

Modelling of Supercapacitors in EVs

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Abstract—Supercapacitors (SCs) are still considered as emerging storage devices. However, the combined operation of SCs and Li-ion batteries, forming hybrid energy storage systems (HESS), has shown real world feasibility, especially in electrified transportation. Thus, this paper is purposed to propose a simple small-scale model of a SC in EV's drivetrain system. Two scenarios are considered – SC replacing Li-ion battery as the first scenario and the second scenario consisting of including SC in tandem with Li-ion battery (HESS). Obtained results are as expected, i.e. SCs being less inert than batteries react faster to the transients whenever regenerative braking occurs.

Keywords — Energy storage, EV, regenerative braking, supercapacitors

I. INTRODUCTION

The ever growing necessity to utilize environmentally friendly energy storage devices has given a rise in popularity of electrochemical storage devices and systems. Among them, most widespread are rechargeable Li-ion batteries (or LiB), but there are newly developed replacements such as Na-ion and potentially Mg-ion or Li-air batteries. Additionally, there are many researchers studying fuel cells. However, aside from batteries and fuel cells, there are also supercapacitors (also known as ultracapacitors) which have been widely studied and developed in recent years. Supercapacitors (SCs) are electrochemical storage devices, comprised of electrodes, electrolyte, separators, current collectors. While the structure may seem similar to that of a battery, SCs do not have any reacting materials [1] and their operation principle has remained as that of standard capacitors, i.e. storing or delivering charge by desorption and adsorption of ions, which are reversible, at the interface between electrolyte and electrode [2], [3]. Furthermore, SCs' capacitance C_{sc} , in Farads or even kiloFarads, can be determined in the same way as a standard capacitor, as in (1) [3].

$$C_{sc} = \frac{\epsilon_0 \epsilon_r S}{d} \quad (1)$$

where ϵ_0 denotes vacuum permittivity (electric constant), ϵ_r represents relative dielectric permittivity, S is the cross-section of the electrode and d is the distance between electrodes.

There are three main categories whenever supercapacitors (SCs) are being classified [3] – [9]. These are electrochemical double-layer (EDLC), pseudo- and asymmetric (or hybrid) capacitors.

A. Supercapacitors' classification

1) Electrochemical double-layer capacitors

EDLCs are based on the EDL phenomenon, discovered by Helmholtz in 1853 [10]. However, this model couldn't take ion mobility due to diffusion and electrostatic forces into consideration, which have been further modified by Gouy and Chapman [6], [10]. Afterwards, Stern have combined both of these models and have introduced two layers – one known for

being named after himself or after Helmholtz and the other is called diffuse layer [6], [10]. The diffuse layer, however, also introduces an internal resistance.

2) Pseudocapacitors

Pseudocapacitors' charge storage is due to faradaic charge transfer reactions at electrodes' surface. The transfer of charges can be caused by mechanisms such as intercalation, oxidation-reduction (redox) reactions or electrosorption [4] – [7]. When compared to EDLCs they are characterized with higher capacitance C_{sc} , but lower charge/discharge rates.

3) Hybrid or asymmetric capacitors

This type of SCs [4] – [7] is usually a combination of the former two. It is usually done by comprising one of the electrodes as a pseudocapacitor's one (faradaic electrode), while the other is an EDLC one (similar to a battery electrode). In many cases they are used to improve energy density, capacitance, electrochemical performance, etc.

B. Supercapacitors' advantages and disadvantages to Li-ion batteries

Primarily, SCs are developed to achieve two objectives, namely an energy density higher than 5 Wh/kg for discharges with high power density, and a life cycle of at least 500,000 cycles with deep discharge. When compared to Li-ion batteries, SCs are characterized with the following advantages and disadvantages, presented in TABLE I. [4], [11] – [13].

TABLE I. COMPARISON BETWEEN SUPERCAPACITORS AND LI-ION BATTERIES.

Parameter	Supercapacitors vs. Li-ion batteries	
	Supercapacitor	Li-ion battery
Massic energy, Wh/kg	1 – 10	150 – 250
Massic power, W/kg	< 10,000	< 2000
Charge/discharge (cycle) efficiency, %	90 – 99	85 – 98
Self discharge rate	Very high (5 – 60 % voltage loss in few weeks)	Low (0.3 – 2 % in a month)
Charge time, s	1800 – 10,800	0.3 – 30
Discharge time, s	1200 – 10,800)	0.3 – 30
Life cycle, № of cycles	> 500,000	1000 – 5000
Calendar (shelf) life, years	20	10 – 20
Operating temperature (discharge), °C	-40 – 75	-20 – 60
Charging temperature, °C	-40 – 75	0 – 45
Specific price, \$/kWh	> 2500	400 – 1000

Even though SCs are still considered as emerging storage devices, due to their advantages and the fact that SCs and Li-ion batteries complement each other's drawbacks, forming hybrid energy storage system (HESS) [14] when utilized

together, they have found their place in the following applications [5], [10]: renewables (even newly developed photo-capacitors [3], [15]), transportation (electric vehicles (EVs) and hybrid electric vehicles [16] – [20], trolleybuses, uninterruptible power supplies, portable devices, etc.

This paper is purposed to introduce comprehensively modelling of SCs in an EV's drivetrain considering regenerative braking. The proposed model can serve as a baseline towards more in-depth studies.

II. MODELLING OF SUPERCAPACITORS

Modelling of SCs [1], [11], [12], [21] – [25] is generally based on respective equivalent electric circuits [1], [10], [12] that can describe adequately SCs parameters and processes in steady-state as well as in transients. Since EDLCs are the most widespread, the equivalent circuit, which is also used in MATLAB/Simulink environment by Simscape library, is the Zubieta equivalent circuit or model, shown in Fig. 1. State of charge (SoC) is estimated by the method of Coulomb counting.

This is a continuation of a previous work, in which the author has studied the energy stored in a Li-ion battery during EV's regenerative braking. The drivetrain in consideration is structured of a battery, power converter and motor configuration and is controlled by a space vector modulation. This can be considered as a base scenario. Hence, in this paper two other scenarios are studied by the proposed model – replacing Li-ion battery with SC as the first scenario, and utilizing LiB in tandem with SC as the second. The model is presented on Fig. 2. The battery and SC's subsystems are shown on Fig. 3 and Fig. 4, respectively. The buck/boost converter and its pulse-width modulation are taken as in the MATLAB example by Blaud and Dessaint [26].

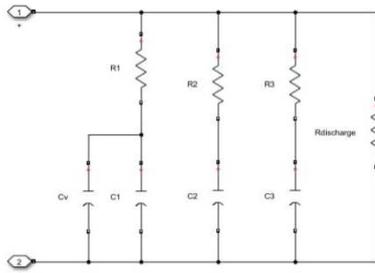


Fig. 1. Zubieta equivalent circuit. Capacitors C1, C2 and C3 have fixed capacitances, while Cv is dependent on the voltage across it.

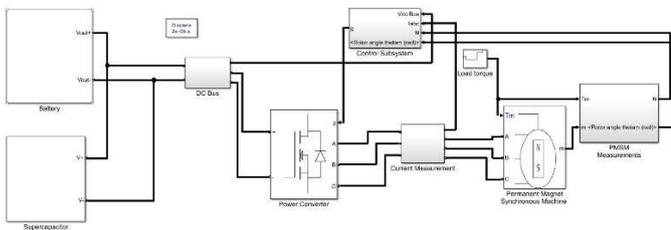


Fig. 2. Modelled EV's drivetrain.

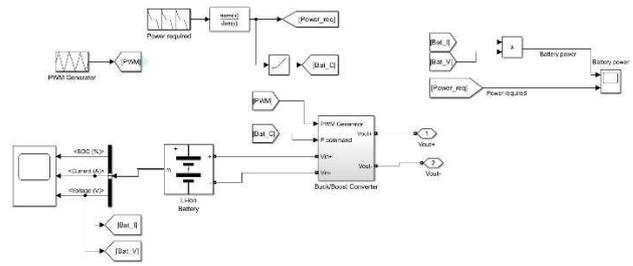


Fig. 3. Li-ion battery's subsystem.

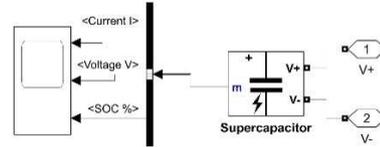


Fig. 4. Supercapacitor's subsystem.

SC's parameters are given in TABLE II. Additionally, self-discharge has not been considered and the inherent Stern's equation is using predetermined parameters. Battery's, power converter's and motor's parameters are kept the same as in the author's previous work. Simulation time is kept to 3 seconds as it is enough to showcase the results' points of interest.

TABLE II. MODELLED SUPERCAPACITOR'S PARAMETERS.

Parameter	Supercapacitor's parameters
	Supercapacitor
Nominal capacitance, F	50
Equivalent DC resistance in series, Ω	2.1×10^{-3}
Nominal voltage, V	4
N $^{\circ}$ of capacitors in series	6
N $^{\circ}$ of capacitors in parallel	1
Initial voltage, V	4
Operating temperature, $^{\circ}\text{C}$	25
Charge current, A	3

Analogously to the author's previous work, the input reference is the motor's load torque T_m , Nm. It is presented in Fig. 5 and is a representation of the EV's power demand. The premise is as follows: first 0.1 second EV starts to travel; 0.1 – 0.3 seconds is acceleration; 0.3 – 1.3 seconds is descending on a slope and regenerative braking is occurring; 1.3 – 1.8 seconds EV is back on a flat road, while further acceleration is given in the time 1.8 – 2.2 seconds. During the final period 2.2 – 3 seconds EV brakes to a stop by regenerative braking.

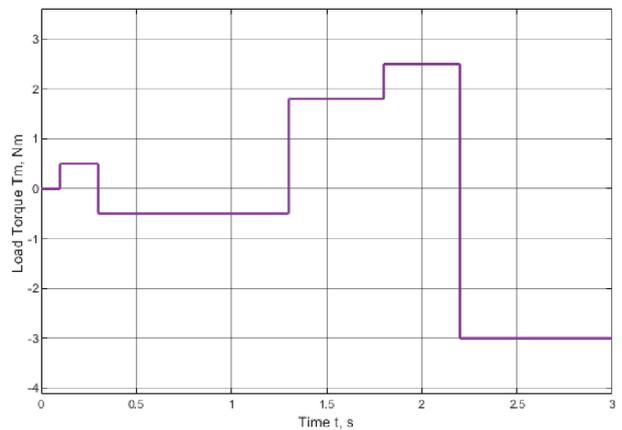


Fig. 5. Input reference – load torque T_m .

III. SIMULATION RESULTS

Simulation results are presented in the following way: section *A* is regarding the scenario in which the *LiB* is replaced by the *SC*, while section *B* is regarding the tandem scenario.

A. Scenario 1: Supercapacitor storage

Replacing Li-ion battery with *SC* presents a necessity to compare *SC*'s current I_{sc} , A voltage U_{sc} , V and state of charge SoC_{sc} , % to battery's ones. Measurements of *SC*'s quantities in time are presented in Fig. 6. When compared to the same measurements of Li-ion battery in the base scenario, the similarities are evident. During the periods of negative torque (descending on a slope and braking), current I_{sc} is also negative as expected, voltage U_{sc} and state of charge SoC_{sc} are rising, representing charging due to regeneration.

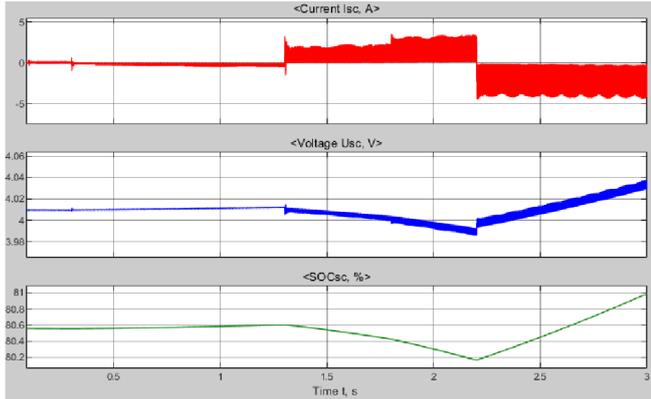


Fig. 6. Supercapacitor's measurement diagram in the case of replacing Li-ion battery. Current I_{sc} is presented in the top plot, voltage U_{sc} – in the middle one, and state of charge SoC_{sc} – in the bottom plot.

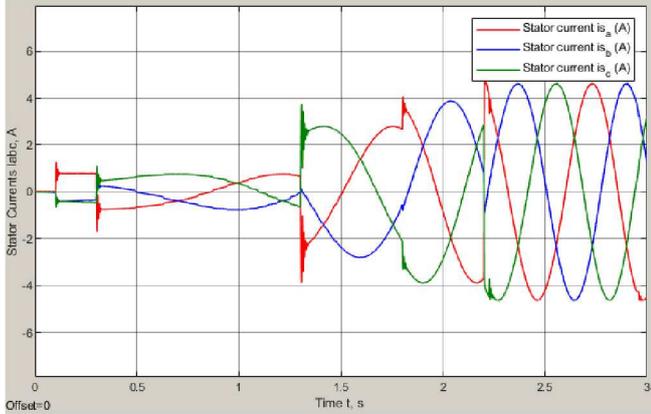


Fig. 7. Motor's stator currents.

However, observing that *SC* is being charged during regenerative braking is not enough of a criterion to judge *EV*'s performance. Hence, as in the case with Li-ion battery, motor's performance ought to be observed as well. Motor's stator currents are shown in Fig. 7 while motor's electromagnetic torque T_e , Nm compared to load torque T_m , Nm is presented in Fig. 8. It is evident that the motor can easily supply the demanded torque and transition between motoring and generating.

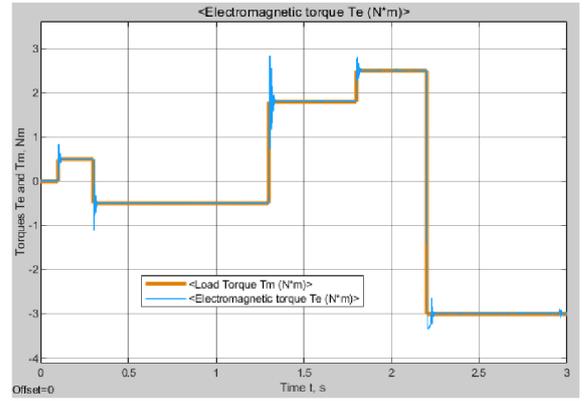


Fig. 8. Load torque T_m vs. motor's electromagnetic torque T_e .

B. Scenario 2: Hybrid energy storage system

Utilizing *SC* and Li-ion battery in combination is regarded as *HESS*. The obtained results in this scenario are as follows. With regards to motor's performance, there is no change and Fig. 7 and Fig. 8 remain valid. There are, however, changes in the *SC*'s and battery diagrams. *SC*'s diagram is presented in Fig. 9, while battery diagram – in Fig. 10. Even though battery's initial SoC_b is set to 30 %, there is an apparent rapid charge of *SC* by the battery when simulation is initiated. This is considered as equalization. Afterwards, *SC*'s behaviour is trying to be analogous to the one of fig. 6. *SC* can react faster than the battery to the transition between motoring and regenerative braking, which is why *SC*'s quantities follow the transients accordingly. This can also be seen by the continued discharge of the battery, as the more inert one.

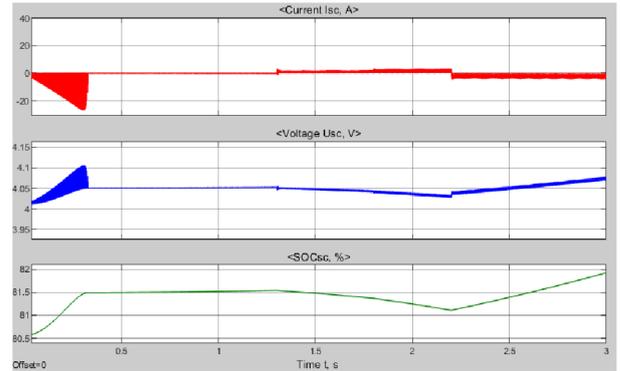


Fig. 9. Supercapacitor's measurement diagram in the case of *HESS*. Current I_{sc} is presented in the top plot, voltage U_{sc} – in the middle one, and state of charge SoC_{sc} – in the bottom plot.

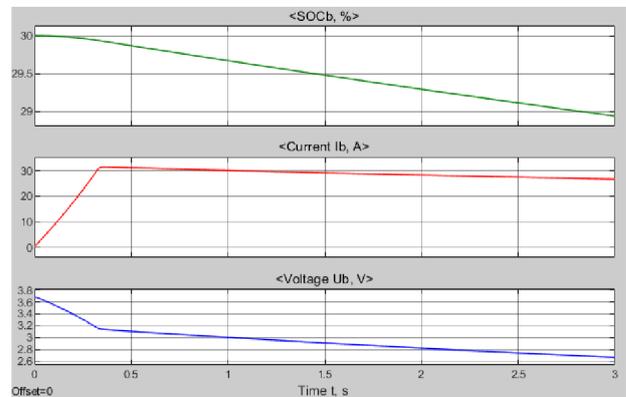


Fig. 10. Li-ion battery's diagram. The top plot presents state of charge SoC_b , while current I_b is in the middle plot and voltage U_b in the bottom plot.

IV. CONCLUSIONS

Even though *SCs* are still considered as emerging storage devices, their incorporation in *HESS* has shown real world feasibility, especially in electrified transportation.

A comprehensive modelling of *SCs* in an *EVs* drivetrain considering regenerative braking has been proposed in this paper. The model is preliminary and small-scale, which makes it simple to repeat in laboratory environment, that can serve as a baseline towards more in-depth studies.

Obtained results have revealed that *SCs* are less inert than batteries and react faster to transients whenever regenerative braking has occurred, as expected.

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