PROPOSAL FOR THE ELECTRIC VEHICLE DRIVE SIMULATOR CONFIGURATION - CASE STUDY AND SIMULATION MODELLING

Ján Markovič, Pavol Špánik, Michal Frivaldský*

Department of Mechatronics and Electronics, Faculty of Electrical Engineering and Information Technologies, University of Zilina, Zilina, Slovakia

*E-mail of corresponding author: michal.frivaldsky@uniza.sk

Michal Frivaldský 0000-0001-6138-3103

Resume

Road traffic remains a major contributor to carbon dioxide emissions, making innovative energy solutions essential. Electric vehicles (EVs) offer a promising alternative, however, current lithium-ion batteries face limitations in power output, energy density, and cost. To address these challenges, hybrid energy storage systems (HESS) combine batteries for energy storage with supercapacitors for rapid power delivery. In this study was explored an optimization tool for EV operation using HESS configurations and evaluates performance through MATLAB Simulink simulations across various driving cycles. The results highlight trade-offs between the performance, weight, and cost, which vary by vehicle class. While HESS improves energy efficiency and extends battery life, its complexity and expense limit feasibility for medium and high-class vehicles. Lower-class vehicles benefit most from this approach. Ultimately, tailored HESS designs adapted to specific driving conditions can enable more sustainable and efficient electric vehicles.

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1 Introduction

Research in the actual extensive electrification of transport infrastructure calls for improvement suggestions and verification of gathered data, further improving the potential of the implementation of electrical vehicles (EVs) and confirm the proposed solutions. It is a vital part of the continuous EVs development since their implementation in transportation structure. Limitations of the EV body construction narrows down usable space for the powerline system, consisting mainly of large volume battery pack and driveline, electrical machines (EMs). Adequate sizing of the energy storage system (ESS) and EMs is critical, as it directly contributes to the final performance levels of the EV. Capacity of the ESS, directly tied to the potential drive range, is limited by its size [1-3].

To obtain the required parameters, calculations and simulations with real time driving scenarios, drive cycles, are done. The drive cycle evaluates the performance of the EV through the defined map, which states acceleration, braking, standing and cruising segments in time. It is defined by change of the vehicle speed through time [1, 4]. Implementation of described benchmark done by drive cycle poses as an experimental method, which is able to optimize parameters of the powertrain system, formulating improved performance and energy consumption [5-7].

Recent researches in HESS designs implemented in EVs indicate improved characteristics in simulated operation of the vehicle during the drive cycle experiments. Researchers implemented two types of HESS systems, single and dual HESS. Experiments have been done in computer simulations, achieving numerous data results, which have been analyzed and compared. Dual HESS systems have been utilized for minimalizing battery discharge peaks by splitting vehicle's traction power demand between the two independent traction systems, while each one was powered by HESS system. Optimized dual HESS configuration in EV reached increased driving range, battery storage life compared to the single HESS configuration, presenting a better configuration in long term operation of a vehicle. Comparison of the configuration of dual HESS and battery-only configuration proposes possible increased battery-pack life, improving the long-term effect of vehicle's operation [7].

Alternatively, verification of the implemented powertrain systems can be done by a physical experimental setup, consisting of two motors, connected together by an axle and inverter for powering the motors. Two motors are required, as one motor is a drive motor and the second is a load motor. Proposed method requires additional calculations, for controlling the torque load on the load motor, simulating inertia from EV's parameters and selected drive cycle [8].

Verification of the parameters of the implemented powertrain system and its further optimization is crucial for prototyping efficient and improved EV, which brings a considerable requirement for a simulator of the EV powertrain. Applying the simulator to the prototyping sequence of the EV enables to design its parameters, suited for the expected operational conditions, based on the expected driving course and calculations. Further details in designing the simulator are described in the next section, as research in actual state-of-art simulators, used in research and development (R&D) centers, universities and training programs.

2 Research in state-of-the-art simulators of electrical drives for EVs

Development centers in universities present numerous experimental setups for developing the electrical drives for electrical vehicles. Conventional and preferred implementations of control methods for electrical drives are being replaced by innovative techniques developed by researchers in focus of improving operating conditions of electrical drives as poor torque ripple, flux ripple and flux instability at low RPMs (Figure 1). Innovative techniques are done by implementation of artificial neural network (ANN) enhanced control methods as direct torque control (DTC) [9].

Faults occurring in EV powertrain appearing e. g. under inverter switch faults, reduce operational reliability of the EV. The fault tolerant control methods of electrical drives are developed, by implementation of ANN control methods to improve stability and improved EV operation [10].

Described approaches are being tested on experimental prototypes of electrical drives for EV powertrain, which are mostly composed of inverters, isolation and auto transformers, voltage source inverters (VSIs), dSPACE controllers and electric motors linked together with torque sensor or shaft. Instead of transformers, a dual-isolated battery emulator is commonly used to power the VSIs, [6]. Electrical motor selected in experimental setups usually use lower power rating, e. g., 5 kW and low operating speed around 1500 RPMs [11].

Alternatively, there are available electrical vehicle simulators on market, used primarily for theoretical training and demonstration purposes for automotive students. Described educational stands are composed of main systems of EVs as electrical motor, inverter, high-voltage (HV) battery and charging port. Components are sourced from commercial EVs, e. g., Renault ZOE. Stand is suitable for training diagnosticians and EV repair specialists.

Educational stands can have alternative form, in electrical vehicle trainer, which is based on a commercial

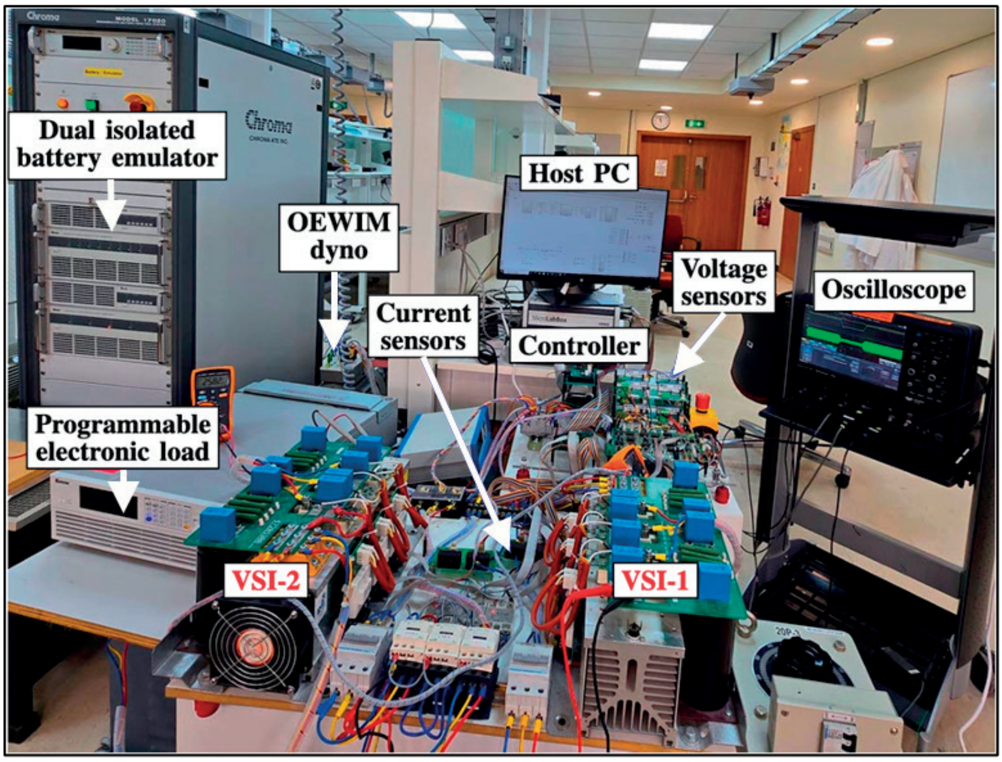

***Figure 1** Experimental prototype of electrical drive, [6].*

EV, e. g., Tesla Model 3. The vehicle is complete, but various panels are removed, with exposed components of the vehicle's system. Measurement devices are connected to the key components to illustrate the dynamic changes in electrical system while it is operating.

Described research and obtained details revealed possible solutions, which are already available on the market, or being used in R&D sector. Experimental setups are the most advanced and useful approach suited for drive cycle experiments, as the training stands, built from EV components, are not suited well for described experiments. Even when they are simpler to operate and easier to manage, they do not allow to build custom operation method, based on the selected drive cycle, which would be usable in experimental field.

3 Specification of the parameters based on the research

Advanced experimental setup of the simulator, described in the previous section, suits required needs for proposed simulator prototype, by utilizing custom drive cycle control method. To be useful and usable in the research and educational sector of university, the prototype must be built on a smaller scale.

The proposed prototype consists of three main operation blocks, energy storage and conversion, primary motor control and drive and secondary motor control and drive. Energy storage and conversion part consists of hybrid battery pack, composed of battery pack and super-capacitor (SC)bank and a DC-DC converter. The battery pack is the main energy storage, posing as a standard EV battery pack and supplying required energy for the motor drive and control. The SC bank is fundamental for improvising the dynamic operational parameters of the EV, mainly acceleration, possibly recuperative braking. The DC-DC converter is a fundamental part, required for converting voltage levels of the battery pack and SC to a HV DC bus level. For this application, buck-boost topology was selected, as it meets the criteria for voltage and current conversion. The primary motor control and drive is the powertrain part of the simulator, used as a simulation of propulsion. The primary, propulsion EM is an asynchronous motor (ASM). The ASM was selected as it is simple to operate and was/is used in EV production. For powering the primary motor, three-phase inverter was used, together with field-oriented control (FOC) and motor speed controller, enabling precise control of the primary motor by utilizing torque or speed control method. In addition, a braking chopper is added as a safeguard from HV spikes by back EMF from primary motor. The secondary motor control and drive block is the load part of the simulator, creating a torque load on the primary motor. Torque load poses as a simulation of the physical laws, hidden behind operation of the EV. This ensures that the simulator does not absolutely omit physical properties of the EV operation. Control and powering method is the same as for the primary motor, by FOC and speed controller.

The proposed diagram offers flexible solution since both the primary and secondary motors can be

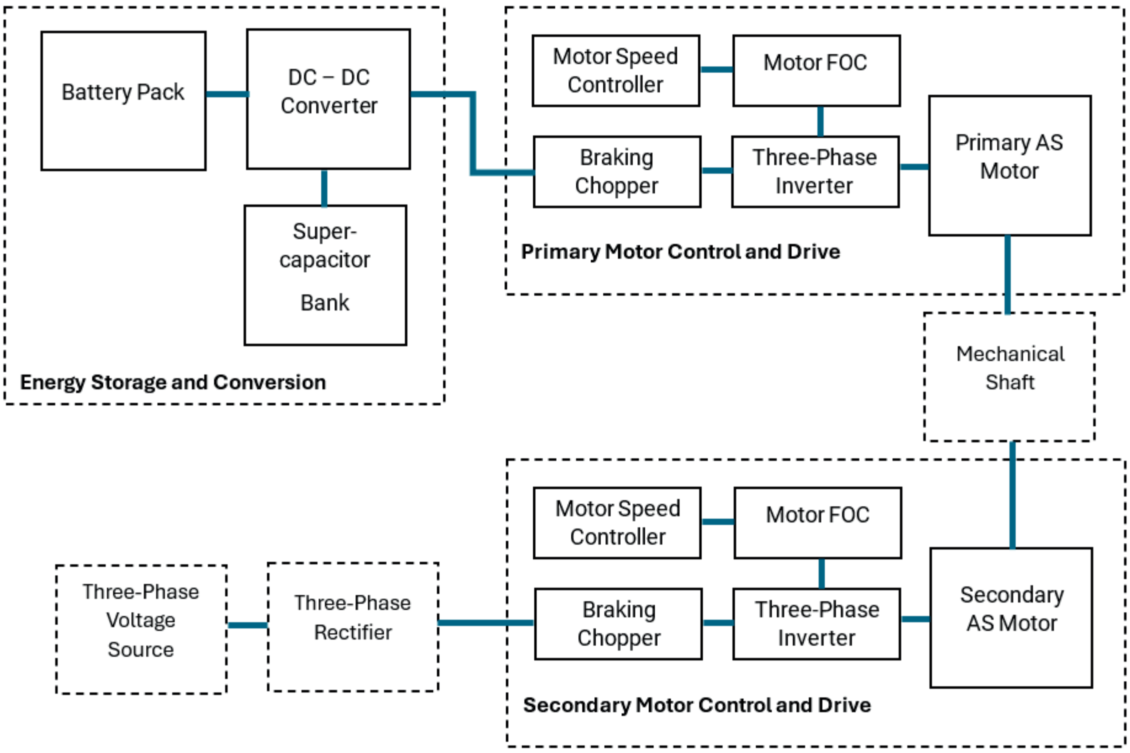

Figure 2 *Block diagram of the prototyped electrical vehicle drive simulator*

operated as synchronous motor, e. g., permanent magnet synchronous motor (PMSM), but only with adjusting the control method and controller accordingly. The FOC control is not mandatory, as there are more advanced and effective control methods available, while the direct torque control (DTC) and maximum torque per ampere (MTPA) can deliver better results, possibly even with artificial neural network (ANN).

Motor speed/torque controllers require external input parameters based on calculations from:

- Physical parameters of the subjected vehicle's body, rolling, resistance and drag coefficients, gravitational constant, with the grade of incline or decline, as the calculations are for the kinematic scenario;
- Selected drive cycle or another predefined plot as the source of the desired speed of the vehicle;
- Electrical parameters of the controlled motor;
- PI controller proportional, integral gain.

As proposed simulator gains complexity in terms of selected strategy of simulating the propulsion and torque load on the driveline components, there is an alternative for reducing the complex nature of it. With the desired drive cycle, parameters set for the vehicle body and other physical parameters, calculations can be done to obtain desired power of the driveline to cover the route of the drive cycle. Calculated power can be used in current load, which can replace powerline components, both motors, inverters and motor controllers. Described change would bring the simulation to more of an ideal nature than of the real-world scenario. Additional calculations, forming an efficiency coefficient (substituting the operational efficiency of omitted powerline components) forms aid in composing simulations of the simulator, taking it closer to the real-life scenario. With the assistance of calculations from [4, 12] in section 3, simulation is light-weight on the computational power and covers only the most important calculations required to successfully cover the stated requirements.

Figure 2 represents the block diagram of the proposed simulator, forming an example, prepared for building simulations of the simulator. Simulations are required for validating functionality of the proposed concept, as it must meet criteria. Necessary calculations and parameters are described in the next section.

4 Composition and description of simulation models of the simulator

Simulations of the simulator are done in Simulink, branch of the Matlab software. Strategy with the two models was selected, as each model represents different stage. Based on the initialrequirements, concept with current load, omitting the powerline components, was selected. First stage (Figures 3 and 4) aims to gather the data of vehicle operation by selected drive cycle. Drive cycle sends reference speed to kinematic calculation subsystem, forming an output of required force to accomplish the selected route. The total force from subsystem, multiplied by reference speed, determines the total power, consumed and created by vehicle operation. Additionally, ideal required and recuperated power from the battery pack and SC bank are calculated, as are required for the next stage. Described total power creates baseline for powertrain calculations, which are done in the second stage of simulations. Requested power from SC bank is set by "SC limit" block, which sets points of charging and discharging current intervals.

The second stage consists of calculations, energy storage system and a DC-DC converter with a controller

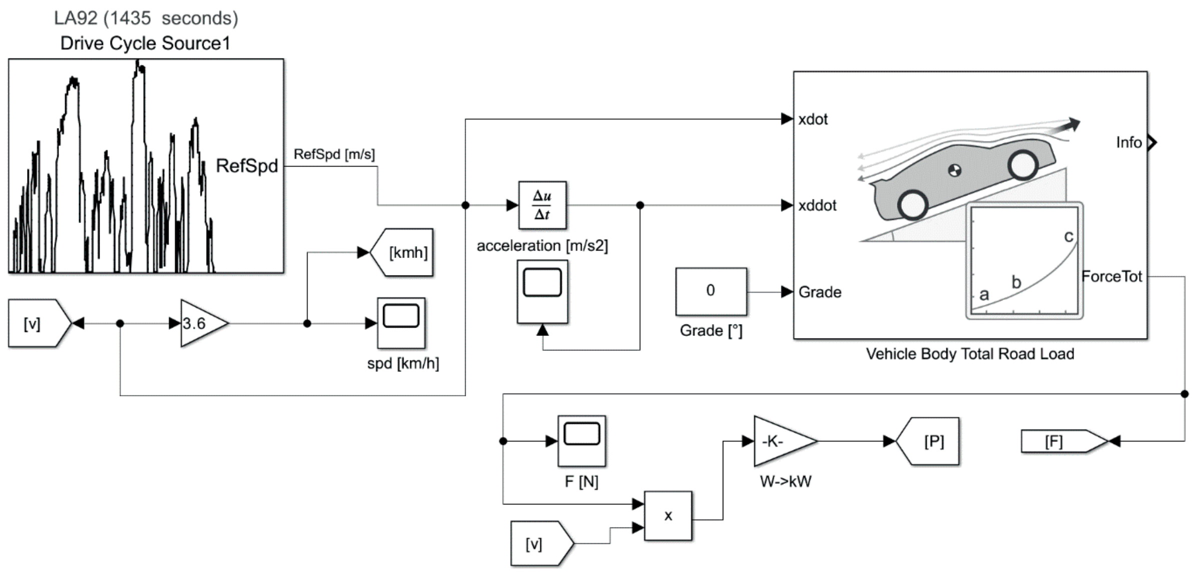

Figure 3 *The first stage of simulation- total force and power calculation*

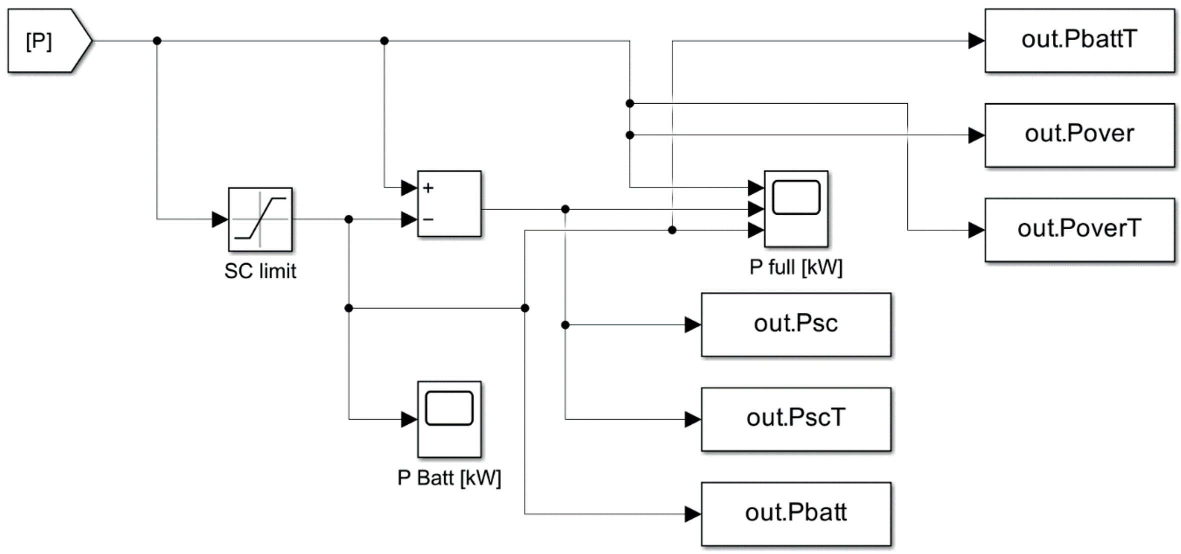

Figure 4 *The first stage of simulation - power of battery and SC calculation*

Table 1 *Component parameters for DC-DC converter*

Parameter	Value	Unit
C1	1.50E-03	[F]
C2	4.00E-03	[F]
L1	2.00E-03	[L]
L2	2.00E-03	[L]
fsw1	5.00E-03	[Hz]
fsw2	5.00E-03	[Hz]
Ts	1.00E-03	[Hz]

Table 2 *Baseline parameters for simulation*

Model	Type	Set parameter	Unit
Vehicle body	Drive cycle	LA92	[-]
	Vehicle mass	1550	[kg]
	Aerodynamic drag coef.	0.3422	[N*s/m]
	Rolling and driveline drag coef.	3.21	[N*s^2/m^2]
Battery pack	Nominal voltage	400	[V]
	Rated capacity	30	[Ah]
	Initial SoC	75	[%]
Super-cap bank	Rated capacitance	5.5	[F]
	Equivalent DC series resistance	155	[mOhm]
	Rated voltage	260	[V]
	Initial voltage	250	[V]

(Figures 5 and 6). Calculations gather data from the first stage, converting power into an electrical current. Calculated current is used as a variable for current load, which is consuming the required current from ESS or producing back to it, substituting a current load or production (recuperation) of EMs. Energy storage system contains battery pack with SC bank, while the battery pack is connected directly to the DC bus in a HV operation. The values of the main circuit components are listed within Table 1, while the baseline parameters for simulation are given in Table 2.

SC bank uses two-level converter to transform current levels, based on a requirement from calculations of the current flow from/to SC bank. The converter operates with current loop, controlling the amount of current flow.

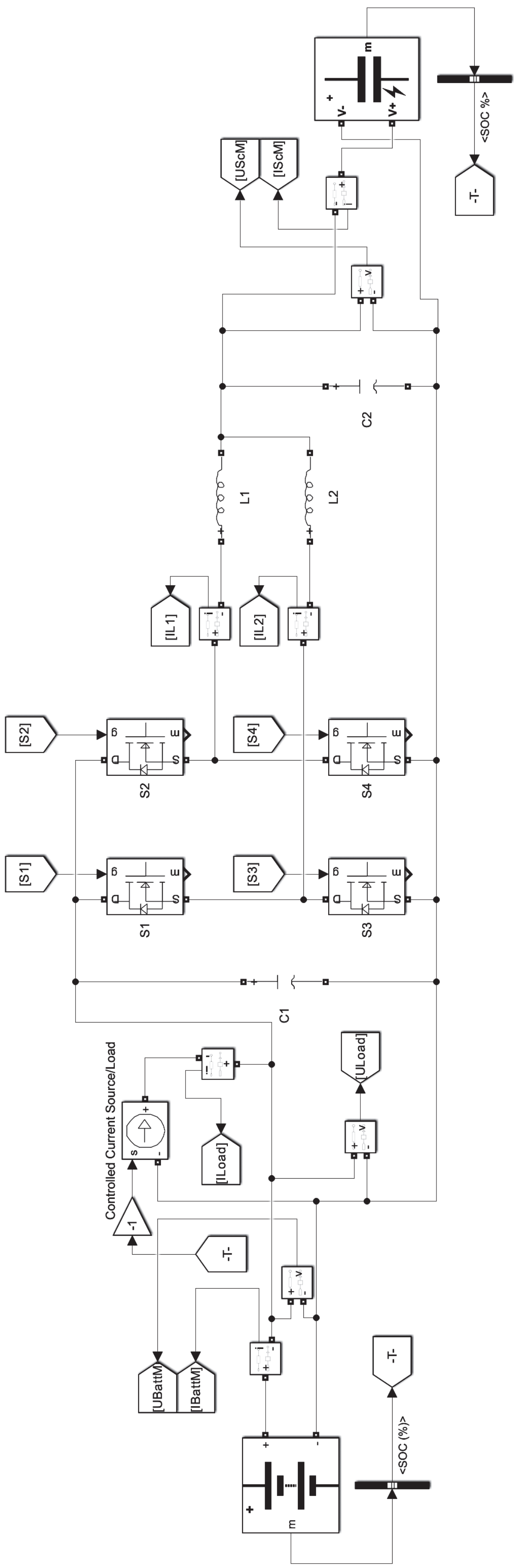

***Figure 5** The second stage of simulation -DC-DC converter with SC and battery*

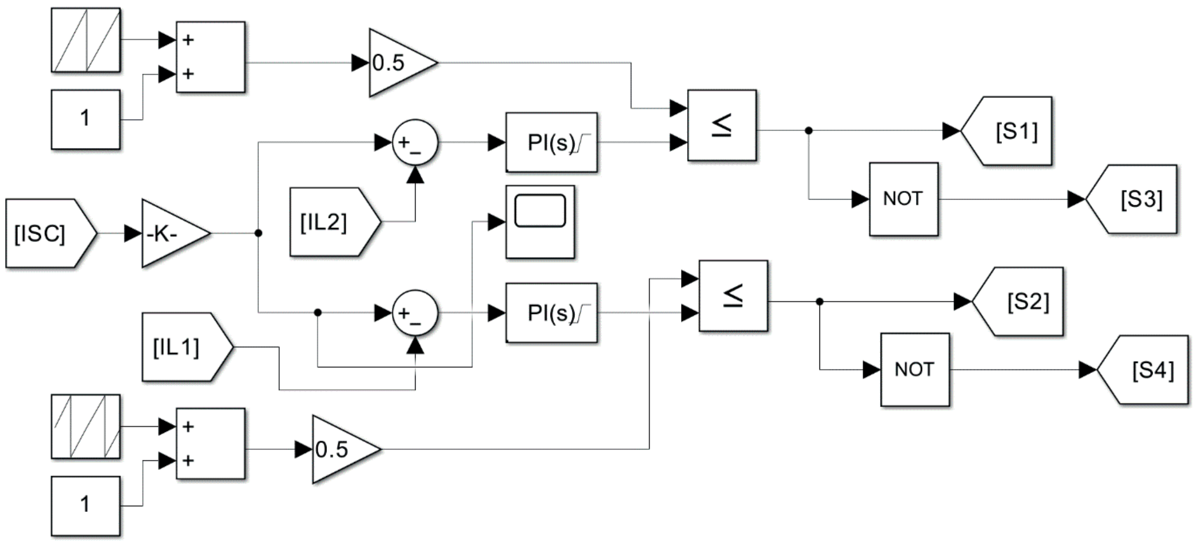

Figure 6 *The second stage of simulation - DC-DC converter controller*

5 Drive cycle experiments

The first parameter setup for simulation has set the baseline, to observe the system functionality without any optimization of parameters. The main points of interest (POI) are power, current flows and state of charge (SoC). Power and current flows describe the requested (calculated) and measured values, allowing throughout comparison. The SoC values show the current state of charge for ESS to observe sufficiency of the battery pack and SC bank capacities. Monitoring the parameters confirms functionality and correctness of the simulation, allowing further optimization of parameters if needed.

Due to the nature of the randomly attributed input parameters for rated capacitance of SC bank, discharging limit at 25 A, charging limit at 25 A, the discharged SC bank is expected even before the major energy consumption by load during the test.

Measured current flows in Figure 7 describe the functionality of the ESS, as SC bank delivers required current in the set intervals, discharged above 25 A and recharged above 25 A. However, the expected depletion of charge of the SC has occurred at simulation time 25 s, pointing out to inadequately set parameters for SC bank. As the charge of SC has depleted, all the required power from the SC bank had to be covered by battery pack.

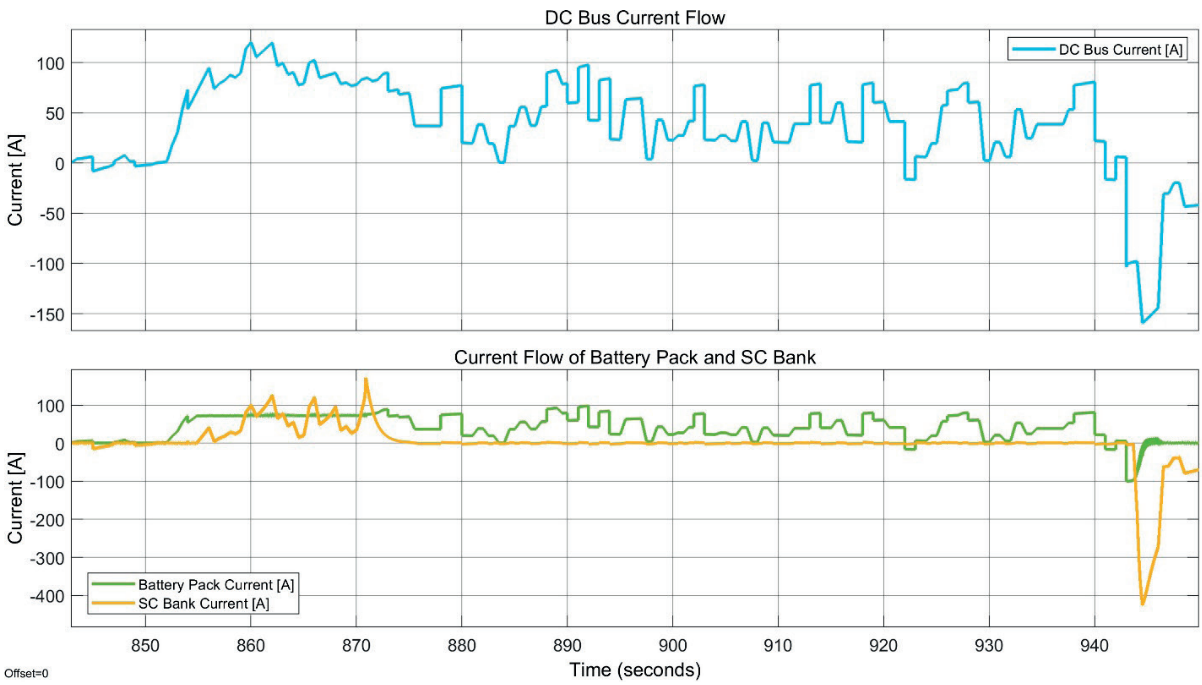

Figure 7 *Measured current flows of DC Bus and ESS from baseline simulation*

This point of switch can be seen in Figure 8, where the measured current flow of battery pack is different that calculated/requested current flow of the system. Around the same time of simulation, 25 s, measured battery current flow increased and distanced from the calculated values. Same phenomena can be seen in Figure 9, where the discharged SC bank could not provide any more energy to the system. The complete discharge of the SC bank is confirmed in Figure 10, where the SoC of the SC bank fell to minimum operational limit under 10 %.

For further examination in the experiment, the drive cycle stays same - LA92. Changes have been done in parameters for the SC bank, as rated capacitance is set to 6.6 F, discharge limit at 30 A and charging limit

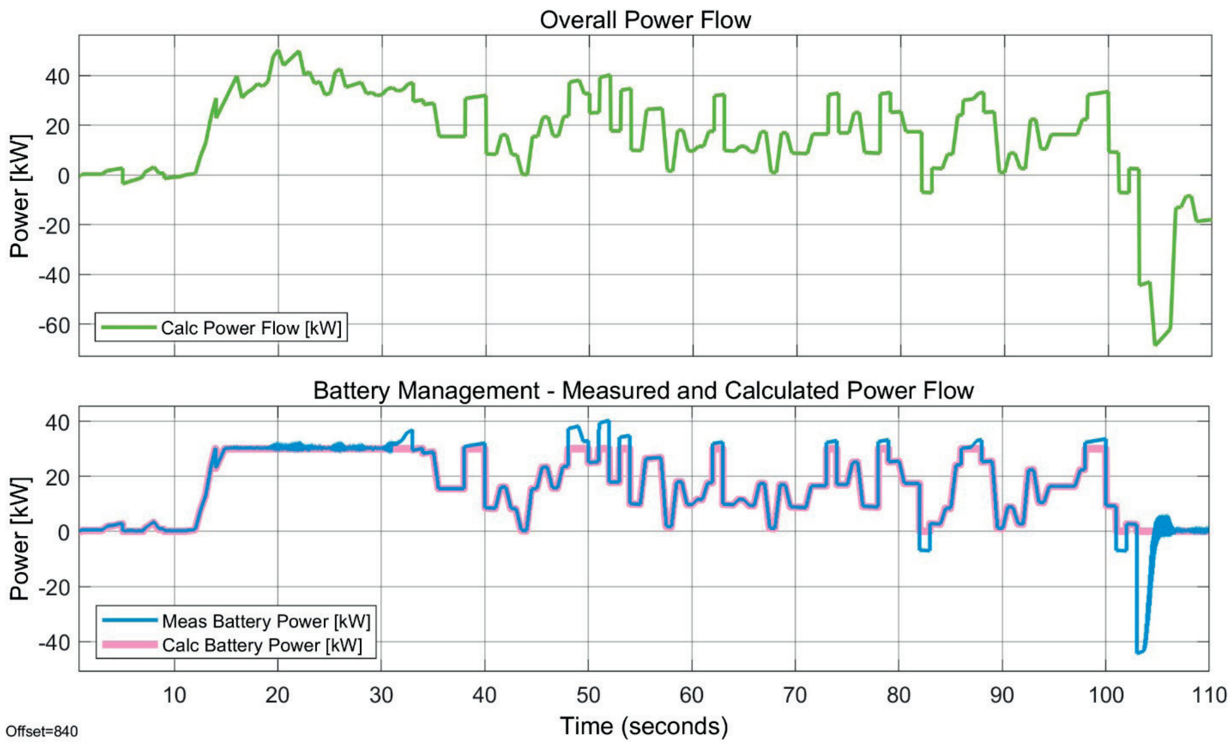

Figure 8 *Calculated and measured battery pack power flow from baseline simulation*

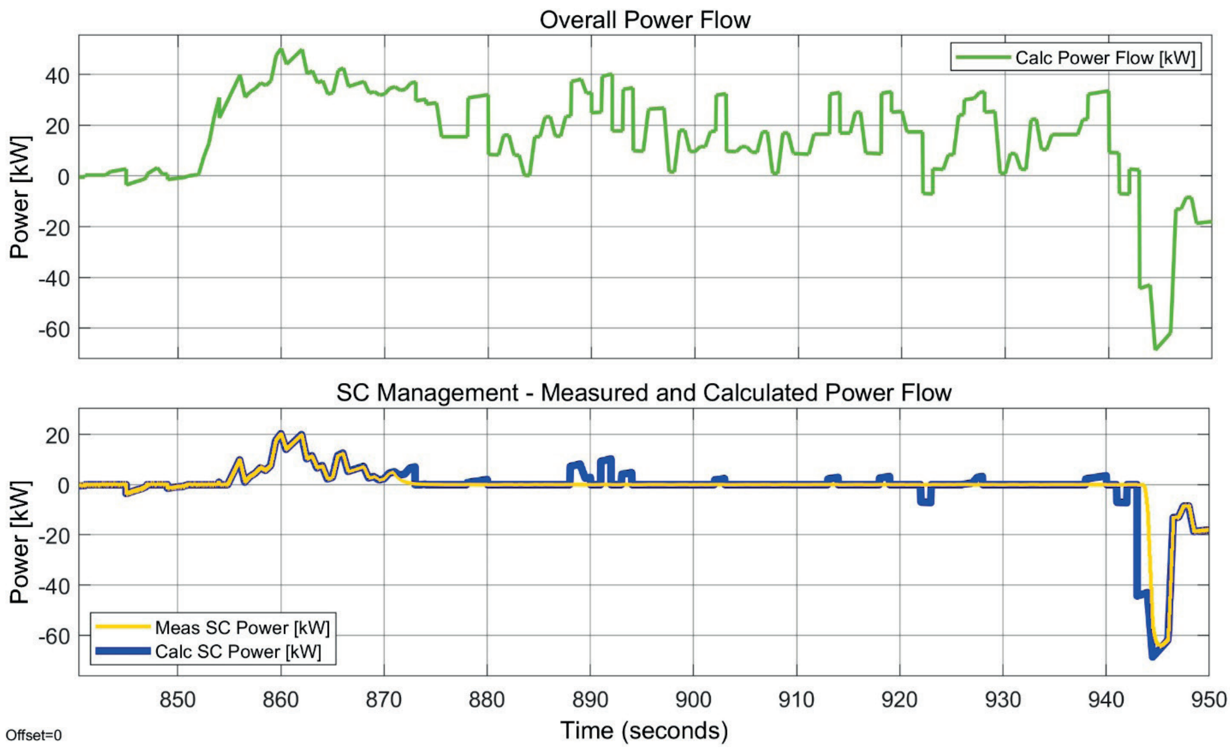

Figure 9 *Calculated and measured SC bank power flow from baseline simulation*

at 25 A. Altered parameters should bring more stored energy in SC bank, allowing it for extended operation and not discharging completely.

Experimental simulation was successfully completed with an expected outcome as altered parameters of the SC bank has increased its available stored energy. Figure 11 displays the successful operation of the ESS system, as SC bank has discharged and charged adequately to set limits. Figure13provides insight into operation of the SC bank, as it was able to cover the required energy by system, without discharging completely as in baseline simulation. This is confirmed in Figure14, where SoC of the SC bank stayed above minimum operational limit of 10 %. Figure12further evaluates the operation of ESS, as measured power flow of battery pack closely followed requested/calculated power flow by the system. Accuracy of measured parameters following closely required/calculated parameters determines ability of the ESS to cover load of the EV drive. Any error or margin between the described parameters indicate requirement of further adjustment or optimization of the SC bank or battery pack parameters.

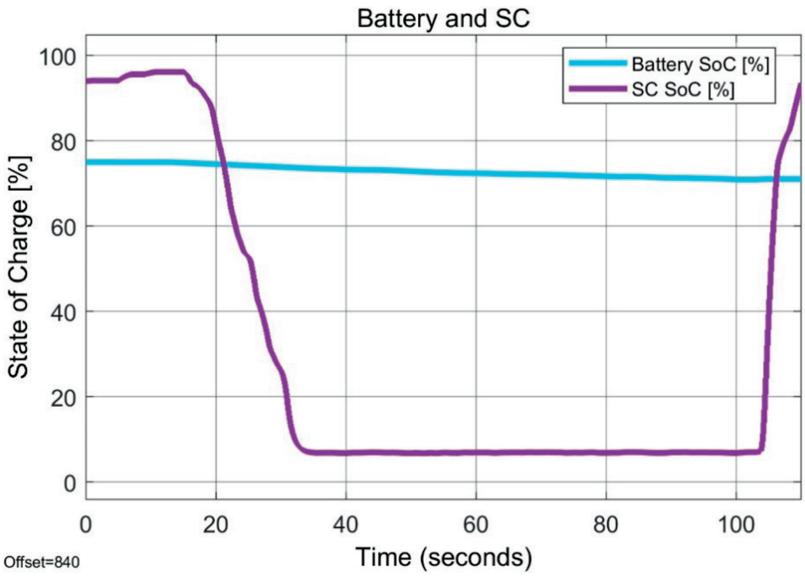

Figure 10 *Measured battery pack and SC bank SoC of baseline simulation*

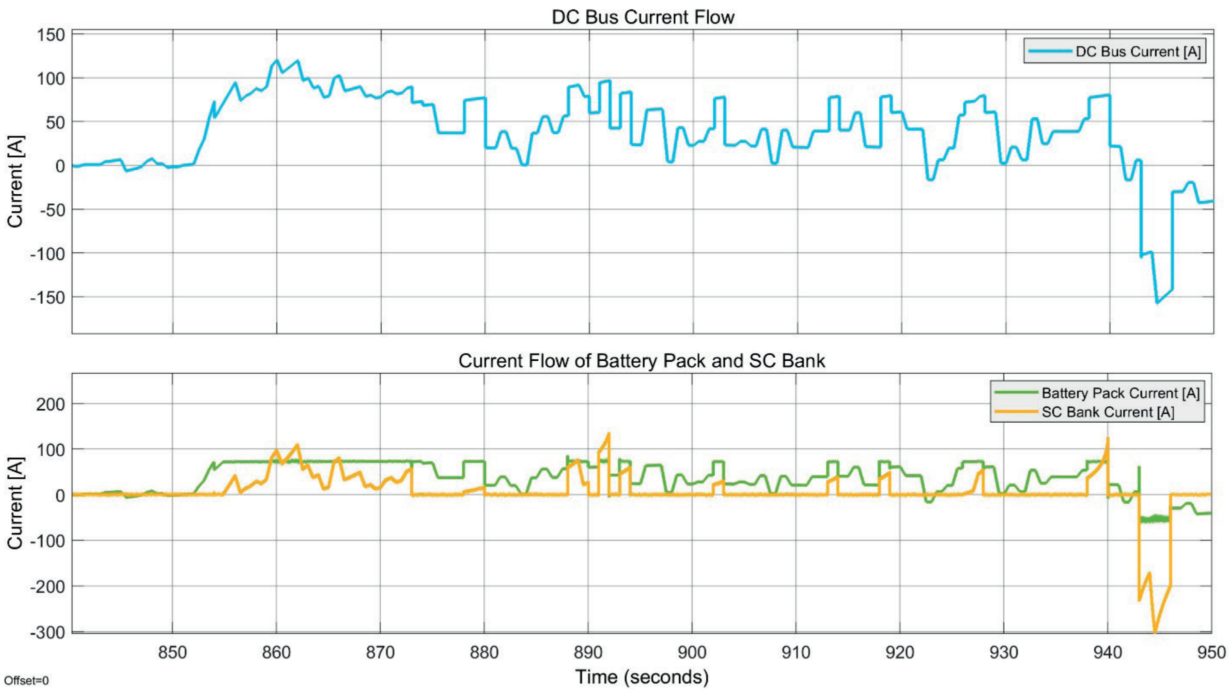

Figure 11 *Measured current flows of DC Bus and ESS from experimental simulation*

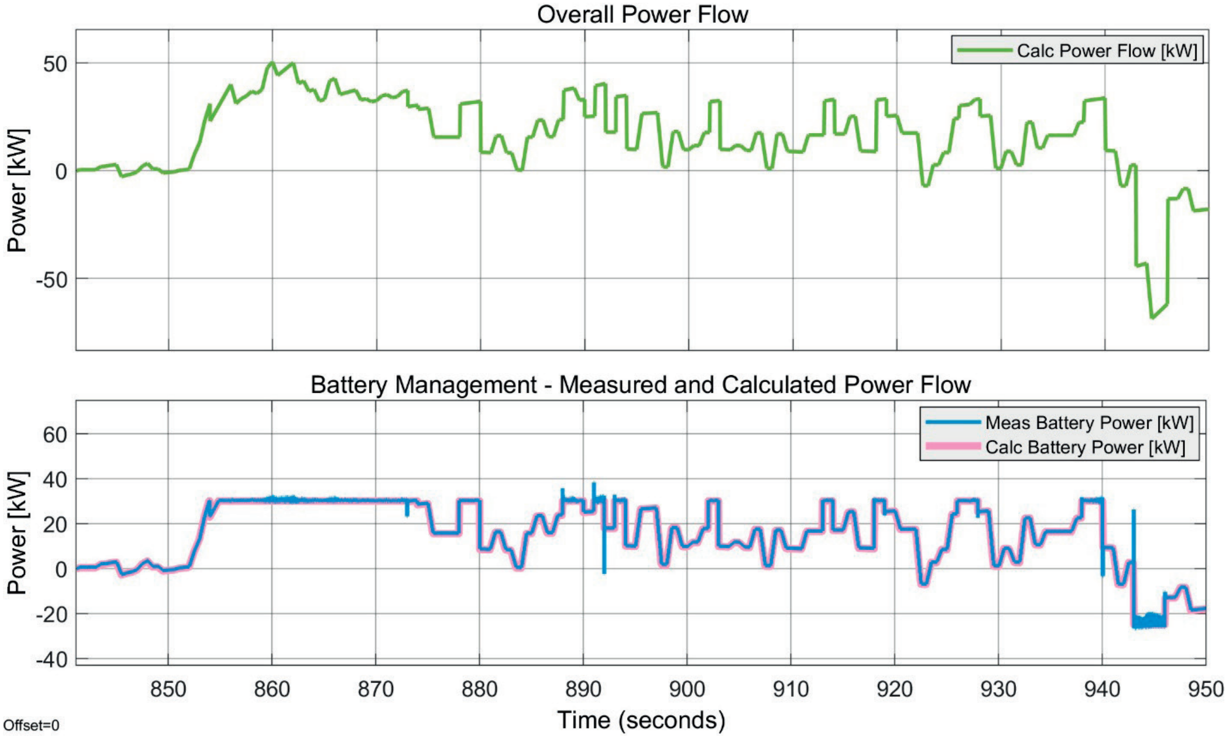

Figure 12 *Calculated and measured battery pack power flow from experimental simulation*

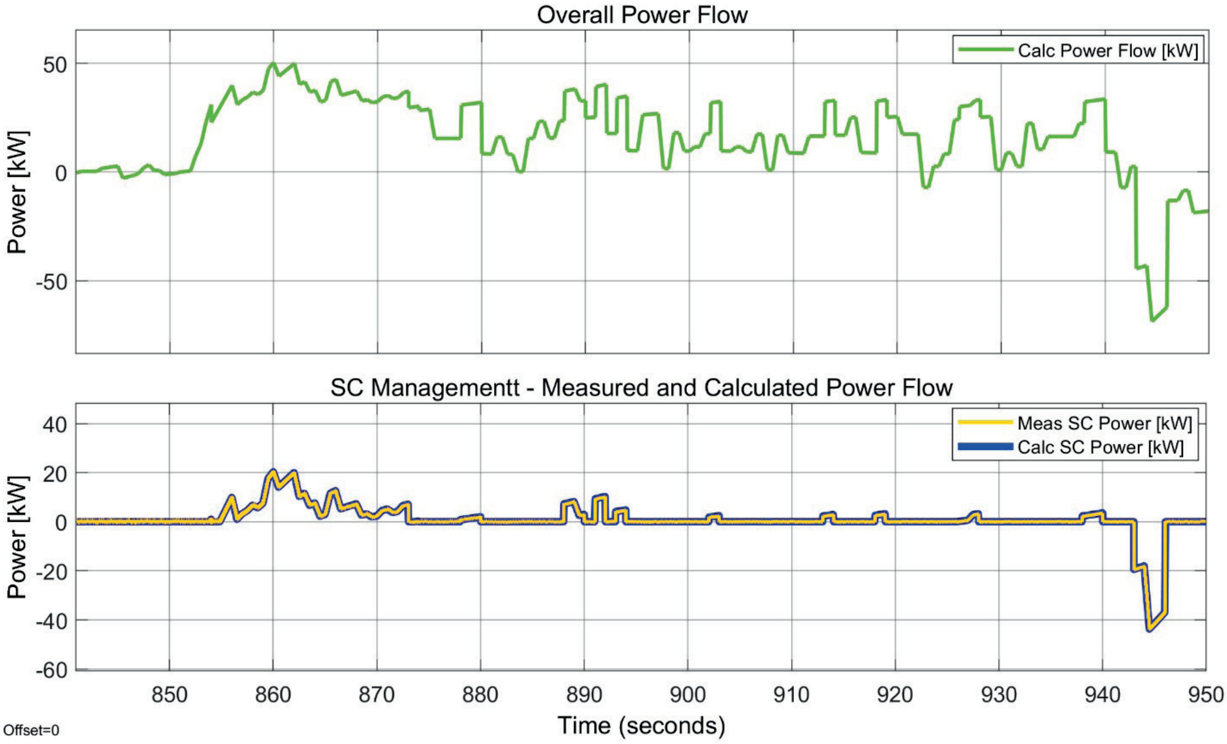

Figure 13 *Calculated and measured SC bank power flow from experimental simulation*

6 Results

Baseline simulations confirmed correctly functioning simulated model of the EV drive simulator. By utilizing input data from Table 2, the first stage of simulations provided operational data required for the second stage of simulations, where required and calculated parameters stated operation of the system. The second stage of simulator has provided baseline data, in form of figures describing current, power flows

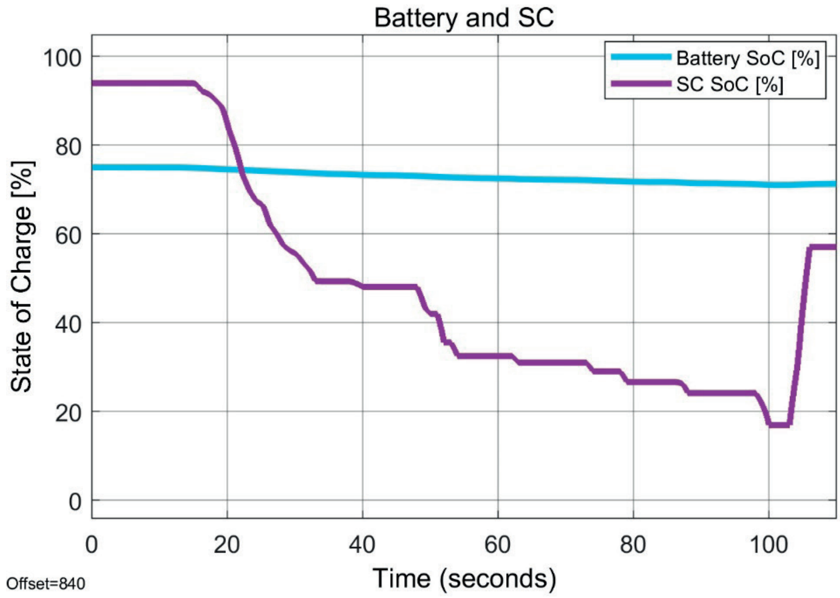

Figure 14 *Measured battery pack and SC bank SoC from the experimental simulation*

in the system and SoC values from ESS. Baseline input parameters resulted in SC bank not holding enough energy for covering extensive power load by system for long time period. Discharging limit of the SC bank has allowed it to discharge sooner than was needed, resulting in quick discharging. Low capacitance of SC bank also could not contain enough energy for extended period of it's operation.

Continuing with experimental simulations, where altered parameters of the SC bank have been used, resulted in operation of simulator meeting the requirements, where the SC bank was able to cover required energy. The SC bank provided enough power for the entire investigated spectrum, while having fraction of energy as a reserve. Experimental simulations confirmed correctness of the system's operation and expected results.

However, glitches have occurred during simulations, creating margins, where improvements are required. In Figure 12 occurred several spikes of current flow from and to battery pack, pointing to a potential error in the DC-DC converter controller, lowering operational efficiency of the system. The same can be seen in Figure 8, where one spike in current flow can be seen before the end of simulation.

7 Conclusion

Research in the field of the state-of-the-art electric vehicle (EV)powerline simulators displayed promising solutions, already utilized at the research and development (R&D) centers and universities. Advanced powerline simulator models, with setup consisting of multiple electrical motors and dSPACE controller, are used for the R&D of the most modern and advanced motor control methods. While described simulator model helps with extensive research of motor control methods, its setup can be adjusted and used in alternative experiments. As this research suggested, simulator of the electrical vehicle drive based on drive cycle would bring an experimental setup, suited to test and verify the prototyped EV drive by subjecting the drive to various drive cycle scenarios. Experimental setup was described by specifications, sourced from the initial research and delivered suitable prototype model. To verify the functionality of the simulator before building the physical model, simulations were preferred as a verification method.

Simulation setup was built from the two stages, delivered baseline data, confirming successful implementation of the simulator into simulations, while being controlled by reference speed of the selected drive cycle. The first stage created timeline data of the requested electrical power from driveline. Requested power needs to be covered by battery pack and super-capacitor (SC) bank. The second stage used generated data to simulate the load/generation of the calculated current and operation of the energy storage system (ESS). For simulations, baseline simulation was done with inadequate capacity of the SC bank and low discharging limit.

The baseline simulation resulted in an SC bank not holding enough charge to cover extensive load caused by the EV drive. Situation projected state, where the SC bank could not deliver any more power to the system and battery pack had to cover the remaining required charge from the SC bank. Increasing and optimizing rated capacitance of the SC bank would recover the system from being subjected to described state, which has been utilized in experimental simulation. Experimental simulation resulted in successful operation of EV drive, where the SC bank was able to cover extensive power requirements, without discharging to operational limit.

Proposed simulations can simulate the EV driveline with a modest and simplified approach. Vehicle body parameters, drive cycle and component parameters can be adjusted according to the requirements, to verify the prototyped vehicle setup, while being operated by reference speed of the selected drive cycle. Simulations generate data of calculated and measured voltage, current and power flows occurring in the EV system during the experiment. User can adjust parameters according to the generated data, as the data confirms the determined requirements stated by user.

Described experimental setup contains unexplained problems of oscillating and spiking current flow during various segments. With omitted powertrain components such as inverters, electrical machines and drive controllers, the simulation is close to an ideal scenario, since the losses from the components are not calculated and included. Before building the physical model of a simulator, simulation must be supplemented by missing components and the necessary calculations for control method of motors must be designed. Due to more of an ideal scenario nature of described simulations, they are valid only to a certain point, as they cannot be compared to the real-life scenarios.

For future research with proposed simulations and experiments, there is an important question left to answer, since it was not in merit of this research. How does the proposed HESS configuration affect the performance efficiency of the EV drive, compared to conventional battery-only system?

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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