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Original scientific paper

Li-ION BATTERY BEHAVIOUR IN AN ELECTRIC VEHICLE DRIVE SIMULATION

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Abstract: Due to various environmental factors, as well as the fuel supply limits, the fully-electric vehicles are more often seen as an alternative to the classic fuel-powered vehicles nowadays. Given that one of the most important aspects of the vehicles on the market is the fuel consumption, it is logical to take the state of charge (SOC) of the batteries during the vehicle performance into consideration, which is not measurable trivially during vehicle operation. The aim of this paper is to predict the behavior of a Li-ion NMC battery against a custom input from the driver, using a model of a full electric vehicle in a simulation environment (Matlab/Simulink).

Key words: electric vehicle; state of charge; regenerative braking; Li-ion battery

ОДНЕСУВАЊЕ НА ЛИТИУМСКИТЕ-ЈОНСКИ БАТЕРИИ ВО СИМУЛАЦИЈА НА ЕЛЕКТРИЧНО ВОЗИЛО

Апстракт: Поради многубројните еколошки фактори, како и ограничените количи гориво кои се на располагање, целосно електрични возила сѐ почесто се гледаат како алтернатива за класичните возила. Земајќи предвид дека еден од најбитните аспекти на возилата на пазарот е потрошувачката на гориво, логично е следствено да се разгледува и состојбата на наполнетост на батериите, којашто не може да биде директно измерена во текот на работата на возилото. Целта на овој труд е да се предвиди однесувањето на литиумска *NMC* батерија при произволен влез во системот зададен од страна на возачот, користејќи на модел на целосно електрично возило во симулациона околина (Matlab/Simulink).

Клучни зборови: електрично возило; состојба на наполнетост; регенеративно кочење; литиумска батерија

1. INTRODUCTION

With the rise of the electric vehicle industry, the application of Li-ion batteries has increased. Naturally, the need for real-time calculations of the remaining available capacity occurs, which is why a lot of researchers constantly work towards finding an effective way for calculating the state of charge. The state of change (SOC) is an important parameter, because it indicates the remaining capacity and reflects the battery performance, as mentioned, and can therefore prevent overcharging or impact the motor control strategies.

One of the main problems with the SOC is that it is not a directly measurable parameter due to the chemical nature of the battery. It is the reason why alternative mathematical models for approximation of its value are needed.

Theoretically, the state of charge of a battery can be defined as the ratio of its current capacity and nominal capacity, which is stated by the manufacturer and represents the maximum capacity a battery can hold (equation 1) [1].

$$SOC\ (t) = \frac{Q(t)}{Q_n} \qquad (1)$$

Another important aspect when calculating the state of charge is the temperature of the batteries, given its impact on the latter parameter through the capacity, which will be discussed in more detail further in this paper.

Moreover, when monitoring the SOC, the regenerative braking, one of the most revolutionary innovations towards maintaining capacity in the vehicle energy source, must be taken into account. During the regeneration mode, the SOC value is expected to increase, thus making greater amount of electrical capacity available for further use and expanding the expected drive range of the vehicle.

Throughout this paper, a mathematical model of the electric vehicle drivetrain and the batteries, considering parameters of interest and excluding the vehicle dynamics, will be presented. Furthermore, the relevant method for determining state of charge levels will be explained. Lastly, the results of a simulation against a custom input will be presented and discussed.

ELECTRIC VEHICLE MODEL

The model used is based on a fully-electric vehicle drive train, with such architecture as shown in Figure 1. It is assumed that the motor is a permanent magnet motor or a high efficiency Permanent Magnet Synchronous Motor (PMSM) [3], which has been widely utilized by numerous vehicle manufacturers, such as Honda, Toyota and Nissan [2, 7]. It has an ideal motor controller, combined with a PI controller, which factors in the battery error i.e. the difference between the actual battery terminal voltage and the one required by the controller [3, 4] The schematic model of the electric motor is shown in Figure 2.

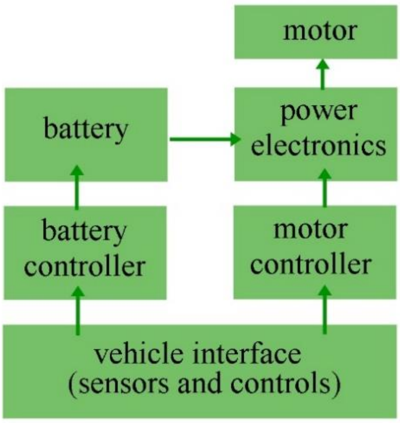


Fig. 1 Electric vehicle drive train

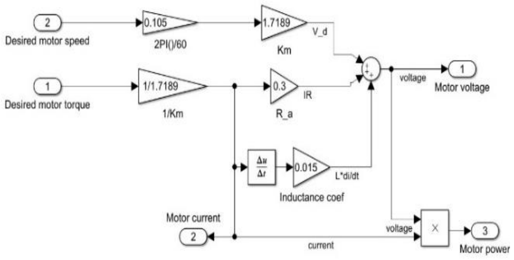


Fig. 2. Electric motor schematic model

The developed torque for this type of motors is calculated as a product of the armature current I_a and the motor constant K_m, given with equation 2. Whereas the developed voltage is proportional to the motor speed (equation 3), as stated in [3].

$$T_d = I_a \cdot K_m \tag{2}$$

$$V_d = \frac{\omega_m}{K_m} \tag{3}$$

Motor controller

The selected type of electric motor uses AC voltage supplied from the motor controller at the right frequency. The relation between the voltage needed for the motor to work in the desired manner, referred to as *high-side voltage* V_H, and the one distributed to the motor controller, or the *low-side voltage* V_L, can be expressed through equation 4, assuming no power loss and no time lag, i.e. an ideal controller:

$$V_H = K \cdot V_L. \tag{4}$$

Here, K symbolizes the controller gain value obtained from the PI controller, whose task is to minimize the *"battery error"* B_{ERR}, as mentioned above. The value of K is calculated through equation 5, where the symbols K_P and K_I indicate the proportional and integral gain, respectfully:

$$K = (K_p + s \cdot K_I) \cdot B_{ERR}. \tag{5}$$

The schematic representation of the motor controller model is shown in Figure 3 [3].

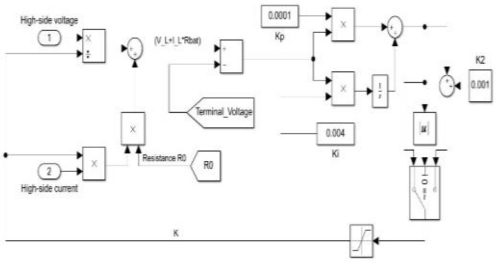


Fig. 3. Motor controller schematic model

Battery model

Li-ion NMC (Lithium-Nickel-Manganese-Cobalt-Oxide) battery is one of the most widely used energy sources in the electric vehicles as of 2020 [1, 6]. A model of Li-ion NMC battery was used in this simulation. As mentioned in the previous section, there are various mathematical methods for estimation of parameters of interest, some of which include indirect measurements through measurable physical battery properties, such as voltage and impedance, book-keeping estimations, adaptive systems through neural networks or SVM, as well as some hybrid methods. In this simulation, the Coulomb coupling method, as one of the book-keeping methods, was used. This estimation method uses the battery discharging current as input, which in this case signifies the current that the motor draws from the energy source, in order to function in the desired manner. Furthermore, the previously estimated SOC values are being used. The current state of charge is calculated in the following manner (equation 6, also shown in Figure 4):

$$SOC\ (t) = SOC\ (t-1) \pm \int \frac{I\ (t)}{Q_n} dt. \qquad (6)$$

It is important to note that the temperature of the battery, which indirectly affects the SOC, is also considered, given that the capacity $C = f\,(T)$. On the other hand, the temperature of the cell can be evaluated using the following equation 7:

$$T = \int \frac{P_{loss} + h_{conv} \cdot A_c \cdot \Delta T}{m_c \cdot C_p} dt \qquad (7)$$

The initial temperature is assumed to have the value of 293.15 K i.e. the standard room temperature.

Disadvantage of this mathematical method of estimation is that the initial value of the state of charge should always be known prematurely, which is almost impossible in real conditions. However, the initial value of the SOC in this simulation is assumed to be 1 (100%), i.e. a fully-charged battery [1].

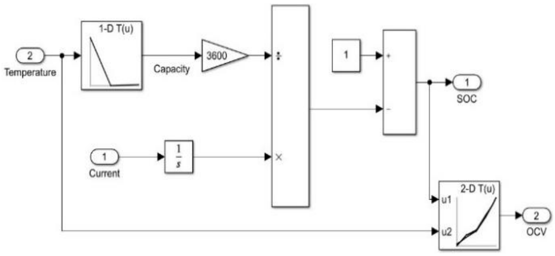


Fig. 4. Estimation of the battery SOC and OCV

Another important parameter, which is one of key factors in control strategy, is the internal cell resistance R_0, which is calculated as a function of the SOC and the temperature, using a lookup table with experimentally gathered data, as shown in Figure 5 [5].

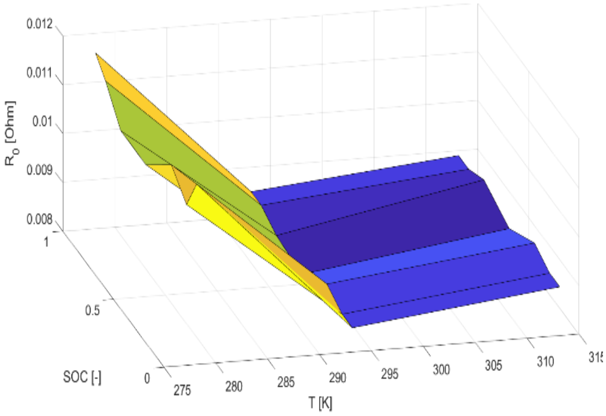


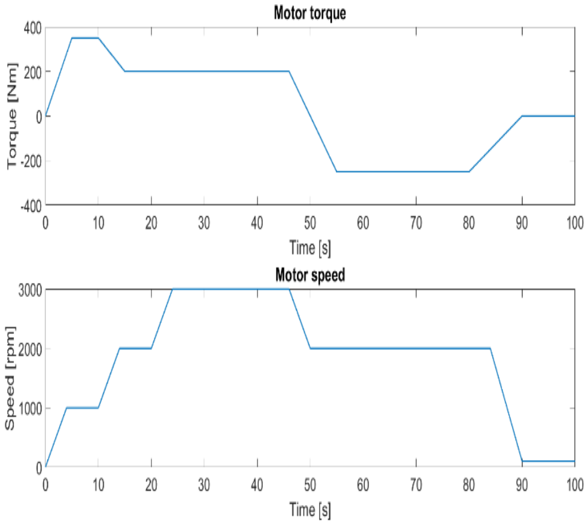
Fig. 5. Internal resistance in function of the SOC and temperature [5]

SIMULATION

In this section, the simulation process will be elaborated. Firstly, the input signals will be presented. Afterwards, the gathered results will be discussed.

Input signals

As mentioned earlier, the aim of this paper is to observe the behaviour of the Li-ion battery against a custom input from the driver. Given the vehicle model utilized in this simulation, the input (Figure 6) consists of motor torque (Nm) and speed (rpm) values, mimicking the desires of the driver, over the span of 100 seconds. By observing these signals, a conclusion can be drawn that the motor will be working in forward motoring mode in the first 50 seconds of the simulated time, due to the positive values of both the motor torque and speed, which consequently means that the SOC is expected to get lower, i.e. the motor withdraws the energy from the batteries in order to maintain proper function. On the other hand, the values of the torque in the second half of the examined time are negative, whereas the motor speed remains positive, hence the motor is expected to work in forward regeneration mode, which is when a rise in the SOC value is expected. In this mode, the motor doesn't need the energy from the batteries, thus there is a positive energy flow towards them.



Fig, 6. Input values for the electric motor model [3]

However, since the accentuated parameters are those of the battery, it is also important to get an adequate input signal for the battery model. Namely, the motor model is used to acquire the values for the necessary motor current, i.e. the above-mentioned high-side current, which is technically the current withdrawn from the energy source and will be used as an input in the battery model (Figure 7).

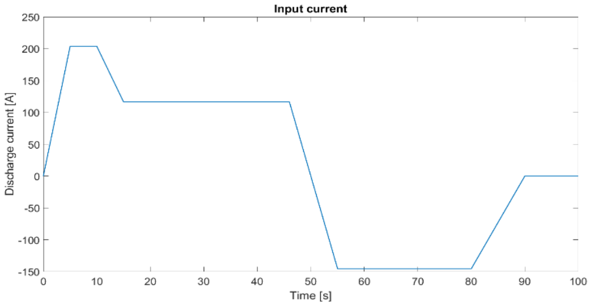


Fig. 7. Discharge current of the battery

Simulation results

The results of the software simulation, referring to the parameters as discussed above, are shown in Figures 8 and 9. As can be seen in Figure 8, the state of charge in the first moment of the observed time is 1, meaning that the battery has been fully charged. As expected, since the motor works in a forward motoring mode in the first half, the SOC value constantly drops, until it reaches its lowest level at 94%, when the value of the dischargeing current becomes negative, leading to a forward regeneration mode of the motor and thus recharging the battery, consequently increasing the SOC value. At the end of the simulation, it can be stated that the SOC has experienced a 1.15% drop in value, which is significantly better than the 6% drop that would've occurred without the regenerative braking.

In addition, the behaviour of the open circuit voltage can be observed. One can state that the values of the OCV throughout the whole simulation correspond to the nominal OCV values of a fully-charged battery, as is the case here. The OCV behaves in a similar fashion as the SOC, which is expected, taking into consideration the correlation between the two (shown in the previous section).

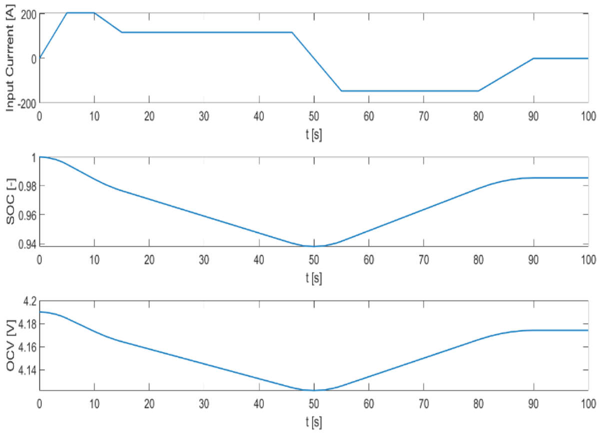


Fig. 8. Simulation results (from top to bottom: input current, state of charge, open circuit voltage)

The temperature of the batteries (Figure 9), whose starting value is assumed to correspond to the standard room temperature (293.15 K), continuously rises over the course of the observed time, until it reaches its final value of 315,51 K. This rise affects the value of the nominal capacity of the battery at a given time.

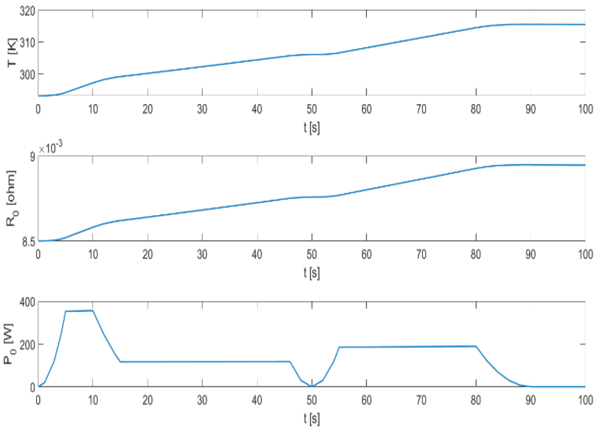


Fig. 9. Simulation results (from top to bottom: temperature, internal resistance, power loss due to internal resistance)

Consequently, a rise in the value of the main resistance, also referred to as ohmic resistance, can be noted. Given the data and the relations presented in the previous section, this change over time is expected. Additionally, there is also an internal resistance caused by the charge transfer, which was intentionally left out in the results set due to its neglectfully small values.

As can be stated from the graphs, the temperature and resistance do not behave in the same fashion as the previously discussed parameters, i.e., they are not affected by the current's change of direction. The reason for this is that there is still current flow present, whereas the flow direction itself is irrelevant.

Lastly, the power loss of the battery due to the internal resistance can be observed. The flow of the power loss graph can be associated with the behaviour of the discharge current, given that it can be represented as a function of the voltage drop and said current [5]:

$$P_0 = \Delta V \cdot I = R_0 \cdot I^2. \tag{8}$$

Taking this relation into consideration, the null-values of the power loss can be justified with the null-values of the current, i.e. the voltage at the given times.

DISCUSSION AND CONCLUSIONS

This paper presents modelling and simulation of the behavior of a Li-ion NMC battery because it finds vast applicability in the electric vehicles. It includes both, the motoring and regeneration modes of the electric motor, meaning both the charging and discharging of the batteries were taken into account. One of the main issues of the electric vehicle modeling is the estimation of the SOC value, which cannot be done in a trivial manner. Coulomb coupling method was used during this study as one of the most common estimation methods. The weakness of this model is its inability to estimate the SOC value at the beginning of the observed period, which is a crucial data piece and cannot always be estimated, as it was done in this simulation.

Nevertheless, from the results it is concluded that the battery itself, without the regeneration mode of the motor, would not serve the vehicle needs sufficiently, due to the relatively high SOC losses over time. However, due to the utilization of the reverse-direction current flow from the motor, a significant rise in the SOC value can be noticed.

The results of this simulation are satisfactory, widening the opportunity for further installation of this type of batteries into electric vehicles. Considering the right configuration of battery parameters for certain type of electric vehicle would give even better battery behavior and millage for fully electric vehicles.

NOMENCLATURE

SOC	state of charge
OCV	open circuit voltage
Q_n	nominal cell capacity
V_H, V_L	high-side voltage, low-side voltage
I_H, I_L	high-side current, low-side current
T_d	developed torque
B_{ERR}	battery error
h_{conv}	convective heat exchange coefficient between the cell and the environment
V_d	developed motor voltage
A_C	cell area
m_c	cell mass
C_p	cell heat capacity
R_0	internal (ohmic) resistance
P_0	power loss due to the internal resistance
K	P-I controller gain
K_m	motor constant
I_a	armature current
ω_M	motor speed

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