LI-ION BATTERY MODEL WITH ELECTROTHERMAL DYNAMICS

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Introduction. Power storage systems are components of power systems, renewable energy, back-up power systems, and electric transport. They work in standby, energy saving, energy recovery and combined modes. Electrochemical storage systems are used to store electrical energy due to electrochemical processes. These systems have the following advantages: efficient energy storage, flexibility in energy management, reliability and durability, the ability to quickly release energy, environmental friendliness and the possibility of integration with renewable energy sources. Various types of batteries are used in electrochemical systems: lead-acid, nickel-cadmium, nickel-iron, lithium-ion (lithium-iron-phosphate) and others. Li-ion batteries are the most widely used in electric energy storage systems due to high energy storage density, small dimensions, low self-discharge, durability and environmental friendliness [1-3].

The efficiency of the control of electric energy storage systems depends on the electrical and thermal models of the battery, which allow accurate determination of battery temperature, static and dynamic processes, battery state of charge (*SOC*) and battery health (*SOH*) [4]. Therefore, the study of Li-ion battery characteristics based on the equivalent substitution circuit, which describes the behavior of the battery during charge/discharge cycles, is an urgent problem for students of the specialty 141 "Electric power engineering, electrical engineering and electromechanics".

The purpose of the work. Investigation of dynamic characteristics of Li-ion battery during charge and discharge cycles using electrothermal dynamics battery simulation model in modern Matlab programming environment based on Simscape language.

Materials and research results. To study the static and dynamic modes of operation of various types of Li-ion batteries, Thevenin models of the second and higher orders are used. These battery models take into account polarization effects that lower the voltage value. Electrochemical polarization characterizes the slowing down of reactions at the electrode, and concentration polarization shows that lithium ions do not have time to diffuse to the electrodes at the required speed [1].

The structure of the equivalent circuit is presented in fig. 1. Variable active resistance $R_0(SOC,T)$ characterizes energy losses in the battery due to the resistive elements of the battery (Ohm). Where *SOC* (State of Charge) is a parameter that shows the state of battery charge (%). *T* (Temperature) – battery temperature (C^o or K). Variable active resistances $R_1(SOC,T)$ and $R_2(SOC,T)$ characterize electrochemical (first) and concentration (second) polarization (Ohm). Variable effective capacities $C_1(SOC,T)$ and $C_2(SOC,T)$ are used to describe transient reactions during energy transfer (F). Variable active resistance $R_{SD}(T)$ (Self Discharge Resistor) characterizes the influence of the internal currents of the battery in the mode of idle operation (self-discharge) (Ohm).

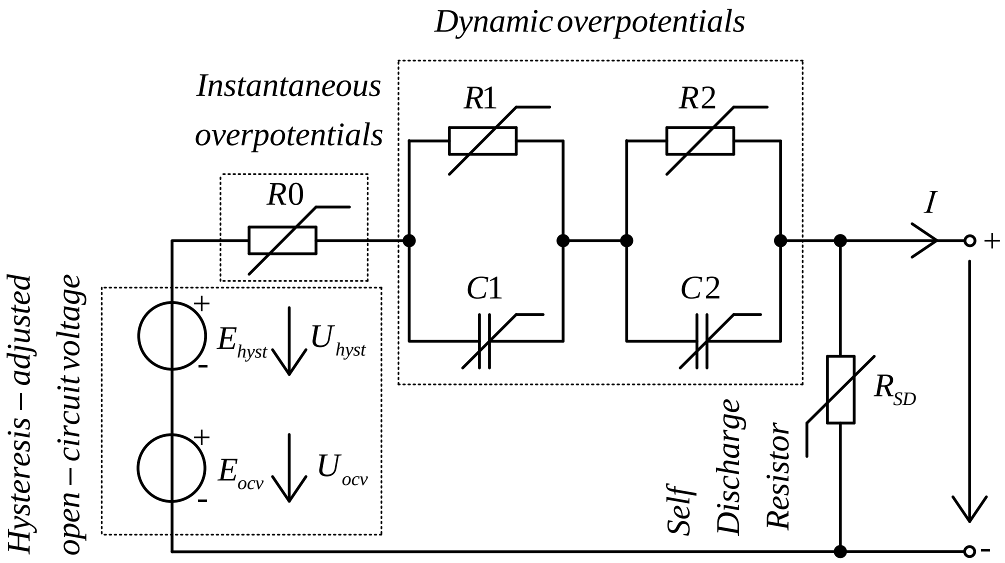

Figure 1 – Equivalent circuit diagram of battery

The voltage at the terminals of the equivalent battery replacement circuit U is determined from Kirchhoff's second law

$$U = \boxed{U_{OCV}(SOC,T) + U_{hyst}(SOC,T)} + \eta_{inst}(SOC,T,CurDir) + ... \\ ... + \eta_{dyn}(SOC,T,CurDir), \quad (1)$$

where $U_{OCV}(SOC,T)$ – non-operating voltage (open circuit voltage);

$U_{hyst}(SOC,T)$ – hysteresis voltage;

$\eta_{inst}(SOC,T,CurDir) = I \cdot R_0(SOC,T,CurDir)$ – instantaneous overvoltage;

$CurDir$ – direction of current during battery charging or discharging;

I – battery current (negative sign when discharging and positive sign when charging the battery);

$\eta_{dyn}(SOC,T,CurDir) = \sum_{i=1}^{2} \Delta U_{RCi}(SOC,T,CurDir)$ – dynamic overvoltage;

$\Delta U_{RCi}\left(SOC,T,CurDir\right) = \dfrac{I \cdot R_i\left(SOC,T,CurDir\right)}{\tau_i\left(SOC,T,CurDir\right) \cdot p + 1}$ – voltage for parallel pair RC; $\tau_i = R_i C_i$ – time constant for a parallel RC pair;

$p \to \dfrac{d}{dt}$ – the Laplace operator;

i – parallel pair number RC, which is associated with the corresponding polarization.

Taking into account the dynamics of the battery when changing the load(charge/discharge) is carried out using parallel RC sections in the equivalent circuit (Fig. 1). The voltage value on the first parallel RC section is due to the activation overvoltage from the chemical reaction at the electrode interface. Time constant $\tau_1 < \tau_2$, which indicates faster dynamics. The voltage drop on the second parallel RC section is associated with concentration overvoltages and has slower dynamics than the activation overvoltage.

Using the Coulomb counting method, the battery's state of charge is calculated SOC

$$SOC = \frac{1}{C_{aged}} \cdot \frac{dq}{dt} = \frac{1}{C_{aged}}\left(I - I_{D,SD}(T)\right) = \frac{1}{C_{aged}}\left(I - \frac{1}{R_{SD}(T)}U_{OCVinternal}\right), \qquad (2)$$

where C_{aged} – the capacity of the battery cell, which takes into account its aging;

$I_{D,SD}(T)$ – self-discharge current;

$R_{SD}(T)$ – active resistance to self-discharge;

$U_{OCVinternal}$ – internal voltage of the idle stroke.

The equivalent battery diagram takes into account the battery's heat generation rate $\frac{dQ_{gen}}{dt}$ (heat generation rate)

$$\frac{dQ_{gen}}{dt} = P_{diss} + \frac{dQ_{rev}}{dt} + Q_{flow,exr}, \qquad (3)$$

where

$$P_{diss} = I^2 \cdot R_0(SOC,T,CurDir) + \eta_{dyn}(SOC,T,CurDir) \cdot I + \frac{1}{R_{SD}(T)}\left(U_{OCVinternal}\right)^2 + ...$$

$... + Q_{flow,series} + Q_{flow,parallel}$ – dissipation power;

$Q_{flow,series}$ – thermal flow of a series resistor;

$Q_{flow,parallel}$ – heat flow of a parallel resistor;

$\frac{dQ_{rev}}{dt} = I \cdot T \cdot \frac{dU_{OCV}}{dt}(SOC)$ – heat recovery;

$Q_{flow,exr}$ – heat flow of an exothermic reaction.

Using a single-state model, the battery hysteresis voltage is simulated $U_{hyst}(SOC,T)$ (dependence of the idle voltage on the charge or discharge history)

$$U_{hyst} = M \cdot H + \mathrm{sgn}(I) \cdot M_0;$$
$$\frac{dH}{dt} = \frac{\gamma}{C_{aged}}\left(I - |I|H\right), \qquad (4)$$

where H – hysteresis state;

γ – hysteresis speed;
M – value of the maximum hysteresis voltage;
M_0 – value of the instantaneous hysteresis voltage parameter.

In idle mode, the battery terminals are open, but there are internal currents that discharge the battery. This behavior is called self-discharge. This phenomenon is taken into account by using a resistance $R_{SD}(T)$ in the equivalent circuit of the battery, the value of which depends on the temperature.

The thermal model calculates the battery temperature for each moment in time

$$M_{th}\frac{dT}{dt}=\left(\frac{dQ_{gen}}{dt}\right)-\frac{dQ_{diss}}{dt}\left(=P_{diss}+\frac{dQ_{rev}}{dt}+Q_{flow,exr}\right)-\frac{dQ_{diss}}{dt}, \qquad (5)$$

where M_{th} – thermal mass of the battery;

$\frac{dQ_{diss}}{dt}$ – heat through the heat port **H**.

Conclusion. The battery model with electrothermal dynamics consists of electrical and thermal models. The electrical model is based on the equivalent circuit of the battery replacement (Thevenin model of second and higher orders) and is able to take into account polarization effects that reduce the idle voltage. The equivalent circuit model accurately shows the behaviour of the Li-ion battery during static and dynamic modes. This allows you to predict the performance of the battery under different operating conditions. Also, the electrical model can take into account hysteresis voltage, cyclic and calendar aging. The thermal model determines the temperature of the battery for each instant of time.

References

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