Mathematical Model of Hybrid and Electric Cars Control System

Vladimir Kozlovsky[1*]

[1]Samara State Technical University, Molodogvardeyskaya street, 244, Samara, 443100, Russia

Abstract. The paper presents development results of the complex of simulation mathematical models of real-time and algorithms for a semi-natural test bench of the control system of a high-voltage storage battery of hybrid vehicles. They are designed to control the physical model of the test bench, simulating the characteristics of the cells of the high-voltage storage battery and other components that make up the high-voltage storage battery. This study aims to implement a complex of mathematical models and software with the required accuracy of parameters and signals that simulate the behavior of a real high-voltage battery. That intended for the development and testing of mathematical algorithms and software for the control system of a high-voltage battery of a hybrid vehicle. The main features of the developed models are an imitation of the characteristics of the cells of a high-voltage storage battery with the ability to set the initial state-of-charge (SOC) and change the charge during the operation of the model. The data were used to develop and evaluate a mathematical model of a high-voltage storage battery cell. The operating result contributes to the acceleration of the software development process for electrical complexes and control systems for high-voltage batteries for hybrid vehicles.

1 Introduction

Lithium-ion batteries are widely used in electric land and hybrid power vehicles because of their low self-discharge, high energy density, and specific capacity. Features of the charging and discharging characteristics of lithium-ion batteries, together with the wide temperature range of their application, make them the main rechargeable electrical energy sources for this type of vehicle. Nevertheless, lithium-ion batteries are very sensitive to overvoltage, overheating, operation at negative temperatures, exceeding the permissible charge and discharge current. Out of the permissible operating modes of the high-voltage battery leads to a decrease in the resource and the failure of the high-voltage battery. Therefore, the most important task when creating a high-voltage storage battery is to reduce the cost, ensure the required safety, increase the resource and extend the life cycle of the high-voltage battery. The optimal design of the storage cell, high-voltage battery, and high-voltage battery management system should be developed[1-4]. To create an effective control system for the processes occurring in the cells of a high-voltage battery, a mathematical simulation model

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* Corresponding author: kozlovskiy-76@mail.ru

is required to be created which studies physical processes and selects the optimal configuration and settings of the control system.

2 The mathematical simulation model

The concept of a physical model of a high-voltage battery was developed to create a mathematical model of a high-voltage battery. The concept includes such elements as the control and balancing unit of the module (BCU), which is part of the electronic control unit (ECU) of the high-voltage battery. That monitors the voltage of each individual cell and balances it [2-8].
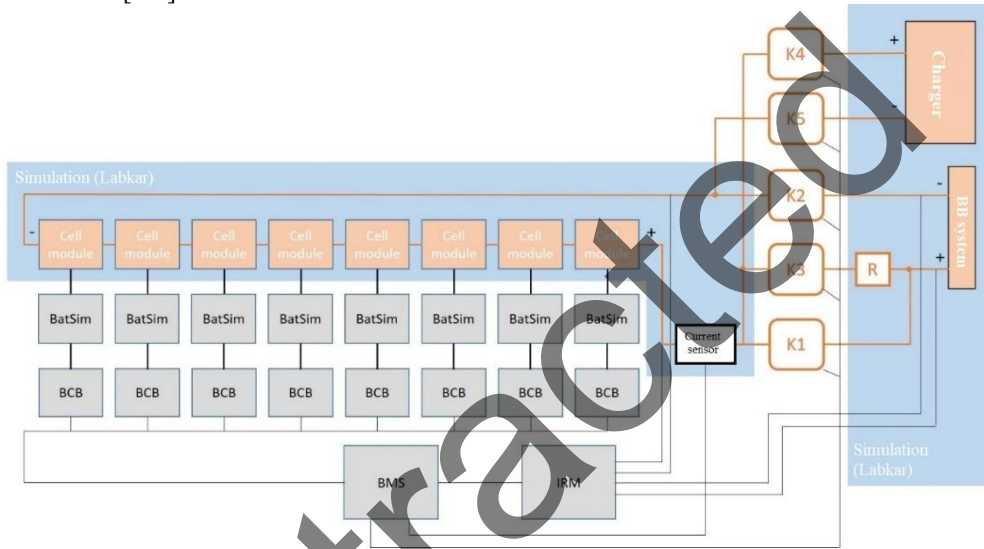
Fig. 1. The physical model of a high-voltage battery.

Simulation of the battery cells, current sensor, charger, and high-voltage control system is performed using MATLAB Simulink on the Labcar ETAS real-time platform in the proposed concept. Contactor modules (Kx) and module control and balancing units, battery management systems and insulation monitoring modules are real physical objects. The software part of the simulation complex also contains a load and temperature model, a protective insulation model, a VCU (Vehicle Control Unit) simulation, and a failure model [9-13].

The high-voltage storage battery model consists of three parts: state machine model, battery cell model, charge calculation model.

1. The state machine model

The state machine model is needed to determine the on\off mode of the battery and turn on the precharge of the electrical circuit from the battery control unit. The model implements a state machine with three modes of battery operation: sleep mode, precharge (capacities of the inverter and power wires), and operating mode (charge/discharge). The signal about the need to change the operating mode comes directly from the contactors, which are controlled by the BMS. This model also includes a pre-charge resistor and wiring and inverter capacitance.

Inputs and outputs of the state machine model include:

- Inputs:

K1_HV+, K2_HV-, K3_Precharge - signals from battery contactors, which are used to simulate battery on\off and precharge of the electric circuit of the hybrid system.

I_load - battery charge\discharge current.

V_batt - the initial voltage in the battery, when the battery is turned on, used to simulate it at the time of pre-charging the electrical circuit.
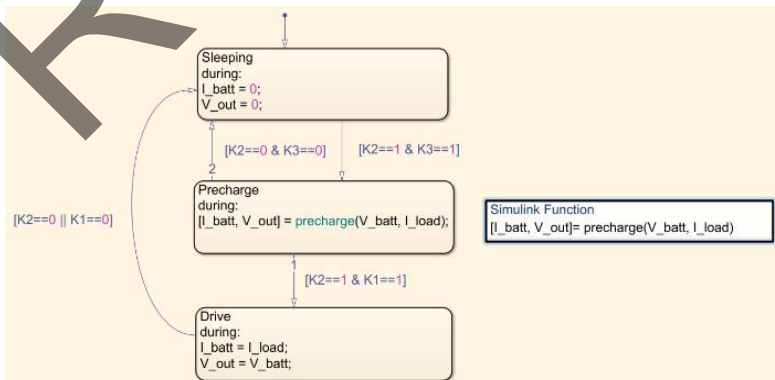
- Outputs:

I_batt - battery charge\discharge current, output from the mathematical model of the electric circuit precharge.

V_out – battery voltage, output from the mathematical model of the electric circuit precharge.

Sleeping, Drive, Precharge – battery states "Off", "On", "Precharge".
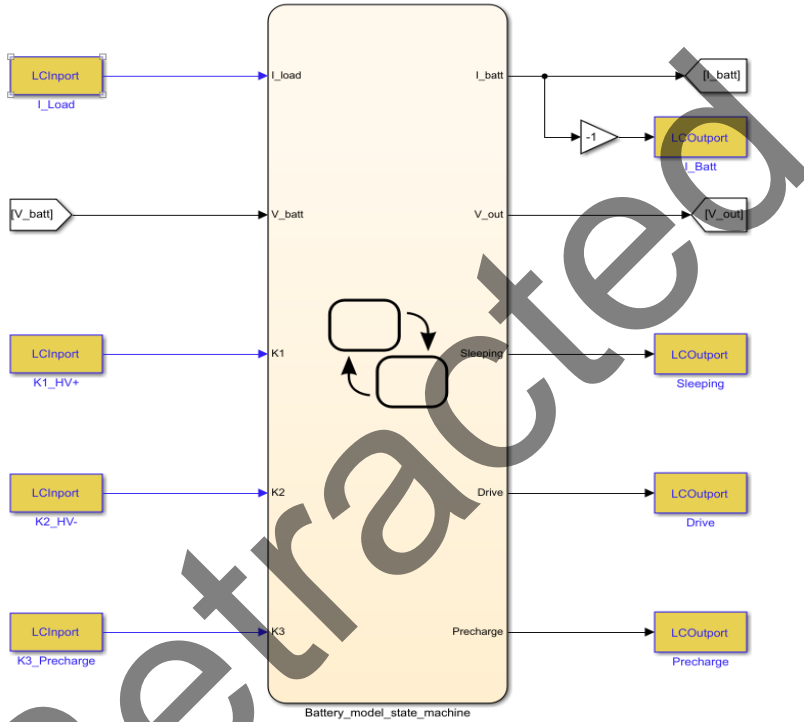
Fig. 2. State machine model.

Fig. 3. State machine (algorithm).

The precharge mode is necessary to charge the capacitance in the electrical circuit of the hybrid system. When the K3_Precharge signal is present, the voltage rises from 0 to a value

equal to the battery voltage. The mathematical model simulates an RC circuit, where R is the resistance of the precharge resistor, C is the total capacitance of the electric circuit of the hybrid system, which includes the capacitance of the high-voltage filter of the inverter and the capacitance of the wires.

The charge of a capacitor with a capacity C from a current source through an external resistance is described by the formula:
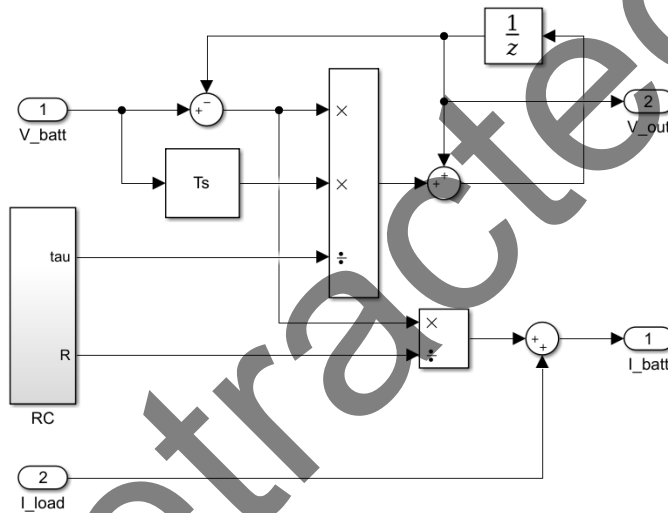
$$U_t = U_0(1 - e^{-\frac{t}{T}})$$

(1)

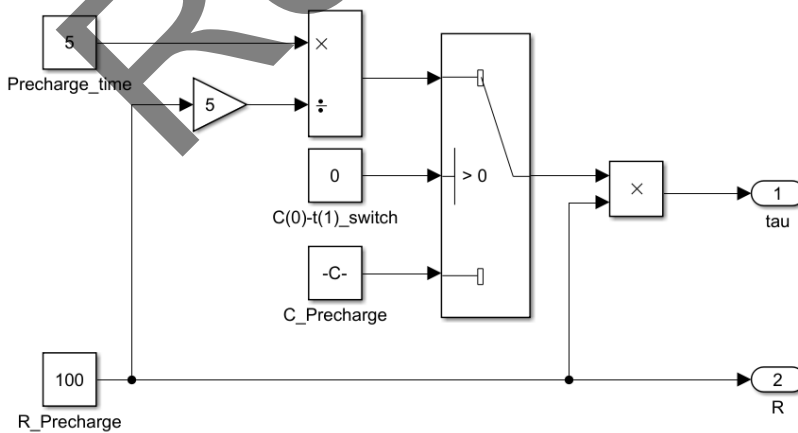where U_0 is the initial voltage, T is the time constant, t is the charging time.

The instantaneous charging current is described by the formula:

$$i_t = \frac{U_0}{R} e^{-\frac{t}{T}}$$

(2)

where R is the resistance of the precharge resistor.

Fig. 4. Simulation model for calculating the output voltage and current of the capacitor charge from the known resistance and charge time.

Fig. 5. Simulation model for calculating the precharge time from the known resistance and capacitance of the electrical circuit.

2. The battery cell model

The equivalent cell model is an empirical mathematical model that is derived from experimental data. The input signals to the model are the current strength and the initial SOC (State Of Charge) of each module. The initial SOC is set during the simulation phase. The output signals are the current SOC of each module and the instantaneous voltage of each module and the battery in general. The battery model simulates electrical performance as a function of cell temperature and load.

3. The charge calculation model

The model calculates the current-voltage and charge of the battery based on the electricity consumption in ampere-hours. The quantity of electricity:
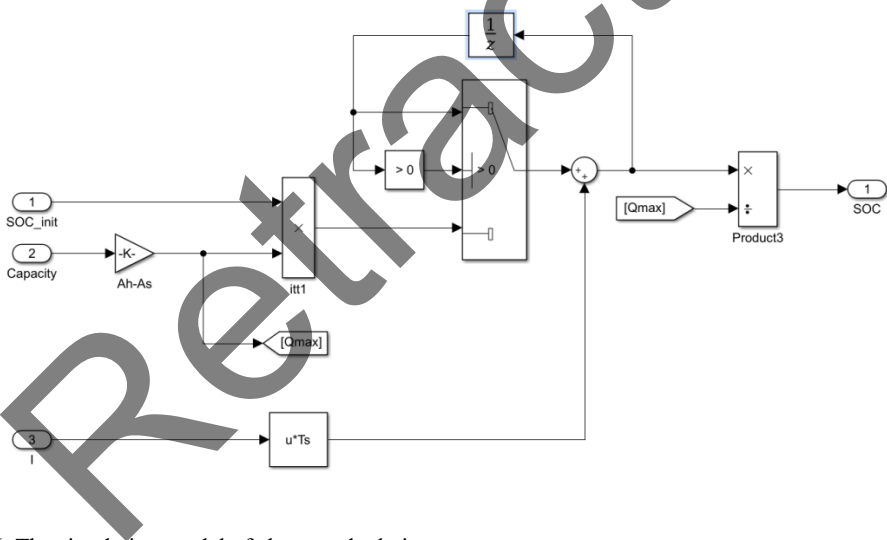
$$Qbat = \int_0^t I_m(\tau)d\tau, \tag{3}$$

where I_m is the instantaneous current per unit of time $d\tau$

The charge of the cell, in this case, will be calculated as follows:

$$SOC = SOC(t_0) + \frac{1}{C_{nom}} \int_{t_0}^{t_0+\tau} I_{bat} dt, \tag{4}$$

where $SOC(t\_0)$ is the initial battery charge, C_{nom} is nominal capacity, I_{bat} is the current flowing through the battery.

The simulation mathematical model of the charge is presented below:

Fig. 6. The simulation model of charge calculation

This mathematical description of the battery model allows us to carry out calculations evaluating the operating modes of the BMS system and the hybrid control and power supply system.

3 Conclusion

The working results of creating a complex of simulation models of a high-voltage battery are presented in this paper, which reproduces the characteristics and operating modes of a real high-voltage battery with high accuracy.

The modes of switching on the contactors of the high-voltage battery and monitoring the pre-charge of the high-voltage battery were optimized by using the high voltage battery state machine model.

The creation of a charge model having the ability to individually set the initial charge for each high-voltage battery cell allowed to develop and test algorithms for balancing high-voltage battery cells and modules.

The developed complex of imitation models of the BB battery made it possible to speed up and simplify the process of developing and verifying algorithms, software, and hardware for ECU of the BB battery and the control units and balancing modules.

A battery cell simulation model allows the reproduction of the characteristics of various types of cells and capacities with appropriate parameterization. The cell model reproduces the electrical characteristics of a lithium iron phosphate cell in this paper.

The developed models contain algorithms for checking the fault tolerance of the tested software and ECU. Based on the test results, algorithms for reactions to the failure of high-voltage battery components were developed and implemented in the high-voltage battery ECU by using these models.

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