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Original scientific article

MATLAB SIMULATION MODEL FOR DYNAMIC MODE OF THE LITHIUM-ION BATTERIES TO POWER THE EV

Ivan BABOSELAC, Željko HEDERIĆ, Tin BENŠIĆ

Abstract: The paper presents a simulation model for the electric vehicles (EV) drive with Lithium-Ion batteries. Explanations of all the input parameters are given. Analysis of the dynamic characteristics of Lithium-Ion batteries was carried out through simulations on standardized driving regime (urban and highway drive cycles). Finally, recuperation of breaking energy of EV is explained.

Keywords: simulation model, Lithium-Ion battery, EV drive, driving cycle

1 INTRODUCTION

Despite the known problems [1, 2] and the development of alternative solutions [3, 4, 5], the development of batteries with increased use of EV has a strong upward trend [6]. Market growth brought lower production rates leading to increased investment in the development of EV. Solutions for the autonomy and longer travel range problems are mainly done in three ways: 1) the design of batteries with a greater energy density [7]; 2) reduction of battery weight; 3) optimization of dynamic modes of charging and discharging the battery [8, 9, 10].

Lithium-Ion battery compared to other battery types has a number of advantages [11]:

- greater efficiency and energy density,
- increased nominal voltages,
- lower specific weight,
- increased lifetime,
- faster and more efficient charging,
- smaller size,
- no need for maintenance,
- greater resistance to external conditions.

One of the disadvantages of Lithium-Ion batteries is that they must not be completely discharged. This shortens their lifetime. Also, discharging a battery with high currents is not recommended since it can cause damage. These disadvantages are commonly avoided by using electronic circuits for protection and for management of charging and discharging the battery.

Dynamic characteristics of Lithium-Ion battery operating in various modes are described and the change of EV operating parameters during charging and discharging of the battery are observed in this paper.

2 MODELLING OF LITHIUM-ION BATTERIES

For the purpose of modelling of the battery, the battery packs and EV drives in different driving modes, the MatLab software is used.

In the MatLab graphical editor Simulink a generic model of Lithium-Ion battery according to Shepherd's model is developed and verified (Fig. 1) [12]. It is modelled as a controlled voltage source dependent on the actual state of the battery charge (SOC).

Idea of this design is the use of a simple procedure to obtain the input parameters for the battery model (shown in Fig. 2) from the battery manufacturer's catalogue data. Within the model, depending on the operating modes, there are different functions for dependency of battery voltage.

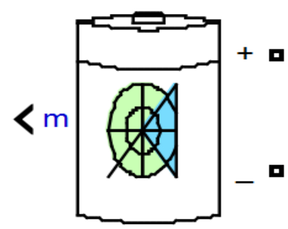

Figure 1 The block mask of Lithium-Ion battery model (SimPowerSystems) [12]

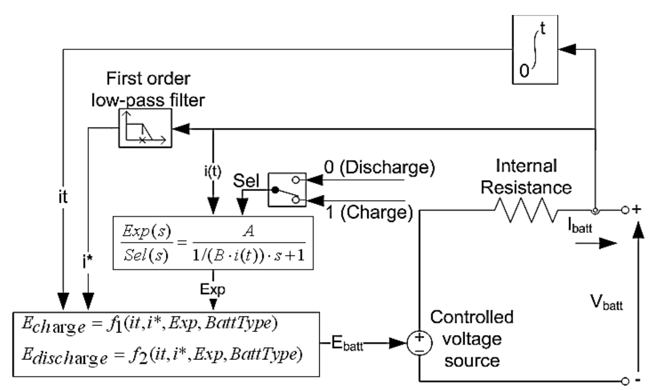

Figure 2 The battery model - block diagram of subsystems within the MATLAB Simulink, which in itself implements a generic model of Lithium-Ion battery [12, 13].

Fig. 3 shows the typical discharge characteristics of Lithium-Ion battery. The characteristics can be separated into three areas. The exponential area that represents battery voltage overshoot above the nominal value. The operating point of the battery is in this area during a period of establishing a stationary value of discharge current after no-load battery mode.

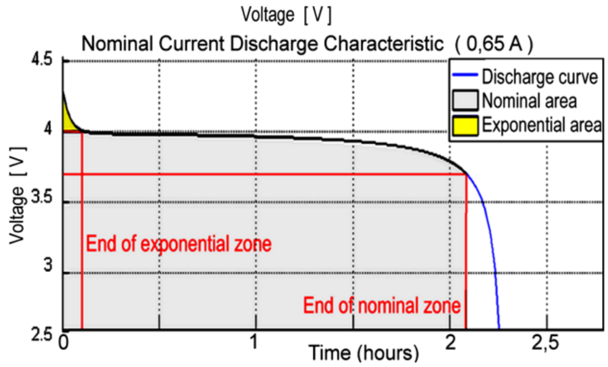

Figure 3 Discharge of the Lithium-Ion battery at nominal discharge current

In the nominal area of the battery operation, during the discharge mode, the voltage is slightly changed. When the nominal capacity of battery power is discharged, it is followed by the third area of operation in which the battery voltage rapidly decreases.

Battery discharge curve, shown as a blue line in Fig. 3, has a nonlinear characteristic and is described by the Eq. (1) in the Shepherd model [11], where the charging current is positive ($i^*> 0$):

$$f_1(i_t, i^*, i) = E_0 - K\frac{Q}{Q-i_t}\cdot i^* - K\frac{Q}{Q-i_t}\cdot i_t + A\cdot exp(-B\cdot i_t) \qquad (1)$$

where: E_0 − Constant voltage (V), K − Polarization resistance (Ω), i^* − Low frequency current dynamics (A), i − Battery current (A), i_t − Extracted capacity (Ah), Q − Maximum battery capacity (Ah), A − Exponential voltage (V), B − Exponential capacity (Ah^{-1}).

Second member of the equation (1) is the polarization voltage, presented as a product of the polarization resistance and the battery current, describes the behavior of batteries in the unloaded state. In Fig. 4 the changes of the discharge characteristics at different currents are presented.

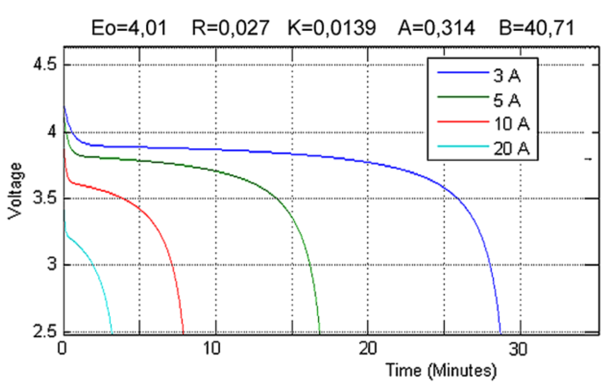

Figure 4 Discharge of the battery at different currents (nominal discharge current is 0.65 A)

Fig. 5 shows the charging curve of the battery and is described by the Eq. (2). It nominally has the inverse shape form of the discharge curve (initially from the empty battery state, through a period of rapid establishment of the nominal voltage, followed by a period of charging at nominal voltage, and finally the exponential area when the no-load voltage is restored).

$$f_2(i_t, i^*, i) = E_0 - K\frac{Q}{i_t + 0.1Q}\cdot i^* - K\frac{Q}{Q-i_t}\cdot i_t + A\cdot exp(-B\cdot i_t) \qquad (2)$$

Since the charging current has an opposite sign ($i^*< 0$), the resistance of polarization is changing, so the function of charging voltage is slightly different. The effect of temperature on operation of the Lithium-Ion battery is not taken into consideration in this paper [12].

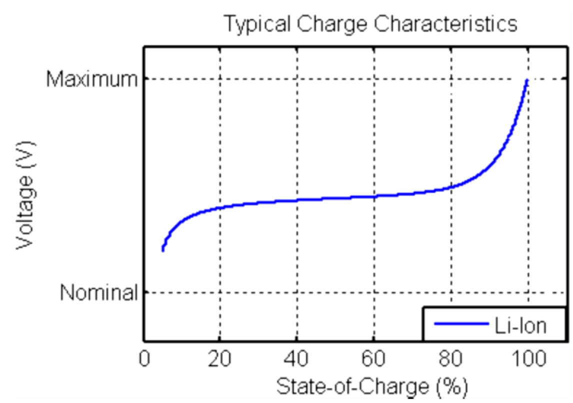

Figure 5 The typical discharge curve of Lithium-Ion battery and indicated characteristic areas

It should be noted that operation of the Lithium-Ion battery, in the areas where a rapid voltage changes are present (the initial exponential area and the area of rapid loss of capacity), requires the use of complex power electronic systems in order to protect the battery from overheating and destruction.

For the analysis of EV drive it is essential to consider all the assumptions of the model presented [14]:

- Internal resistance, considering operating mode of charging or discharging is unchanging, and the amount of battery current does not affect it,
- Hysteresis feature of the battery voltage curve is negligible,
- Battery capacity does not change in respect to amount of the charging current,
- The temperature dependences of battery parameters are neglecting,
- The possibility of self-discharge of the battery is ignored,
- The battery has no memory effect.

Since the simulations give away only discrete states of battery, the following restrictions on battery model with concentrated parameters are introduced [14]:

- Battery voltage and capacity cannot have negative values (in a state of total discharge the battery voltage is equal to zero)
- In the case of overcharging the battery, the maximum SOC may be over 100%.

For verification of the model, input parameters of EV Mitsubishi i-MiEV were selected. In this regard, the base of the battery pack in model is a battery cell with nominal voltage 3.75 V. By using these parameters within MATLAB program the curves of battery discharge for different currents (Fig. 5) can be obtained. The parameters obtained from the catalogue of the manufacturer, according to the method described above, are shown in Fig. 5.

3 EV DRIVE PARAMETERS SETTING

EV design is comparable when crossing a certain distance, according to predefined driving dynamics, starting with the full capacity of the battery. Multiple standardized driving cycles exist [15], and in this paper two are selected:

1. Urban Dynamometer Driving Schedule UDDS (Fig. 6, total distance 12 km, total time 1380s=23 min, average driving speed 36.6 km/h)
2. EPA Highway Fuel Economy Test HWFET (Fog. 7, total distance 16.5 km, total time 780s=13 min, average driving speed 77.6 km/h)

The initial parameter setting is done according to the UDDS driving cycles, followed by a simulation verification of the model carried out on the combined driving cycles (UDDS 10 km + HWFET 30 km).

In order to calculate the dynamics of the battery through a simulation, it is necessary to define all the parameters of EV that affect the dynamics of the battery.

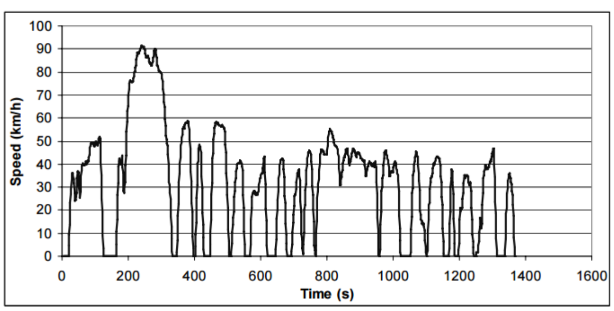

Figure 6 Urban Dynamometer Driving cycles UDDS

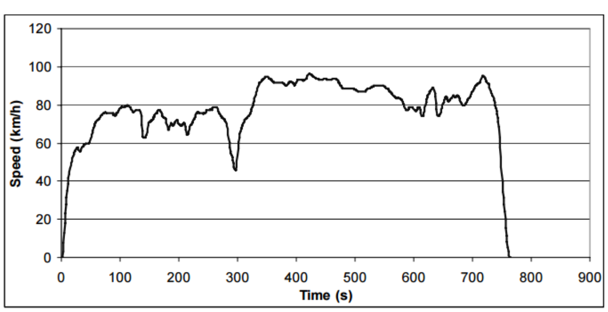

Figure 7 EPA Highway Fuel Economy Test HWFET

The calculation of the necessary energy is carried out - it is energy that mechanically burdens the EV drive, based on the driving mode and the basic parameters of the EV. This energy is transferred through electric drive and is considered as the electrical load of the battery (*discharge* - acceleration and driving, *charge* - recovery of braking energy).

For simplicity, this paper does not take into account any losses of energy within the vehicle (losses of control electronics, transmission losses or losses of the electric motor) which in real case may reach up to 20%. Also, a standard route is taken into calculation, possible changes of inclination of the vehicle (driving uphill - downhill) were not taken into account.

The total mechanical power is equal to the sum of the product of the total resistance force of vehicle movement and speed of the same at a given time [16]:

$$P_{\text{meh}} = \sum F \cdot v \tag{3}$$

The total resistance force of the vehicle movement consists of three components: rolling resistance, air resistance, and gradients resistance [14, 17]. Each component is individually modelled in the Simulink. Afterwards, they were united in a shared subsystem called "UDDS load". The mentioned subsystem and its structure can be seen in Fig. 8.

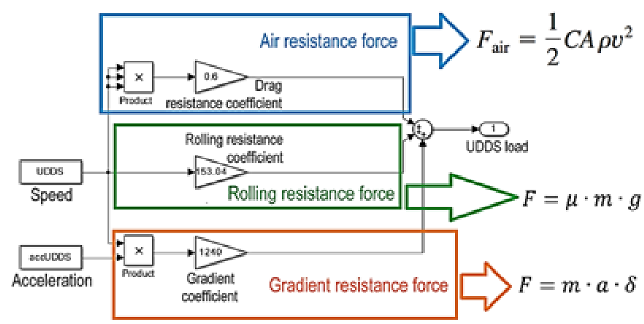

Figure 8 The simulation block "UDDS load"

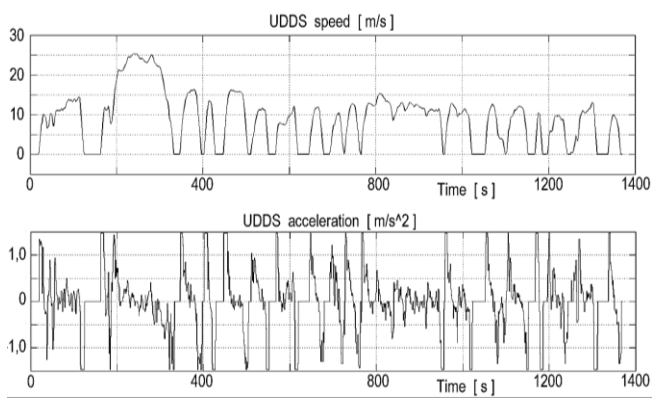

Figure 9 Speed and acceleration of EV for UDDS driving cycle

The value of C (drag coefficient: 0.0425) and A (an area of the front side of the vehicle) are taken from Mitsubishi i-MiEV that is based vehicle model in this paper.

The same is valid for the value of air density (1.2 kg/m3), the coefficient of rolling friction (0.013), and transmission coefficient (1.03) [17].

Input parameters in the MATLAB model of EV are vehicle speed (according to the selected driving cycles) and acceleration (derivation of the vehicle speed). Fig. 9 shows the change in speed and acceleration of EV for UDDS driving cycles.

Finally, by multiplying related force that opposes the movement of vehicles according to (3), with associated speed, function of the mechanical load of the DC motor that drives EV is obtained. The simulation output from the DC motor block that represents the electric energy demand provided by battery pack, is shown in Fig. 10.

Calculations of the EV model are based on the i-MiEV vehicle, where nominal voltage value battery pack is equal to 330 V. The battery pack is composed of 11 series-connected modules with the 8 battery cells in parallel with a nominal voltage of 3.75 V. Model of battery pack is shown in Fig. 11.

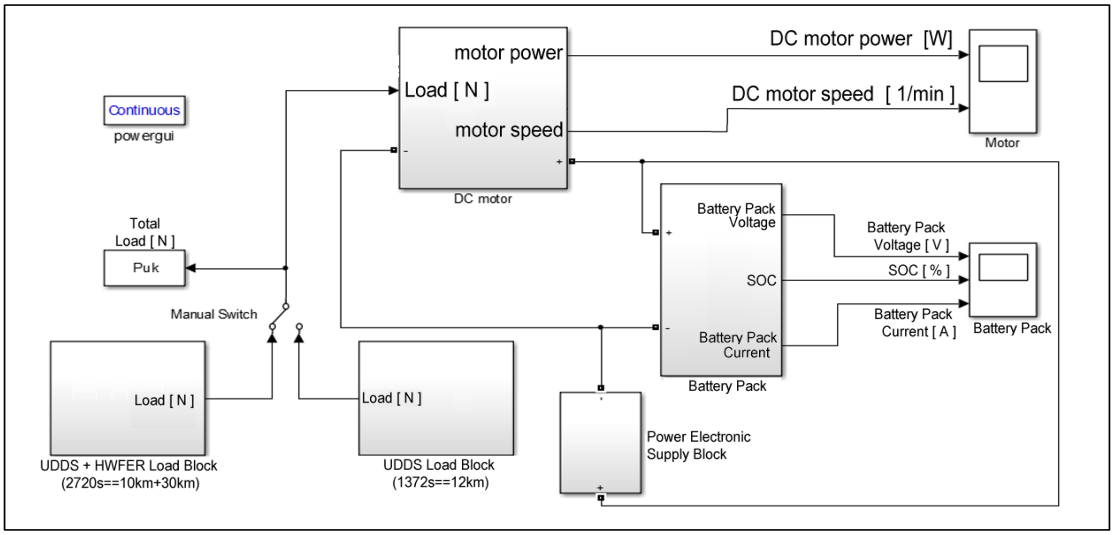

Figure 10 Simulink model of electric vehicles powered for driving cycle UDDS and HWFET

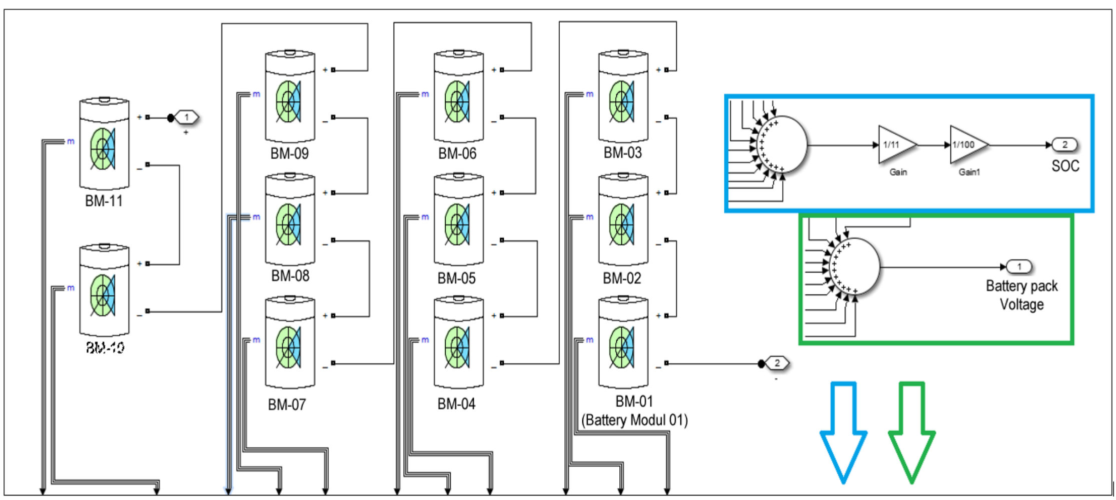

Figure 11 Battery pack4. Battery pack

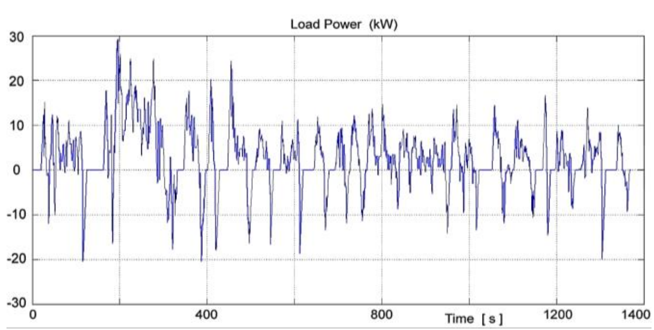

Figure 12 Display of the necessary power during UDDS driving cycle

The diagram in Fig. 12 provides an overview of changes in power that EV drive must provide for UDDC drive cycle.

The power of the DC motor is determined by the maximum calculated value of power, shown in diagram in Fig. 12, which is rounded up to the first higher value according to the standard determined power. Maximum power of 29.2 kW appears in diagram at 196 s, which leads to 30 kW selected power of the DC motor for the EV drive [18]. Periods of negative power that occur during the deceleration can be seen in Fig. 12. In these intervals, when energy flow is directed from the block DC motor to the battery pack, process of regenerative braking is being carried out.

By integration of the function of power in time, the energy required for EV drive during the drive cycle is calculated.

To determine the capacity of battery pack, from demanded energy at certain voltage, the following relation is used:

$$C = \frac{W}{3600 \cdot U} \tag{4}$$

where: C - capacity of battery pack (Ah), W - total energy required for the drive cycles (J), U - nominal voltage of battery pack (V).

The calculation of energy for the simulated driving cycle, by summing the function of power in time, the total electrical energy to be stored in the battery is obtained (W_{TOTAL} = 40.1 MJ). Since Lithium-Ion batteries work in capacity range 25% – 95%, with regard to the safe use of the batteries, only 70% of theoretical capacity is available. The calculated value of total energy that battery has to provide must be divided by 0.7 in order to get correct values [16]. It follows that the required theoretical capacity of the battery is about 47 Ah.

5 SIMULATION RESULTS AND ANALYSIS

By setting the parameters of all relevant parts of EV, based on the initial selection of the structural elements of the well-known model of EV i-Miev, and adjusting other parts of a drive according to UDDC drive cycles, verification of the model can be initiated.

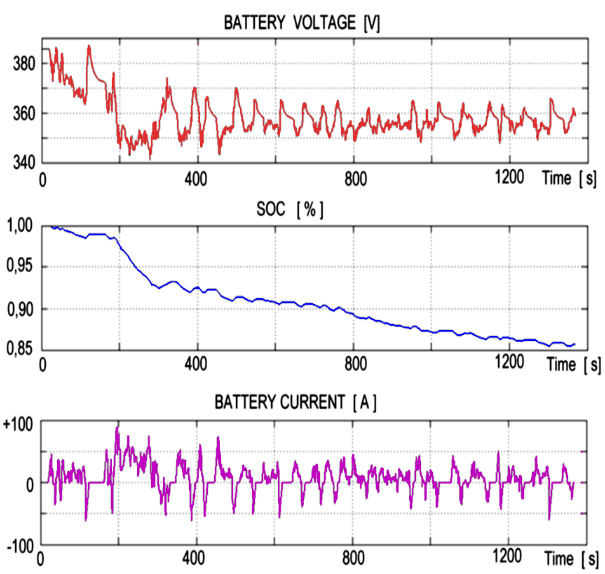

Figure 13 Change of the battery pack parameters for UDDC drive cycles

Confirmation that the modelled EV can provide drive distance, according to UDDC drive cycles, is the first step in model verification. The dynamic characteristics of the battery pack, at loads caused by UDDS driving cycles, are shown in Fig. 13.

The output from the block DC motor is speed and power of the DC motor for driving EV. Figure 14 shows that speed of the DC motor follows the default speed of the vehicle according to UDDC drive cycles.

In Fig. 14, red marks the intervals when the battery is discharged and green marks a period of braking energy recovery. By analyzing power in time shown in Fig.14, it can be seen that during acceleration of the EV motor power ranges from 70 to 95%, which represents about 20% of drive cycles.

These are the intervals with the maximum battery load and the largest discharge current (Fig. 13). In periods when the EV is driving with the cruise speed, engine power ranges from 30% to 40%, which represents about 55% of drive cycles [17]. In these intervals, the discharge current of the batteries is almost twice lower, and stress of the batteries is reduced. Since the duration of the discharge lasts longer, more intense changes of the SOC are shown in the diagram in Fig. 13.

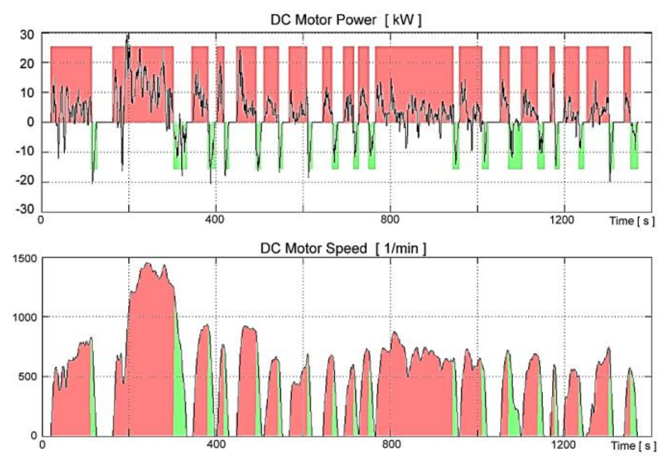

Figure 14 The speed and power of the DC motor during UDDC drive cycles

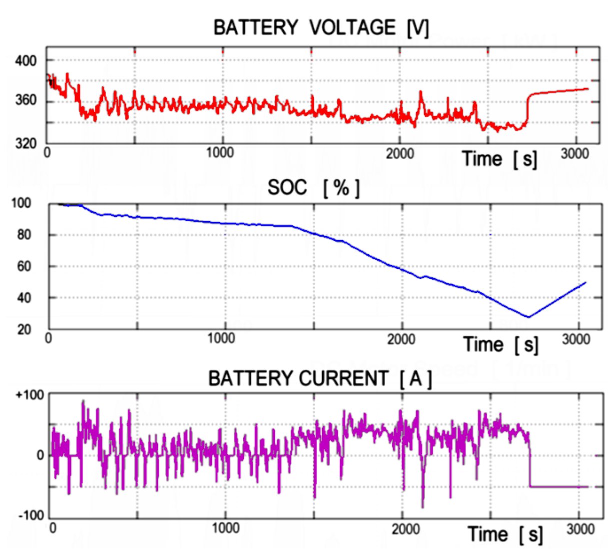

Figure 15 Change parameters battery pack for UDDS + HWFET drive cycles

The second phase of the simulation is to test a model through the combined driving (10 km UDDC + 30 km HWFET). This simulation lasts for 3760 seconds.

The first 1370 seconds (*distance of 10 km*) the vehicle is moving towards urban driving cycle (*UDDS*), and from 1370 to 2720 seconds (*distance of 30 km*) it is moving according to highway driving cycles (*HWFET*).

After 2720 seconds the vehicle arrives at the destination, and the battery is charged for 1040 seconds with a constant current of 50 A. Figure 15 shows the dynamic characteristics of battery pack; SOC, voltage and current for UDDS + HWFET drive cycle. The power and the engine speed are shown in Fig. 16.

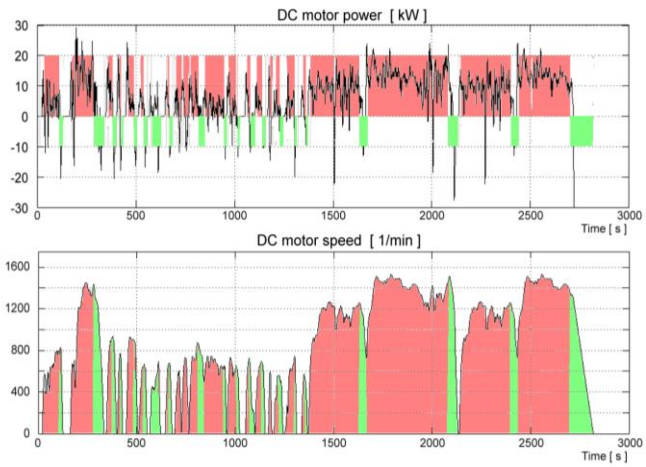

Figure 16 The speed and power of DC motor for a combined UDDC + HWFET drive cycles.

The analysis shows that, during the first 10km (*UDDC drive cycles*), the vehicle has numerous stops and energy recovery is achieved. Therefore, SOC has a slower decrease (Fig.15). However, switching to highway driving (HWFET *drive cycles*), discharge current of batteries is substantially increased; there is practically no recovery, which is why the SOC decreases twice as fast.

Also, at the end of the cycle, the battery pack is not discharged below the 25%, which was the intention of the design.

6 CONCLUSION

This paper shows the parameterization of the EV drive using the Matlab-Simulink. The emphasis of the paper was on studying the dynamic characteristics of the Lithium-Ion battery during various charge and discharge regimes.

Essential parts of modelling process for the EV have been shown. The way to determine the parameters for Lithium-Ion battery from catalogue data producers has been presented. From the base drive cycle data, the parameters of the model have been selected and the EV drive required power has been calculated. Based on this power and the drive cycle data battery capacity has been selected.

Explanations of the model simplification, as well as limitations of the model have been given. In further research the model can be upgraded so it includes all the parameters that describe realistic EV which ultimately reduces the distance range of the EV.

Based on these simulations and analysis of results the boundary areas of the Lithium-Ion battery, operation in EV may be defined. Also, the measuring signals for control electronics can be selected.

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Authors' contacts:

Ivan BABOSELAC, Master student
Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek,
Kneza Trpimira 2b, 31000 Osijek, Croatia

Željko HEDERIĆ, PhD, Associate Professor
Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek,
Kneza Trpimira 2b, 31000 Osijek, Croatia
zhederic@etfos.hr

Tin BENŠIĆ, PhD student
Josip Juraj Strossmayer University of Osijek, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek,
Kneza Trpimira 2b, 31000 Osijek, Croatia
tin.bensic@ferit.hr