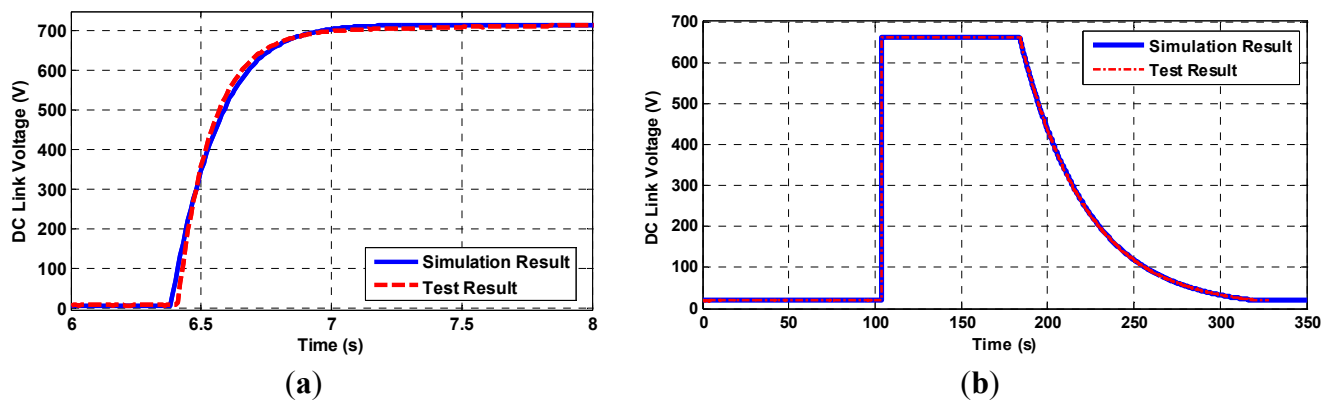
Figure 7a shows the pre-charging process when the relay is closing. At 6.4 s, the pre-charge and the minus relay have been closed, and then the plus relay has also been closed at about 7 s. Figure 7b shows opening process.
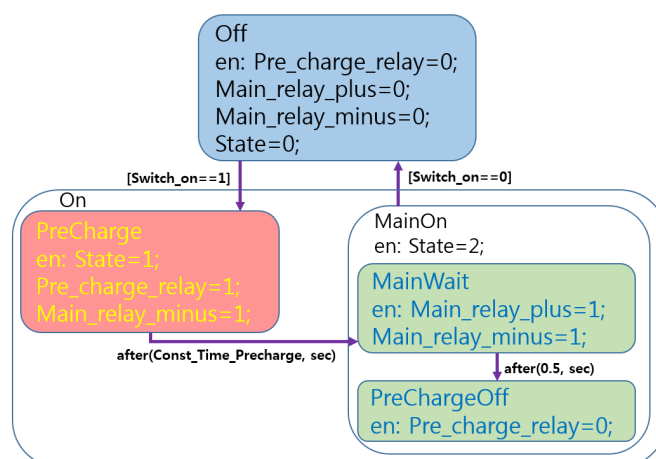
Figure 7. Relay assembly model identification: (**a**) Pre-charging, (**b**) Closing.

(**a**)   (**b**)

The DC Link voltage is slowly decreased from about 180 s due to power consumption of load components. This circumstance is implemented by R_{DCLink} in equivalent circuit. Generally as shown in Figure 7, the comparison results by operation of the relay between the real battery system and the battery model show a similar tendency and values.

3.3. BMS Algorithm Sub-Model

The BMS communicates with the other controllers and controls the relays in the relay assembly according to the commands from the supervisory controller. The relay control algorithm is implemented using the State-Flow of the Matlab/Simulink as shown in Figure 8.

Figure 8. State-Flow chart.

The "Switch_on" signal is the control command transferred from the supervisory controller. This command signal and pre-charge time constant, tuning parameter "Const_Time_Precharge", determines the state of the three relays. In addition, various information such as the measured voltage, current, and temperature are gathered to deliver them to the supervisory controller using communication architecture as an actual vehicle. This communication architecture is implemented by "bus selector/creator" of Matlab/Simulink. The developed BMS model can emulate the same signals just like the real system including the control signals and the fault diagnosis signals as 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 electric propulsion system. The test results are acquired by an actual military electric propulsion vehicle as shown in Figure 9 and Table 3. Then, to simulate the situation of a fault occurring, a fault injection simulation was performed.
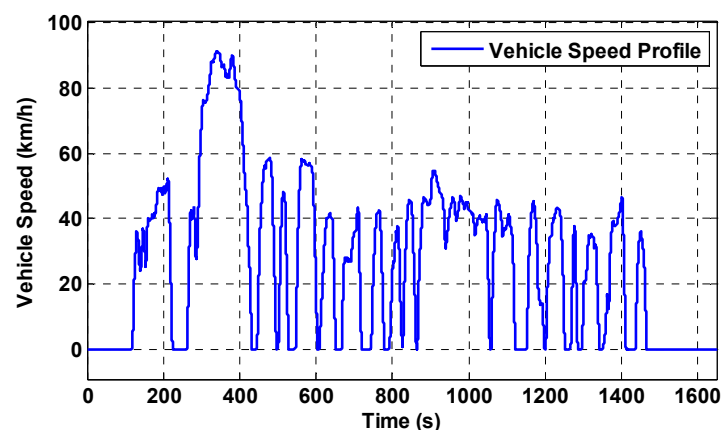
Figure 9. Test vehicle.

Table 3. Vehicle parameters.

Component	Parameter	Value	Component	Parameter	Value
Vehicle	Mass	5500 kg	Motor 1	Peak power	120 kW
				Rated power	75 kW
Engine	Type	Diesel	Motor 2	Peak power	120 kW
	Rated power	171 kW		Rated power	75 kW
Battery	Type	Li-ion Polymer	Generator	Peak power	120 kW
	Rated voltage	680 V			
	Rated capacity	31 Ah		Rated power	85 kW

4.1. System Characteristics Evaluation

In this study, to confirm the characteristics of the model, the test result of a real system's power load during the FTP-72 cycle, which has been commonly used as a fuel economy test, is inserted as the charged or discharged electric power in the battery system model. The FTP-72 cycle has fast and slow speed sets that are appropriate to show the loading of the highly transient power as shown in Figure 10.

Figure 10. FTP-72 driving cycle.

To confirm the battery system model, the current load has been input to the DC link terminal and the supervisory control commands such as the relay command have been input to the BMS model. In comparison with the test data, the actual terminal voltage of the battery and the simulation value is generated as shown in Figure 11a and there is some close-up part of the test data as shown in Figure 11b. The FTP-72 cycle has low and high speed regions, 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 of around 700 V, the result shows less than 2 percent error.

Furthermore, in order to evaluate the military tactics situation, the internal developed driving cycle as shown in Figure 12 is applied to the simulation. The internal developed driving cycle is based on the actual military tactics strategy.

In comparison with test data, the actual terminal voltage of the battery and the simulation value are generated as shown in Figure 13. From the result, it is clear that the difference between the simulation and the test result is very small compared to the entire driving cycle. In addition, the tendency of a

rise/drop is very similar. Since the test vehicle is a series type HEV, there are some charging cases in spite of the driving situation.

Figure 11. Battery characteristics evaluation result: (**a**) Entire cycle; (**b**) Partially close-up.


(**a**)

(**b**)
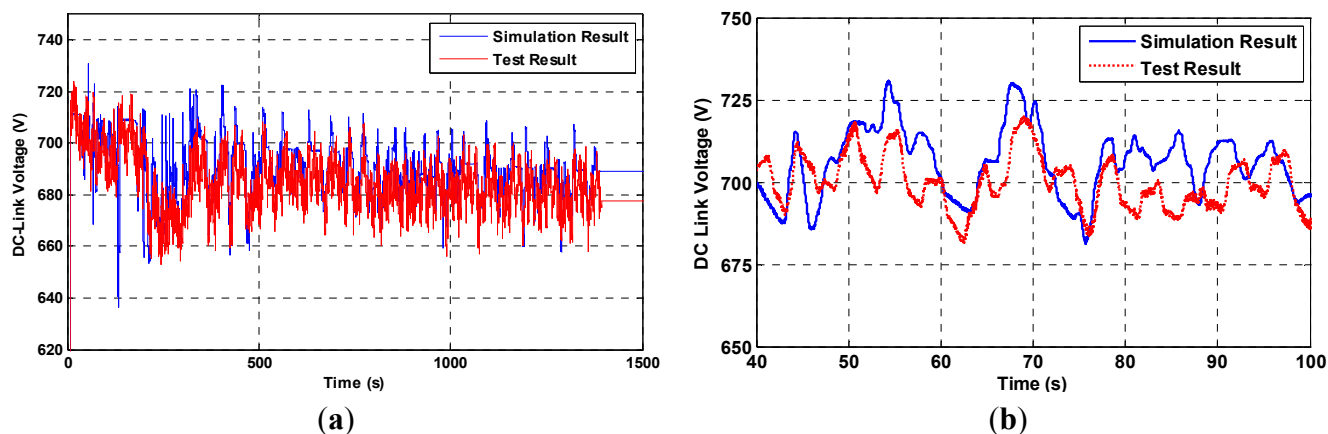
Figure 12. The internal developed driving cycle related to military tactics.
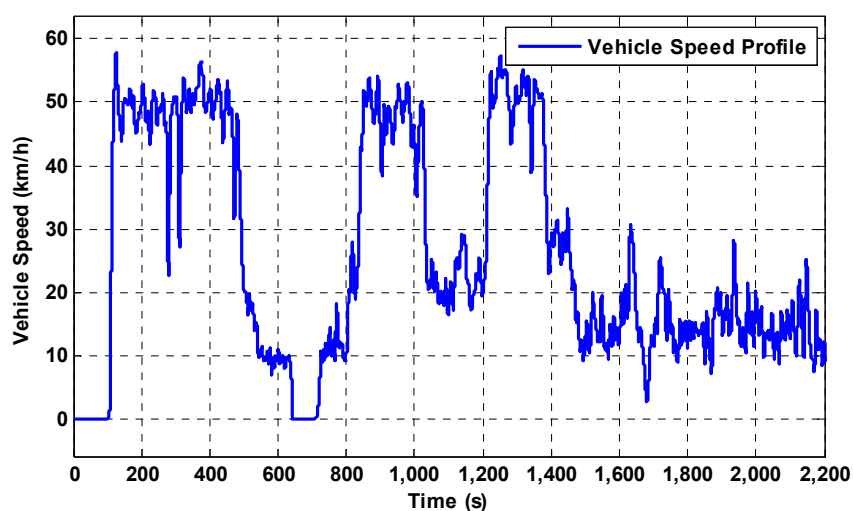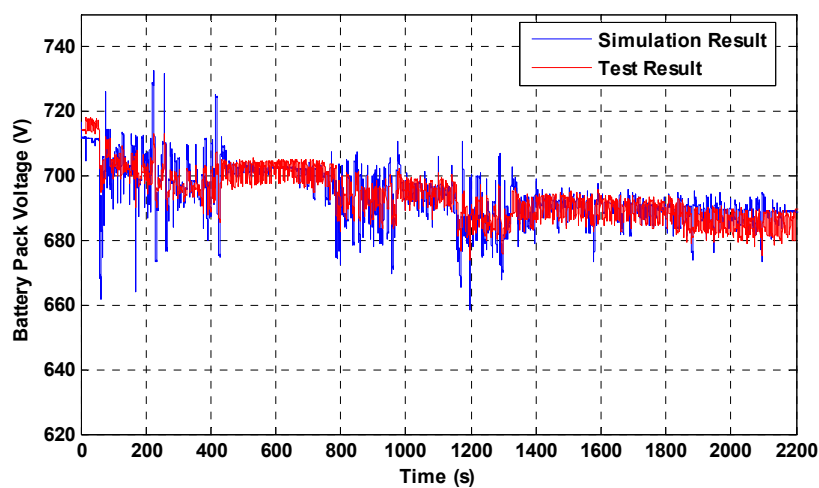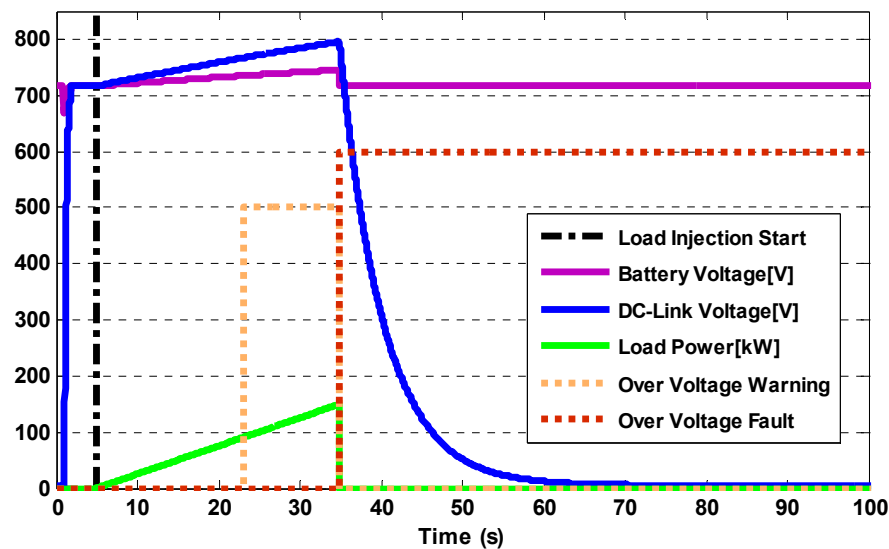

Figure 13. Battery characteristics evaluation result about the own driving cycle.

4.2. Fault Simulation

The test scenario of the fault simulation that is used to confirm the performance for the fault situation is the battery voltage variation for 100 s. To reflect a failure situation, the load power, one of the battery system's inputs, is handled by a specific fault scenario. With this condition, the BMS performed its own operations for fault diagnosis. Figure 14 shows the situation and results of this fault simulation.

Figure 14. Fault simulation result.

There is a command of the supervisory controller to close the relay at the one second instant, 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 of 5 s, the load power is increased gradually. Then, a warning flag occurs at 23 s on the basis of Table 1. Even at this point, there are no actions to prohibit the rise of the battery voltage. When the battery voltage exceeds the fault limitation, at 770 V, a fault flag is generated. Regardless of the supervisory controller's instruction, the relay is automatically operated by the own behavior of the BMS. From the evidence that the relay was opened and the current flow through the battery and the DC Link voltage decreasing rapidly, it is possible to confirm that the battery was separated from the DC Link. Through a fault simulation like this, the system developer can figure out how the failure of a battery system can affect other components of 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.

5. Conclusions

In this paper, a battery system model with a real-time property to evaluate the control and fault diagnosis strategies was developed. In the development process of a supervisory controller for the electric propulsion system, the proposed 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 so the developer can easily change the battery system specification.

2. Part of the battery system model is a fault simulation model to force the physical values freely. Furthermore, it has been configured to be able to accept an own fault diagnosis of the BMS to behave as the actual BMS. The results confirmed that the fault simulation of the battery system affects the other components in the configuration of the electric propulsion system. The purpose of this design is to reflect the design of the control strategy in the supervisory controller.

3. As future work, the proposed battery system model connecting other component models of an electric propulsion vehicle system will be designed to validate not only the control strategy of the overall system, but also the effect of a fault in the sub-system on the entire system. This performance evaluation environment shows promise as a fast and safe development process.

Acknowledgments

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Campbell, C.J.; Laherrere, J.H. The end of cheap oil. *Sci. Am.* **1998**, *273*, 78–83.
2. Pisu, P.; Serrao, L.; Cantemir, C.G.; Rizzoni, G. Hybrid-Electric Powertrain Design Evaluation for Future Tactical Truck Vehicle Systems. In Proceeding of the ASME International Mechanical Engineering Congress and Exposition, Chicago, IL, USA, 5–10 November 2006; pp. 271–278.
3. Hashimoto, T.; Yamaguchi, K.; Matsubara, T.; Yaguchi, H.; Takaoka, T. Development of new hybrid system for compact class vehicles. *Trans. Soc. Automot. Eng. Jpn.* **2010**, *41*, 43–47.
4. Linden, D.; Reddy, T. *Handbook of Batteries*, 3rd ed.; McGraw-Hill: New York, NY, USA, 2001.
5. Doyle, M.; Fuller, T.F.; Newman, J. Modeling of galvanostatic charge and discharge of the lithium/polymer/insertion cell. *J. Electrochem. Soc.* **1993**, *140*, 1526–1533.
6. Gu, W.B.; Wang, C.Y. Thermal-electrochemical modeling of battery systems. *J. Electrochem. Soc.* **2000**, *147*, 2910–2922.
7. Kawamura, A.; Yanagihara, T. State of Charge Estimation of Sealed Lead-Acid Batteries Used for Electric Vehicles. In Proceedings of the 29th Annual IEEE Power Electronics Specialists Conference, Fukuoka, Japan, 17–22 May 1998; pp. 583–587.
8. Bhatikar, S.R.; Mahajan, R.L.; Wipke, K.; Johnson, V. Neural Network Based Battery Modeling for Hybrid Electric Vehicles. In Proceedings of the 2000 Future Car Congress, Arlington, VA, USA, 2–6 April 2000; Paper No. 2000-01-1564.

9. Chan, H.L.; Sutanto, D. A New Battery Model for Use with Battery Energy Storage Systems and Electric Vehicle Power Systems. In Proceedings of the 2000 IEEE Power Engineering Society Winter Meeting, Singapore, 23–27 January 2000; pp. 470–475.

10. Johnson, V.H.; Pesaran, A.A.; Sack, T. Temperature-Dependent Battery Models for High-Power Lithium-Ion Batteries. In Proceedings of the 17th Electric Vehicle Symposium, Montreal, Canada, 15–18 October 2000.

11. Xie, H.; Ding, Y.B. The Study of Plug-in Hybrid Electric Vehicle Power Management Strategy Simulation. In Proceedings of the 2008 IEEE Vehicle Power and Propulsion Conference (VPPC), Harbin, China, 3–5 September 2008; pp. 1–3.

12. Xu, C.H.; Niu, J.G.; Pei, F.L. Design and Simulation of the Power-Train System for an Electric Vehicle. In Proceedings of the 2011 2nd International Conference on Artificial Intelligence, Management Science and Electronic Commerce (AIMSEC), Zhengzhou, China, 8–10 August 2011; pp. 3868–3871.

13. Johnson, V.H. Battery performance models in ADVISOR. *J. Power Sources* **2002**, *110*, 321–329.

14. Aziz, A.; Shafqat, M.S.; Qureshi, M.A.; Ahmad, I. Performance Analysis of Power Split Hybrid Electric Vehicles Using Autonomie. In Proceedings of the 2011 IEEE Student Conference on Research and Development, Cyberjaya, Malaysia, 19–20 December 2011; pp. 144–147.

15. Zhang, P.Z.; Yin, C.L.; Zhang, J.W.; Chen, L. Integral power management strategy for a complex hybrid electric vehicle—Catering for the failure of an individual component. *Proc. Inst. Mech. Eng. D J. Automob. Eng.* **2008**, *222*, 719–727.

16. Ehsani, M.; Gao, Y.; Emadi, A. *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2009.

17. Jang, J.H.; Yoo, J.Y. Impedance-based and circuit-parameter-based battery models for HEV power systems. *Int. J. Automot. Technol.* **2008**, *9*, 615–623.

18. Kim, T. A Hybrid Battery Model Capable of Capturing Dynamic Circuit Characteristics and Nonlinear Capacity Effects. Master's Thesis, University of Nebraska, Lincoln, NE, USA, July 2012.