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BATTERIES AND SUPERCAPACITORS FOR POWER SYSTEMS USED IN TRANSPORT

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Abstract **– The paper relate to the design, modeling and simulation of a power system containing batteries and supercapacitors, used in transport. Several characteristics of batteries are presented and advantages of using supercapacitors are listed. A power system structure is proposed and it's analyze is done. Modeling and simulations comes to prove the benefice of using batteries and supercapacitors in automotive power systems.**

Keywords: *batteries, supercapacitors, power systems, transport.*

1. INTRODUCTION

The research regarding power systems for road transportation represents an open subject in technical domain [1], [2].
In a hybrid/electrical vehicle though, energy supply and recovery using only batteries represents a limitation for concept design. Battery weight, occupied volume and price reduce considerably the number of solutions for vehicle design and construction. Therefore, researches are nowadays carried out in order to optimize the architecture of power systems vehicles [3]. The solution adopted by most researchers and vehicle constructors is based on multiple energy sources [4], one of the modern solutions proposed being to use together battery and supercapacitors (SBSC).

The paper presents several characteristics of both energy sources. Then, an analysis upon power systems containing batteries and supercapacitors it is done and a general architecture of a power system is described.
In [7], [8] has been analyzed a power system used for a DC motor propulsion, configuration according to the electrical vehicles.
Containing the researches, in this paper, another SBSC system is developed for electrical propulsion: SBSC utilized in hybrid electrical vehicle (HEV) with a synchronous motor.

The research performed regarding system structure, functioning and mathematical modeling are concerned with the increase of energy efficiency. The architecture is analyzed and simulations are performed, the results being presented and discussed.

2. RECHARGEABLE BATTERIES FOR VEHICLES

In the evolution of battery for electrical vehicles, following types are relevant: Pb-acid, Nickel/Cadmium (Ni-Cd), Nickel/Metal Hydride (NiMH), Li-ion, and Lithium-polymer [5].
Electrical characteristics (voltage, specific power) and construction characteristics (electrodes, electrolyte) are indicated in Table 1.

Table 1: Main characteristics of automotive battery packs used for traction.

Battery type	Voltage [V/cell]	W_{spec} [W/kg]	Electrodes (+) / (-)	Electro-lyte
Lead acid	2	35-50	PbO_2 - Pb	H_2SO_4
Ni-Cd	1.2	40-55	NiOOH - Cd	KOH
NiMH	1.2	50-80	NiOOH - Metal hydride	KOH
Li-ion	3.6	100-150	Li (1-x)MnO_2 - LixC	Organic

Functional and constructive particularities of the mentioned batteries are analyzed in the following.
Classic wet Pb-acid batteries require periodical maintenance consisting of filling with water the battery's elements. Apparition of Pb-acid with regulation valve (valve regulated lead-acid (VRLA) battery) represents an alternative to the classic model that requires less maintenance. The VRLA battery,

whose technology is based on gel instead of solution, has been largely adopted in automotive traction projects. Ni-Cd batteries tend to be replaced by NiMH batteries, due to toxic properties of Cd.
The construction of Nickel/Metal Hydride (NiMH) has been made possible due to researches regarding metal alloys capable to store hydrogen. The cathode consists of a compact structure containing thin metal particles. In the figure 1 is showed self-discharge characteristics for a NiMH battery [6].

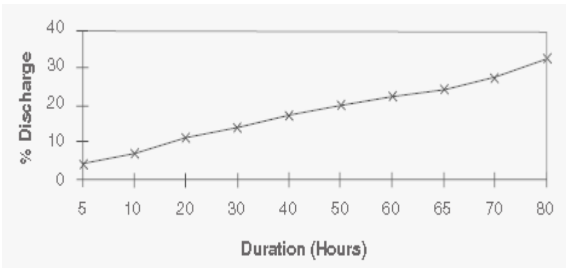

Figure 1: Typical self-discharge for a NiMH battery [6]

Li-Ion batteries are characterized by higher electrical performance (energy density, voltage, no memory effect), lower weight in comparison to other types. During a Li-Ion battery's discharge process, lithium ions (Li+) are released from the anode and travel through an organic electrolyte toward the cathode. Li-Ion batteries produce the same amount of energy as NiMH cells, but they are typically 40% smaller and weigh half as much. First Li-Ion cell to be used in automotive traction applications utilized $LiCoO_2$ (lithium-cobalt-oxide) cathode and stored 30 Ah. Later on, other oxides have been introduced as cathode for this battery. Nowadays, $LiCoO_2$, $LiNiO_2$ and $LiMnO_4$ oxides are utilized. All Li-Ion cells have a prismatic steel casing and stacked electrode configuration. The performance of large prismatic cells with a specific energy greater than 100 Wh/kg and specific power greater than 200 Wh/kg meets the requirements of electric vehicle battery applications. In the Table 2 the main characteristics of the presented types of batteries are listed.
From the table following can be observed:
- High-energy density in order to obtain a stable power delivery process when discharging high currents, e.g. when the vehicle starts moving;
- Long lifetime with maintenance free and high safety mechanisms built into the battery;
- Easy recycling possibility

Table 2: Main characteristics of automotive battery packs used for traction

Characteristics	Pb–Acid Battery	NiMH Battery	Li-Ion Battery
Voltage/element, V/cell	1.2	1.2	3.6
Specific energy W_{sp}, Wh/kg	30-50	60-90	90
Specific power P_{sp}, W/kg	150 – 400	200 – 300	200 – 300
Lifetime, cycles number	300- 700	up to 1000	up to 1000
Charge period, h	Normal: 6-10; Fast: 1h	Normal: 2-4; Fast: 1h	Normal: 2-4; Fast: 15 min. to 60% capacity
Operating temperatures, ^oC	-20 …+ 60	-20 …+ 60	-20 …+ 60
Self-discharge	Low	Longer than other types	Low
Advantages	Low price, well know technology	High W_{sp}, long lifetime	High W_{sp}, long lifetime
Drawbacks	Low W_{sp}, sulphation, pollution	Low cell voltage, high price, self discharge	No overcharging, expensive, highly reactive

An important feature for batteries used in automotive traction is a high charge/discharge capability, which depends on the internal resistance of the battery. The reduction of internal resistance has been achieved in modern batteries by constructing thin high area electrodes.
Fast charging method is applied according to battery's functional characteristics. The charging circuit has to continuously adjust current level in function of the acceptance degree of the battery. The internal resistance of the battery is generally an obstacle to the fast charge/discharge process. Maximum limits of charge/discharge rates are battery design dependent.
Charging Pb-acid, Nickel/Cadmium, Nickel/Metal

Hydride batteries implies the use of constant current method, while Li-Ion batteries are charged by constant current – constant voltage method applying a constant current up to 4.2 V/cell and then constant voltage for 2 hours.
Functioning regimes of batteries are influenced, besides charge/discharge process, by other factors, which are neglected in the model take in account in this paper.

3. SUPERCAPACITORS

Double layer electric capacitors are high storage capacity devices, known as supercapacitors. Nowadays models are characterized through:
- High power density (much higher than 1000 W/kg);
- Long lifetime (longer than 100.000 cycles);
- Relatively high efficiency (generally higher than 80 %).

Due to these characteristics, supercapacitors are suitable for equilibrating charge transfer for the battery or combustion cell. Energy density is lower than in the case of other supply sources, amounting 3 to 7 Wh/kg. Due to weight and packing considerations, only hundreds of Wh stored energy are reached, capable to sustain short power consumption peaks. During discharge process, the voltage across terminals of a supercapacitor decreases almost linearly, creating therefore problems in certain applications. An electronic interface is required in mentioned cases, capable to accept rapid variable continuous voltage.
Energy of a supercapacitor depends on its capacity and voltage across terminals, while power depends on its internal resistance and electric current strength crossing the supercapacitors.
The advantages offered by these components are multiple:
- Long lifetime in comparison to batteries, without deterioration of characteristics;
- High power density (2000-4000 W/kg), 10 times higher than high power Li-Ion batteries;
- High charge storage capability;
- Fast power supply (the energy can rapidly be delivered);
- Low internal series resistance;
- Fast charging.

Among drawbacks, following can be considered:
- Limited voltage range;
- Prices higher than for batteries;
- Low specific energy density in comparison to batteries;
- Limited discharge speed, in function of internal temperature (open circuit risk).

In hybrid/electrical vehicles batteries can store up to 40 Wh/kg electric energy, while power density delivered by gasoline reaches 13.000 Wh/kg.

4. POWER SYSTEMS WITH BATTERIES AND SUPERCAPACITORS USED IN TRANSPORT

From power delivery point of view, batteries are not a reliable device, its value decreasing in time lowering acceleration capabilities and driving smoothness [3], [6]. In order to eliminate this inconvenient, power systems composed from two or more energy sources are utilized for energy supply/recovery processes. In this manner, the complementary advantages offered by each component are utilized. The strategy becomes highly reliable in the case of power applications, like in transport.
Considering mentioned aspects, complete structure of a power system is composed from:
- Main energy source, that deliver medium power;
- Secondary energy source, designed for sustaining transitory power transfer;
- Converter interface for associating the two elements.

Main source is sized for delivering the medium power required for the application. The secondary source, that develops supplementary electrical power for short periods, is capable to recharge itself during system operation, recovering different types of energy. The source can be utilized during the entire system operation, without design over sizing the element.
The general architecture of a hybrid energy supply/recovery system is presented in Fig. 2.
Main source could be an electric generator such a pack of batteries, while the secondary source could be a pack of supercapacitors.
The load is connected to the main source and the secondary source is interconnected by a reversible converter, in order to ensure energy flow for both charge and discharge processes during operation.
Main task of the reversible converter is adapting voltages between main and secondary energy sources. Furthermore, the configuration allows controlled energy recovery, by reversing energy flux from the load towards secondary source [7], [10].

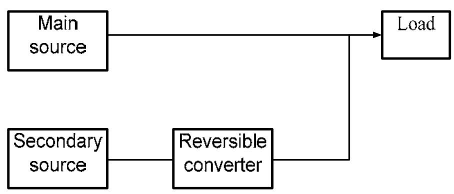

Figure 2: General architecture of a power system connected to a load

Presents researches [4], [9] prove the advantages of SBSC power systems, in which batteries ensures a continuous voltage, while supercapacitors deliver and receive the transient picks of power.
In [7] and [10] has been presented and analyzed a power system used for a DC motor propulsion. In the next paragraph a SBSC structure used for a synchronous motor propulsion is proposed and studied.

5. POWER SYSTEM USED IN A SYNCHRONY MOTOR PROPULSION

5.1. System description

The architecture of the proposed power system utilized in a hybrid vehicle is shown in Fig. 3.
The battery pack is directly connected to the DC bus, providing a constant voltage for the system. This approach represents an improvement because voltage control on the bus is not a requirement anymore.
Mechanical load of the system is represented by the inertia and brakes of the vehicle. Propulsion is ensured by MSA traction motor. DC/AC inverter, coupled to MSA transforms the electrical DC power provided on the bus to AC power and controls its parameters.
The power supplying the inverter is delivered by both main and secondary power source. Supercapacitor module represents the secondary power source, ensuring optimal performance for the motor in punctual operation regimes- acceleration and breaking. The bidirectional DC/DC converter connects the supercapacitor module to DC bus, controlling current flow and allowing energy recovery while breaking.

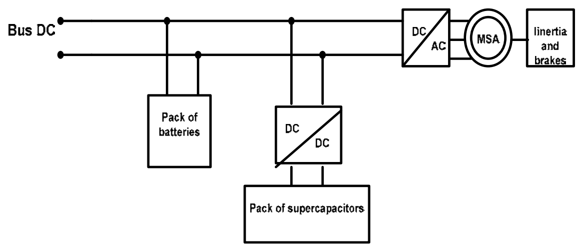

Figure 3: General schemas of a power system used in VEH

Main objectives of the SBSC utilizing syncronous motor study are:
- Modeling of the SBSC-synchronous motor system;
- Simulating of operating motor regimes under different running conditions.

5.2. Power control for SBSC system used in synchronous motor propulsion

The power system connected to a synchronous motor is described in Fig.3. The sources connected to the system have the role to ensure power transfer towards propulsion motor and to recover electric energy while breaking the vehicle.
The entire power demand is ensured by the battery and supercapacitor modules, designed according to the speed cycles described in simulation requirements.
The purpose of simulations is to obtain a quick and consistent response to transient power requests from the motor, in order to obtain a high energy efficiency of the entire system.

The model used for simulations includes a battery module consisting of 23 elements, providing a constant voltage in amount of 280 V.
Supercapacitor pack introduced in the simulation model has the following parameters: total capacity in amount of 5.8 F, voltage across terminals 150 V and internal resistance 0.19 Ω (corresponding to a model obtained by connecting 10 BMOD0058E01B1 modules in series).
Electrical propulsion motor is a permanent magnet synchronous motor, with the parameters: $U_n = 230$ V; $I_n = 42.9$ A; $M_n = 35$ Nm; $n_n = 3300$ rpm; $P_n = 12.1$ kW, described in [9]. Energy efficiency is to be determined in simulations, by analyzing obtained responses.
Variable character of the load is modeled according to the proposed running cycle – 3ECE.
The 3ECE cycle set is composed from several European urban running cycles, containing different accelerations, constant speeds and breaking phases. The phases described in 3ECE are presented in Table 3.

Table 3: 3ECE running cycle

No. crt.	Duration, s	Speed, km/h	Rotation speed, rot/min
1	0-7.5	0	0
2	7.5-12.75	Increase to 25.8	Increase to up to 1100
3	12.75-17.5	25.8	1100
4	17.5-21.75	Decrease to 0	Decrease to 0
5	21.75-27.5	0	Constant 0
6	27.5-37.5	Increase to 51,6	Increase to 2200
7	37.5-42.5	51,6	2200
8	42.5-50.75	Decrease to 0	Decrease to 0
9	50.75-57.5	0	0
10	57.5-72.75	Increase to 77	Increase to 3300
11	72.75-77.5	77	3300
12	77.5-89.75	Decrease to 0	Decrease to 0
13	89.75-97.5	0	0

The power control strategy for this system and in the 3ECE running conditions must ensures a good supply characteristic for the motor, allowing:
- A longer lifetime for the motor;
- The increase of energy efficiency;
- Higher motor efficiency during functioning cycles.

The power control principle utilized for this SBSC, that establishes the contribution of each source in supplying the motor, is based on the separation of medium power demand from the transitory power demand and consists of a first order low pass filtering function. The filter is applied to the motor current obtaining a reference output current for controlling the supercapacitor pack.
Control diagram of the supercapacitor module is presented in Fig. 4.

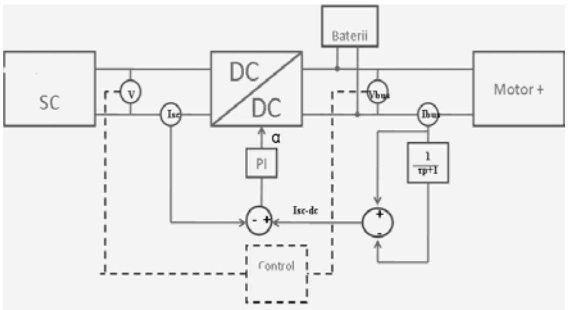

Figure 4: Control schema of the supercapacitors pack.

The battery module that establishes the voltage on the DC bus is considered the voltage source of the system, while the supercapacitor pack represents the current source, ensuring power peaks demanded by the propulsion motor.

Current control of the converter establishes actually output current from the supercapacitor pack, I_{sc}. The reference for $I_{sc\text{-}dc}$ current is determined by measuring load current I_{bus}, followed by a low pass filtering that allows separation between low frequency and high frequency components.

Command variable of the converter is the cycle ratio α , determining the output value of current and voltage across terminals of the induction coil.

Current loop of the supercapacitor pack has a quick response characteristic, allowing an efficient filtering of current on the DC bus and avoiding voltage fluctuation. Furthermore, the peaks will not transit battery module, increasing their lifetime.

By convention, positive transfer power is from battery towards DC bus. The same “generator” convention has been chosen for the supercapacitor pack too. Therefore:

- if I_{sc} <0 → the supercapacitor pack is charging;
- if I_{sc}>0 → the supercapacitor pack is discharging.

Electrical model of supercapacitor pack utilized in simulations is detailed in [10]. Battery module is modeled as an ideal voltage source. The synchronous motor model is detailed in [9].

Functioning regimes for the motor and entire system implicitly are determined by 3ECE demands. In order to implement control strategy for the supercapacitor pack, the transfer function of a first order filter has been utilized, with the time constant of 6 s. Simulations has been done using the Matlab Simulink software.

The current and the power of the motor are shown in Fig. 5 and Fig. 6. In Fig. 7 and Fig. 8 there are described the current and power evolution of the batteries modul, obtained after the control strategy detailed. Fig. 9 shows the converter current as reference current for the supecapacitors applied after the filter. In Fig. 10 the power converter curve is layout.

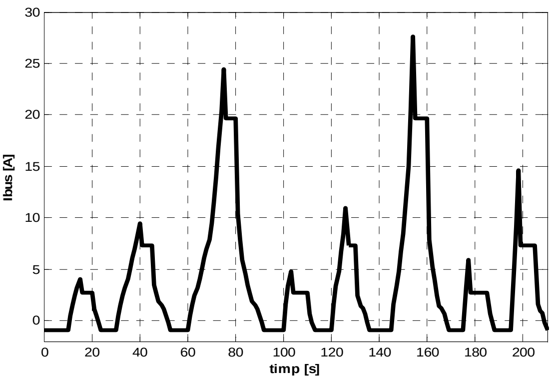

Figure 5: Motor current Ibus

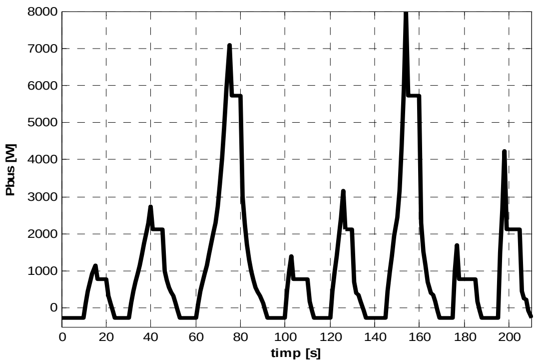

Figure 6: Motor power Pbus

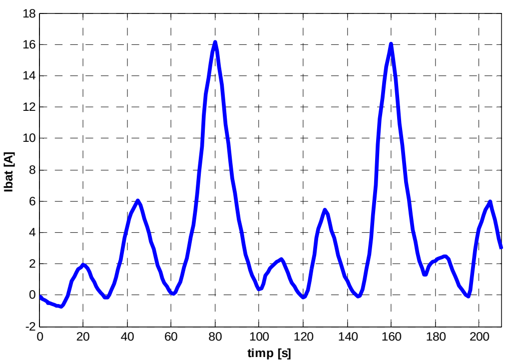

Figure 7: Battery current I_{bat}

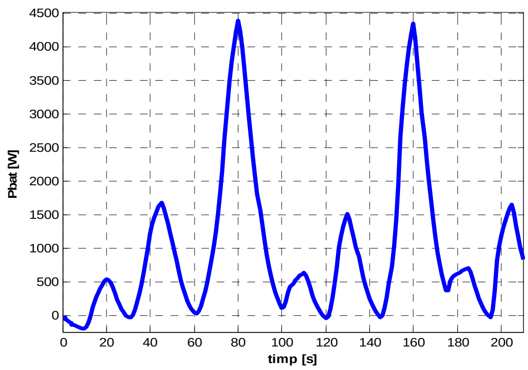

Figure 8: Battery power P_{bat}

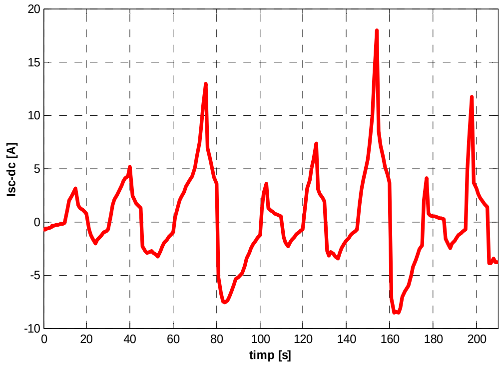

Figure 9: Converter current $I_{sc\text{-}dc}$

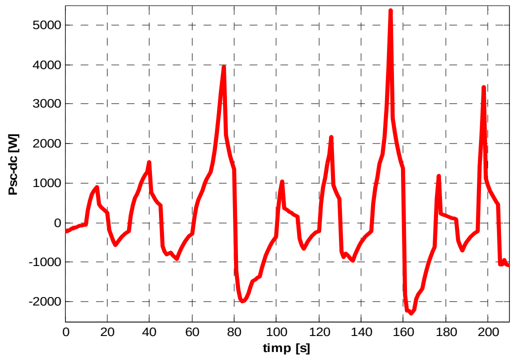

Figure 10: Converter power $P_{sc\text{-}dc}$

Graphics prove an important filtering of the batteries current in comparison with the DC bus current. It can be observed a better distribution of the current between both energy sources: batteries and supercapacitors.

6. CONCLUSIONS

The paper presented an analysis regarding power control and energy management when utilizing SBSC-synchronous motor system, in imposed functioning conditions of running cycle. A control strategy has been implemented for the supercapacitor pack in order to optimize system performance and energy efficiency.
Performed researches demonstrated that SBSC hybrid systems presents a series of advantages, when the batteries provide a constant voltage and power, while supercapacitors deliver/accept high currents in punctual working regimes.
The advantages offered by power systems with batteries and supercapacitors recommend them for applications in transportation, especially where high power peaks are required.
Results obtain through simulations demonstrate the efficiency increase when combining batteries and supercapacitors in power systems used in transport.

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