Parameters selection of extended-range electric vehicle powered from supercapacitor pack based on laboratory and simulation tests

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Abstract. In this study, the concept of selecting the propulsion system parameters of an extended-range electric vehicle (EREV) powered from a supercapacitor (SC) pack and a range extender (REX) consisting of Internal Combustion Engine (ICE) and Electric Generator (G) was presented. The methodology of parameter selection was verified by computer simulation as well as by laboratory tests. On the basis of initial laboratory tests, parameters (capacitance as a function of the terminal voltage) of the supercapacitors pack were determined and subsequently used in the EREV simulation model. The tests were carried out for the Worldwide harmonized Light vehicles Test Cycle (WLTC), and the vehicle parameters were scaled to the capabilities of the laboratory stand. Research on EREV powered from supercapacitor pack allowed to conclude that it is possible to properly select the capacitance of SC pack and the power of the REX, so that the WLTC cycle can be realized. Thanks to EREV powered from SC it is possible to work at the point of the highest efficiency of ICE, which is associated with the least fuel consumption.

1. Introduction

Over the past few years, the expansion of cars with electric or hybrid-electric propulsion has been systematically taking place [1]. Nevertheless, these vehicles are constantly struggling with the same limitation, i.e. pure electric range [2]. This is mainly related to the electric energy density of accumulators. Currently, almost all constructions of electric vehicles are powered exclusively from electrochemical batteries. This is not the best solution as the batteries in addition to the limitations in the amount of accumulated energy, have a limited lifespan depending on the charging and discharging cycles. Moreover, they are sensitive to high current loads (fast charging, regenerative braking, vehicle accelerating) and temperature changes [3]-[4]. Consequently, after a certain time (a few years), the battery pack should be replaced with a new one, which entails significant costs.

An alternative approach to an electrochemical battery can be a fuel cell or supercapacitors. In the case of a fuel cells, there is still an issue with problematic process of obtaining and storing hydrogen. Moreover, another drawback constitutes their sensitivity to fuel contamination. On the contrary, supercapacitors can be loaded with high powers, both during charging and discharging [5]. They are characterized by a much longer lifespan than electrochemical batteries, however, they have a lower density of accumulated energy and are relatively expensive. Supercapacitors seem to be an attractive solution for use in a vehicle, but their low energy density makes it necessary to cooperate with another source of electricity. One of such solutions can be EREV power train.

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2. Structure of extended–range electric vehicle supplied with supercapacitor pack

Due to the similarity of the structure of EREV to the structure of hybrid drives in a series configuration [7]-[8], they are often classified in the same category. The difference lies mainly in the capacity of energy storage (greater than in hybrid drives, but smaller than in electric drives) and in the method of controlling the power flow in the system [9]. The use of a small combustion engine allows a significant extension of the EREV driving range in relation to pure electric cars. At the same time the size of the electric energy accumulator is reduced and the current load is lowered. Depending on the mode of operation of the vehicle powertrain, it is possible to drive only with the use of an electric motor – driving mode with "zero emission" of pollution and reduced noise and vibrations transmitted from the vehicle to the environment. This is an unquestionable advantage, as in a growing number of large urban agglomerations (e.g. London) the city centres are closed for conventional vehicles powered by internal combustion engines. Another advantage of this solution is the support of the electric motor by Range Extender (REX) in conditions of high power demand (acceleration, driving at maximum speed, driving uphill). Moreover, EREV vehicles are equipped with a regenerative braking system, which reduces energy consumption [10].

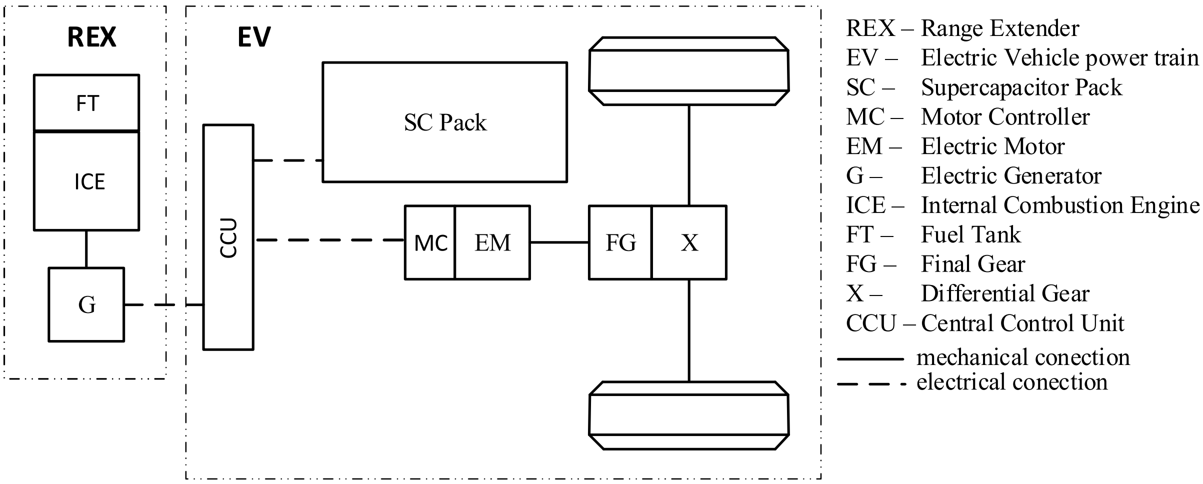

Figure 1. Block diagram of Extended-Range Electric Vehicle powered from supercapacitor pack

According to the scheme presented in Figure 1, the vehicle is driven by an electric motor (EM) controlled by a motor controller (MC) powered by a supercapacitor pack (SC). The braking/accelerating torque is transferred via a reducer with a fixed ratio (FG) connected to the differential gear (X) and drive shafts. The vehicle range extension system (REX) consists of an internal combustion engine (ICE) and an electric generator (G) that simultaneously can operate as a starter motor for ICE. The fuel tank (FT) is connected to the internal combustion engine (ICE). The central control unit (CCU) defines the operation of the electric drive system (EV) and the range extender (REX). The central control unit (CCU) decides about switching REX on and off based on the information on the SC State of Charge (SoC) and the parameters given by the driver and related to the current driving conditions. Mechanical and electrical connections are presented with continuous (––) and dashed (– – –) lines, respectively. The drive system shown in Figure 1 can work in the following operating modes: 1. Driving in pure electric mode, 2. Driving in hybrid mode: a) with energy usage from the SC pack and from REX, b) with energy usage only from REX. 3. Regenerative braking – charging the supercapacitor pack.

3. Parameters selection

The supercapacitor's energy capacity can be calculated using the equation 1:

$$\Delta E = \frac{1}{2} C (\Delta U_C)^2 \quad (1)$$

where:
ΔE –maximum variation of energy in supercapacitor,
ΔU_C – maximum variation of supercapacitor voltage.

On this basis, considering the voltage range ΔU_C of the SC pack in the designed system, the capacity of the supercapacitor pack can be determined (equation 2).

$$C = \frac{2\Delta E}{(\Delta U_C)^2} \quad (2)$$

The test bench real time simulation results of electric vehicle powered only from SC pack (without REX) are presented in Fig. 2a. The tests were carried out for the Worldwide harmonized Light vehicles Test Cycle (WLTC) [6], (see Fig. 7a). The parameters of real vehicle were scaled to the properties of the laboratory stand (described in section 5). The cycle has not been completed. The voltage U_C at the SC pack terminals dropped almost to zero, which caused the system to shut down, which means that available energy accumulated in SC pack was consumed before end of the cycle. The current I_C at the SC pack terminals (Fig. 2b) depends on vehicle speed from drive cycle. During vehicle accelerating the current is positive, which means that energy is consumed, while during vehicle deceleration the current is negative and energy is accumulated due to regenerative braking. The current level depends on energy demand from the cycle as well as on the SC pack voltage which decreases with discharging process.

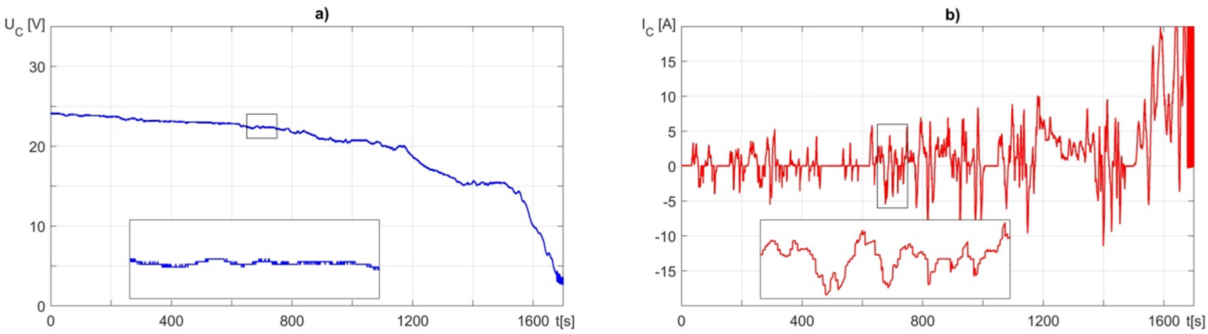

Figure 2. Results of supercapacitor test bench without range extender support

For this reason, it is necessary to use a different power source in the vehicle, which may be REX. The REX power is selected based on the average power of the analysed cycle (equation 3).

$$P_{REX} = \frac{1}{T_{end}} \int_0^{T_{end}} P_L(t)dt \quad (3)$$

where:
P_L – load power during driving cycle,
T_{end} – the end time of driving cycle.

In such a situation, the energy of the supercapacitor is determined on the basis of maximum deviations from the average power value, i.e. the REX power. The energy of the cycle is determined from the equation (4).

$$E(t) = \int P_L(t)dt \tag{4}$$

Maximum variation of energy in driving cycle can be calculated from formula:

$$\Delta E = max[E(t) - P_{REX}t]_0^{T_{end}} - min[P_{REX}t - E(t)]_0^{T_{end}} \tag{5}$$

The determined in such a way energy accumulated in the SC pack should allow to perform the analysed cycle. The first part of the formula $max[E(t) - P_{REX}t]_0^{T_{end}}$ means point of the biggest energy demand insufficiently compensated with energy from REX. While the second part $min[P_{REX}t - E(t)]_0^{T_{end}}$ describes the point of minimum energy demand (e.g. during regenerative braking). If taking into account only the biggest positive energy deviation from average level without recuperated energy, SC pack will be oversized.

4. Simulation model

Load power of electric drive is calculated from driving cycle and motion resistance. Considering drive structure with supercapacitor and REX, load current is calculated from equation 6.

$$I_L(t) = \frac{P_L(t)}{U_C(t)} \tag{6}$$

Due to the presence of two sources of energy in EREV power train, the supercapacitor current is the difference of traction motor (load from cycle) and REX current (equation 7). The I_L current can be positive or negative depending on cycle phase. The sign of current I_C depends on actual power demand, positive means energy usage while negative energy accumulation.

$$I_C(t) = I_L(t) - I_{REX}(t) \tag{7}$$

The relation between supercapacitor parameters (current, voltage and capacity) is described by the equation 8.

$$I_C(t) = C\frac{dU_C(t)}{dt} \tag{8}$$

Applying to equations 7 and 8 Laplace transform the capacitor voltage can be obtained:

$$U_C(s) = \frac{1}{sC}I_C = \frac{1}{sC}(I_{REX}(s) - I_L(s)) \tag{9}$$

where:
s – is Laplace operator.

The simulation model was designed using the formulas 3, 6 – 9. The model in Matlab/Simulink software is presented in Fig. 3. For the analysed study in this work, the I_{REX} current always took a fixed (constant) value. However, another type of REX control strategy is possible (e.g. presented in work [9]).

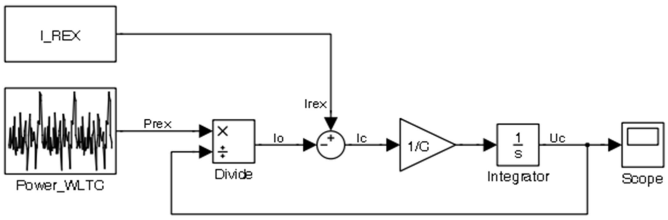

Figure 3. Simulation model of supercapacitor energy storage supported by range extender

5. Laboratory stand

The bench stand operates based on loading the supercapacitor with time depending power profile, consisting of charging and discharging phases. The phases correspond to the analysed drive cycle of an electric vehicle movement, e.g. WLTC. Charging resembles the regenerative braking phases of the cycle (simulated by DC power supply 1) and the operation of REX as well (simulated by DC power supply 2). Therefore, two controlled DC power suppliers Voltraft DPPS 32-15 were used. Vehicle acceleration results in energy consumption which is resembled by electronic load TTi LD300. All of the DC power suppliers and electronic load are controlled by voltage analog signals, through two NI USB-6008 acquisition and control cards. This bench stand is managed by the specially designed program in LabView environment. The measurement of voltage and current at SC terminals is conducted by Chauvin Arnoux E3N current probe and differential voltage Elditest GE8100 probe. For performed tests the Maxwell 165 F 48 V SC pack was used. The scheme and the photo of the laboratory stand is shown in Fig. 4 and 5, respectively.

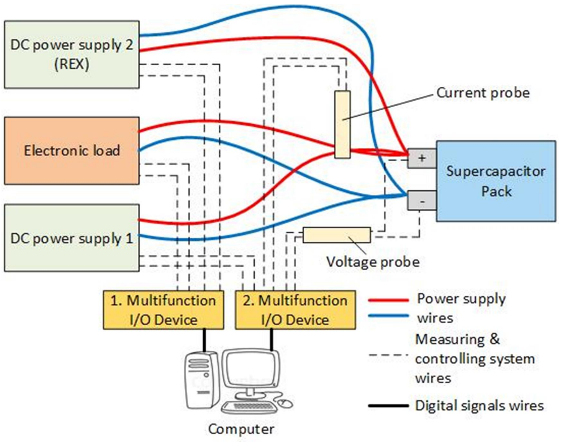

Figure 4. Scheme of the laboratory stand connection n.

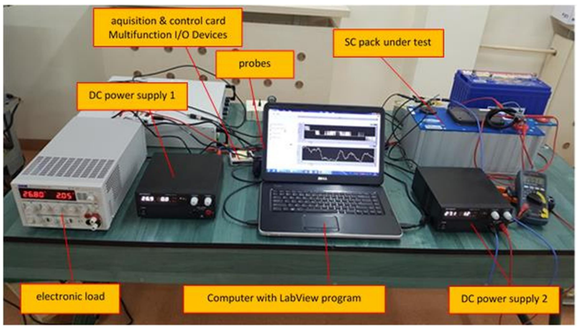

Figure 5. Laboratory stand for real time simulation of EREV powered from supercapacitor pack.

The program pseudocode written in the LabView environment is presented in the form of a block diagram in Fig. 6. The input data to the program are: power profile set in the form of a file and analog input signals corresponding to the supercapacitor voltage and current (measured by current and voltage probes). The power value (taken from the power profile) is divided by the scaled voltage value of the measured voltage to calculate the value of the required supercapacitor current.

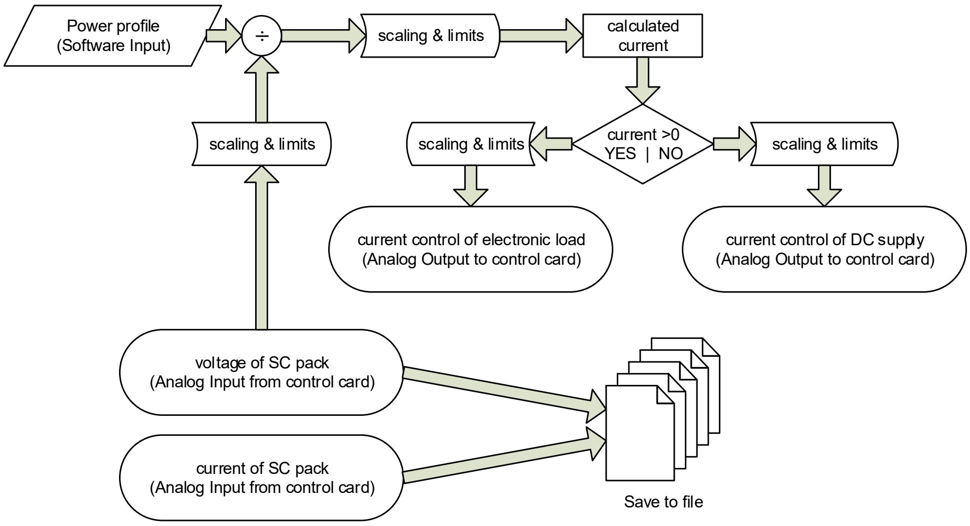

Figure 6. The block diagram of a program written in the LabView environment that controls the elements of the laboratory stand.

The voltage signal is additionally limited on both sides (max and min values) therefore there is no risk of dividing by zero and generating a too high set point current. Subsequently the value of the required current is compared to zero. Positive current values, after the appropriate scaling, are used to generate signals controlling the electronic load, and negative - to generate signals controlling the DC power supplies. The program, apart from the current value, also controls the voltage value of the DC power supply so that the current and voltage limits of the supercapacitor are not exceeded. At the same time, analog input signals corresponding to the supercapacitor voltage and current (measured by current and voltage probes) are saved to a file for later use and analyses.

6. Comparative analyses

Simulation tests were carried out for the parameters of a typical family city car. The vehicle data used in the presented study are included in Table 1.

Table 1. Vehicle data used in simulation study.

Mass m (kg)	Frontal area A (m^2)	Drag coefficient C_x (-)	Rolling resistance coefficient f_t (-)
1676	2.5	0.28	0.012

The WLTC cycle (Fig. 7a) and the vehicle characterized by parameters in Table 1 were applied both in laboratory and simulation tests. On this basis, the profile of power on the wheels of the vehicle was determined, as shown in Fig. 7b. The power profile was an input parameter for both simulation and laboratory bench tests.

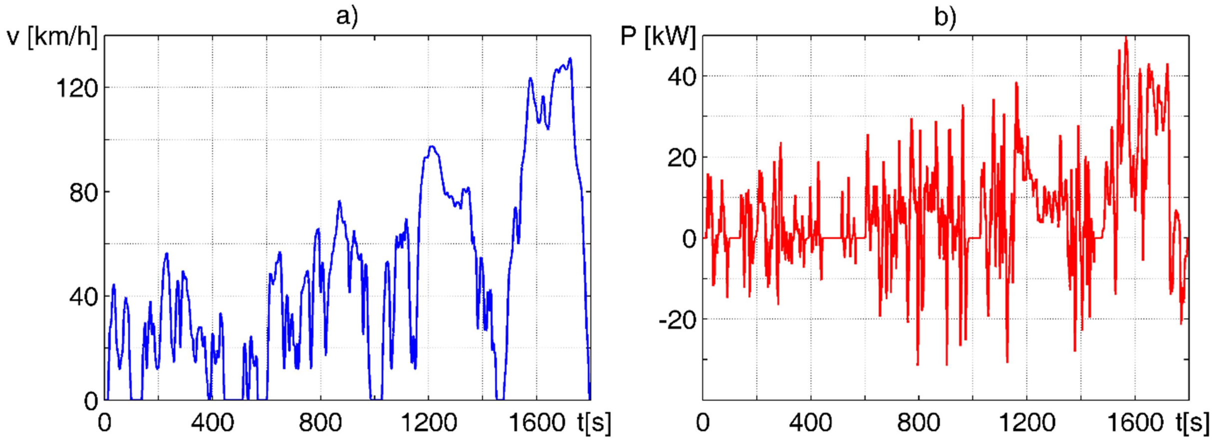

Figure 7. a) WLTC Cycle [6], b) Power profile from WLTC cycle used in the tests.

The results from both test methods are summarized in Fig.8.

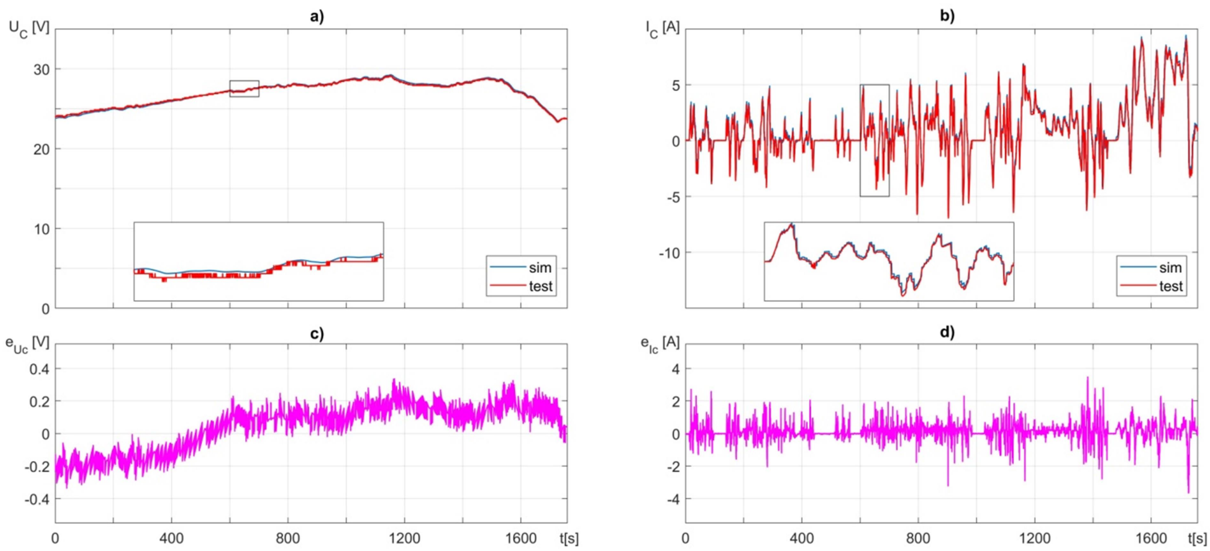

Figure 8. Comparison of simulation and laboratory bench test results: a) supercapacitor voltage, b) supercapacitor current, c) error of voltage, d) error of current.

The voltage profile at the SC pack is shown in Fig. 8a, while the current profile in Fig. 8b. The voltage at the terminals of the SC pack corresponds to the actual State of Charge (SoC) of SC. Whereas, the current on the terminals determines the instantaneous power of vehicle movement resistance. Figures 8c and 8d present errors, i.e. the difference between values from simulations and laboratory bench tests for voltage and current, respectively. The voltage error is small, which means that results from both tests are well correlated. The current error may seem to be relatively high but the difference at the level of 2 A is related only to current pics in real time test which take only few milliseconds. It is visible on the magnified waveform fragment (in Fig. 8b) that both values are well correlated.

The WLTC cycle was fully realised and good correlation of results was obtained. The voltage level at the SC terminals after the end of the cycle is at almost the same level as at the beginning (Fig. 8a). It means that for such REX power, the energy usage in the cycle is balanced with that coming from

REX. This is consistent with the assumptions of the methodology for selecting the parameters of the EREV power train system supplied from SC pack.

7. Conclusions and final remarks

Research on EREV powered from supercapacitor pack allowed to conclude that it is possible to properly select the capacitance of SC pack and the power of the REX, so that the WLTC cycle can be realized. Thanks to EREV powered from SC it is possible to work at the point of the highest efficiency of ICE, which is associated with the least fuel consumption. What is more, by replacing the electrochemical battery with the SC pack, the more reliable EREV system could be obtained. Additionally, it will allow to increase the use of regenerative braking and can improve the dynamic parameters of the vehicle (acceleration) as a result of the possibility of loading the SC package with more power. However, the replacement of the electrochemical battery with supercapacitors would be quite expensive. For a typical urban electric car, even equipped with REX, it is necessary to use many SC packages, which nowadays seems to be economically unjustified. However, for special applications (e.g. military ones) extended -range electric vehicle powered from the supercapacitor pack may prove to be the right solution.

The method of the parameters selection of the EREV power train powered from SC pack presented in this paper is sufficient to fully perform the most of typical driving cycles. Nevertheless in real application the available energy can be too small to perform a random drive or to drive uphill.

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