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VEHICLE AND ROBOT APPLICATIONS SPECIFIC DEVELOPMENT SYSTEM FOR HYBRID ENERGY STORAGES WITH NOVEL ELECTROCHEMICAL COMPONENTS

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Abstract: *In the paper a system for development of hybrid energy storages, with novel electrochemical system batteries and supercapacitors, by physical testing and performance evaluation, in emulated vehicle and robot applications, is presented and discussed. The development system allows optimization by testing a wide variety of: components, capacities, storage structures, charging and discharging methods, control strategies; missions; designs of supplied object (vehicle, robot). Experimental results are reported.*

Key words: *battery, supercapacitor, vehicle, robot*

1. INTRODUCTION

The increased interest to the electrochemical power sources is largely stimulated by the growing needs of the electric driven vehicles, robots and other mechatronic devices driven by electric motors. The sources can be able to supply sufficient energy to achieve the missions of the driven mechanical system, to ensure power bursts at accelerations and to allow storage and use of the braking and down-movement mechanical energy, regenerated by the motors. In many cases it is ineffective to achieve these system requirements using only battery supply, as the batteries have limited power capabilities and shortened cycle-life at high power loading. Therefore hybrid electrical storages are used, in which batteries and supercapacitors are connected (active paralleled, integrated) by electronic DC converters to ensure the system energy, power, regeneration and economics requirements. The batteries deliver steady-state medium power and supercapacitors the transient high power. Thus the supercapacitors unload batteries from harsh charging/discharging conditions, prolonging their cycle-life and enhancing the energy efficiency of the supplied system. Proper energy management strategies can optimize the storage system energy efficiency, operation effectiveness and cycle-life. The development of novel battery charging and discharging methods and algorithms can assure high reliability and cycle-life. However, extensive testing has to be performed to optimize power system performance.

A team of researchers in the Bulgarian Academy of Sciences investigates novel type electrochemical systems, including symmetric and asymmetric supercapacitors and Ni-Zn batteries. A lab-system for testing the experimental cells was specifically developed for that research. The design of the system, based on multiple four-quadrant energy converters managed by computer software, allows determination and evaluation of experimental electrochemical cells characteristics, by wide variety of dynamic and cyclic charge/discharge tests. The system also gives opportunities for testing and assessment of the cells at simulated hybrid storage (HS) operation (e.g. for electric vehicle or robot supply), as well as energy management system (EMS) structure, components capabilities and performance optimization. Thus the lab-system can be used as a development system for HS and EMS also, especially for vehicle and robot applications.

2. THE NOVEL ELECTROCHEMICAL SYSTEMS

The batteries (B) show high energy density but they have medium and low power density, and limited cycle-life. The supercapacitors have lower specific energy characteristics (from 1 to 10 Wh/kg), but much higher specific power characteristics (from 1000 to 10 000 W/kg). The asymmetric supercapacitors have better specific energy (from 10 to 100 Wh/kg) than symmetric [1].

Ni-Zn batteries

The Ni-Zn batteries have high power and medium energy characteristics compared with other type batteries. They are: 25% more compact; 30% lighter; 25% more powerful; than Ni-MH и Ni-Cd batteries, and up to 50% cheaper than Li-ion batteries. Their disadvantage is the limited cycle-life, due to the grown of dendrites on the Zn electrode.

Symmetric supercapacitors

The electrochemical double-layer supercapacitors (SC) are usually symmetrical with two identical electrodes. They tend to have lower energy density compared to batteries, but can provide much higher power capability, high efficiency and long cycle life. They consist of low cost and environmental friendly materials (carbons). However, despite of the current remarkable improvement of supercapacitor performance, they have some disadvantages, such as low energy density, as well as higher self-discharge and equivalent series resistance. The cells voltages are low, typically 2.5V-2.7V. Figure 1 shows the lab-system computer screen at cyclic voltammetry (CVAM) testing of SC cell set. (CVAM provides both quantitative and visual notion of the tested cell capacitance/voltage relation. The capacitor voltage is forced to change with a constant rate $s = du/dt = const.$, while measuring current. The differential (instantaneous) capacitance (c) of the tested SC is proportional to the measured current (i): $c \sim i_{cvam}$, as $c = dq/du = d(\int i.dt)/du = i/(du/dt) = i/s = i_{cvam}/const.$)

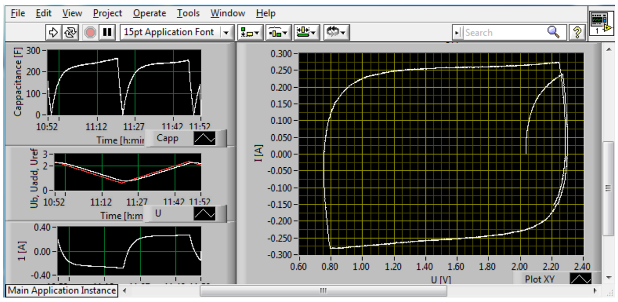

Fig. 1. Supercapacitor cell cyclic voltammetry

Asymmetric supercapacitors

In order to improve the energy density while keeping long cycle life, hybridization of a battery-type electrode with a capacitor-type electrode (named "asymmetric supercapacitors" - ASC), are introduced. Thus, various hybrid capacitor configurations, consisting of activated carbon as a positive electrode and a negative electrode based on metal oxides (nickel, lead or manganese oxides), conducting polymers or Li intercalation oxides, are suggested [2]. For some of newly developed electrochemical systems, the hybrid nature of ASC causes voltage and frequency dependent capacitance and non-negligible equivalent series resistance. Fig.2 shows ASC cell CVAM tests at 5 and 10 mV/s.

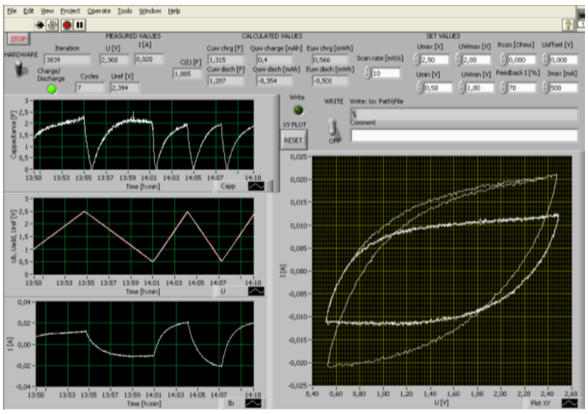

Fig. 2. Asymmetric supercapacitor cell cyclic voltammetry at 5 and 10 mV/s

3. HYBRID SYSTEM PERFORMANCE PROBLEMS SOLVING

Caused by the driven apparatus (vehicle, robot)

The vehicles and robots with intensive start/stops, as well as those with a lot of simultaneously starting motors (like multi-leg robots) impose harsh power requirements to the supply system. Accelerations of the driven mechanical system cause high power bursts, which must be delivered by the storage. Deceleration, breaking and down-movement cause regenerated power, which is efficient to be stored in the storage. To match the appropriate charging voltage and current, the electric motors power must be reconditioned by power electronics converters (PEC).

Caused by the Ni-Zn *batteries*

When the Ni-Zn batteries are recharged, the zinc does not redeposit at the same places on the zinc electrode that were leaved during discharge. Over time, the electrode is becoming misshapen, which leads to the physical weakening and eventual failure of the electrode. This shortens the lifetime of Zn based electrochemical systems. Proper charge and discharge management is a critical factor in Ni-Zn systems utilization, in order to assure optimal battery capacity, cycle life and safety. An inappropriate discharging or charging control may result in unwanted side electrochemical reactions, excessive heat and formation of gasses due to the electrolyte decomposition, degradation or loss of stability of the battery materials. That leads to reduced performance and cycle-life, as well as potential safety hazards. However the new materials, production technology and sophisticated methods of charging and discharging, are going to make possible a comeback of the Ni-Zn batteries for high-discharge, long-life applications. The usable charging methods include: constant current/constant voltage, pulsed charging, interrupted charging, pulsed trickle charging, negative pulse charging. The influence of the charging method on the discharge capacity of the Ni-Zn batteries is shown on Fig.3 [1].

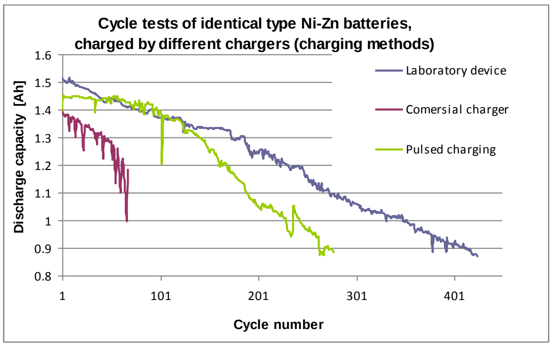

Fig.3 Cycle-life tests of 3 identical Ni-Zn batteries charged by different methods (chargers)

The ways of discharging Ni-Zn battery strongly affect their capacity, as well as cycle-life. Very slow discharging can recondition the zinc electrode by reducing the dendrites, but that is possible only in multi-battery systems. The HS gives the opportunity to control the power flows between the batteries and the supercapacitors and thus to improve the discharging (and charging) regimes of the Ni-Zn batteries. The discussed development system brings the potential of testing and optimizing a wide variety of sophisticated and novel discharging and charging algorithms that recondition dendrites, as: pulse discharging with interruptions or even positive pulse discharging in which positive (charging) pulses (from the supercapacitors) are applied periodically to the battery at discharging. Intensive testing has to be done to evaluate the influence of the different charging and discharging methods on the hybrid supply system performance, life and economical characteristics.

Caused by the supercapacitors

To achieve voltages higher than 2.7V, additional voltage equalization electronic circuits are necessary for series connected supercapacitors. At long high current operation the internal equivalent series resistance causes significant power losses. The energy stored in a supercapacitor depends strongly on both size and position of the working voltage window, since the energy is proportional of the voltage square. That makes the extraction of the full energy worthless in practice. The most commonly used operating voltage window (*w*) is $w \equiv u_{max} \div u_{max}/2$, as it exploits 75% of the stored energy at the cost of 50% of the voltage range. An increase in the operating window width in the direction of lower voltages does not lead to a significant increase in energy, while the decrease of the maximal voltage reduces substantially the stored energy.

Caused by the components joint operation

The batteries have different potential versus cell capacity behavior than the supercapacitors. The batteries are Faradaic devices, which hold near constant potential, as they produce energy via reduction-oxidation reactions, or mass transfer processes. Supercapacitors on the other hand are non-Faradaic (energy accumulators), which require a potential change to absorb or deliver charge. With the charge variation the battery voltage u [V] and supercapacitor capacitance $C=q/u$ (or $c=dq/du$) are relatively constant. The stored energy in a supercapacitor is proportional to the square of its voltage, but in a battery is relatively independent of it. The supercapacitor voltage varies linearly with charge, however, battery voltage is relatively constant. Therefore the passive connections (paralleling) between supercapacitors and batteries are impractical in the majority of applications, and PECs are needed to connect (integrate) them in the storage.

Caused by the DC converters and controllers

The converters and their control, play key role for the integrated HS systems. High efficiency, switch-mode, DC-DC, buck, boost and buck/boost converters are applicable. The insufficiently charged supercapacitors are short-circuits for the voltage sources, what are the most of the energy storage and supply devices (batteries, motors/generators, fuel cells). Therefore the converters must control the currents between the different supply components, transforming input to output voltages. The DC-DC converter controller must also assure the implementation of the energy management system (EMS) strategies, as energy economy, performance, cycle-life, effectiveness and efficiency optimization.

Caused by the HS and EMS optimization

The algorithms and strategies for HS energy management are application-specific and depend on HS structure. In a HS, that combines supercapacitors with batteries, the ratio of the capacities depends on the rated autonomy, the load predictability and the flow management strategy. The EMS design optimization leads to components (B and SC) capacity optimization, but it strongly depends on the control strategy and algorithms used. Therefore simulation of the application system operation is necessary, to evaluate the influence and optimize EMS at different: components capacities, missions and control strategies.

4. THE DEVELOPMENT SYSTEM

The presented development system allows testing and control of the HS operation with real electrochemical components: batteries and supercapacitors. The principal part of the system hardware is a set of devices, each of which consists of four-quadrant (bipolar voltage and bidirectional current) PEC, as well as data acquisition and computer interface module. The modules are connected to a computer via USB cables. Application specific, LabView based, computer software is developed to control the connected cells voltages and currents, as well as to acquire data (voltages, current, temperature, gas generation, pressure etc.).

Due to the multipurpose of the hardware and LabView based software, the presented development system can perform variety of cyclic tests of electrochemical cells, with dynamic bidirectional currents and voltages, by development of specialized computer program only. The system can emulate physically the performance of HS and their EMS. It can monitor system power flows, battery and supercapacitor currents, voltages and charges, and manage the power flows with accordance to wide variety of missions and control strategies. Active management of power flows can: prolong the batteries life by reducing their current stresses, improve the supercapacitors energy and capacitance utilization, and optimize the design by maximizing (or minimizing) specific utility metrics, e.g. life, costs, fluctuations, losses, capacities, weight, volume, etc.

Thus the novel electrochemical systems cells can be tested compared and evaluated at real operation conditions, as well as the hybrid storage component capacities and performance can be optimized.

5. VEHICLE AND ROBOT HYBRID STORAGE DEVELOPMENT

To determine the power load of the HS, the supplied object (vehicle, robot or other mechatronic apparatus) is modeled in LabView. The LabView platform is particularly convenient for this purpose, due to the presence of wide variety of virtual instruments (vi-s).

Computer modeling of vehicle or robot power

The mission of a vehicle/robot EMS is "energy supply that assures the load variation". It can be defined by a dataset of load dynamics, like the standardized vehicle driving cycles [3], as shown on Figure 4, which is a file of records (r) of its moving parts (m) positions (q_{mr}) or speeds (ε_{mr}) versus time (t_r). As the charge/discharge processes in the presented development system are real, but the supplied object (vehicle, robot) is virtual (modeled in

LabView), it's important to match the computer iteration (k) time (t_k) with records time (t_r): $t_r=t_k$. The positions (q), speeds (ε) and accelerations of the object can be determined from the mission file records: x_r or ε_r, or by calculation $\varepsilon_k=(q_r-q_{r-1})/(t_k-t_{k-1})$, and $(d\varepsilon/dt)_k=(\varepsilon_r-\varepsilon_{r-1})/(t_k-t_{k-1})$.

The moving parts (platforms, arms) of the simulated vehicle or robot motions can be translational and rotational. Unified symbols for similar translational or rotational values are used here, to simplify the explanation of the modeling and to unify the equations. Thus the symbol $Ŧ$ denotes force (F), torque (T) or inertial effects ($Ŧ_i$,$Ŧ_c$) i.e.: $Ŧ\equiv F\vee T\vee Ŧ_i\vee Ŧ_c$, ($\vee$ means *or*); $ɱ$ denotes moments translated to a motor driver - mass (M) or inertia (J): $ɱ\equiv M\vee J$; q denotes coordinates - linear (x) or angular (φ): $q\equiv x\vee\varphi$; ε denotes speed - linear (v) or angular (ω): $\varepsilon\equiv v\vee\omega$. The forces, torques or effects with different nature (physical phenomena) (n) are designated by their index $n\equiv i,r,g,a,e,c$. The "n" index meanings are i - "inertia"; r- "resistance"; g- "gravitation"; a- "aerodynamic", e- "external", c- "centrifugal & Coriolis". The external forces/torques ($Ŧ_e$) determine the influence of the other parts (arms, links, units) of the mechanism. The inertia effect ($Ŧ_i$) is time derivative: $Ŧ_i=ɱ.d^2q/dt^2=ɱ.d\varepsilon/dt$. The centrifugal and Coriolis effects ($Ŧ_c$) compensate rotating coordinate system acceleration, and are applicable only in that case. According to their nature (n), forces/torques ($Ŧ$) are calculated as functions of speed (ε), its time derivative ($\acute{\varepsilon}=d\varepsilon/dt=d^2q/dt^2$) and exponent ($\varepsilon^2=(dq/dt)^2$). As the modeled object moving units positions, velocities and accelerations are known, the determination of a motor power $P_m=Ŧ_m.\varepsilon$ becomes inverse dynamics problem – determination of the units forces/torques/effects $Ŧ_{nm}$ and summation: $Ŧ_m=\sum_n Ŧ_{nm}(q,\ \varepsilon,\ \acute{\varepsilon})$, which can be done just by LabView vi-s. A unit (part of the mechanism, arm, link, etc.) driving motor (m) power (P_m) is $P_m=Ŧ_m.\varepsilon_m/\eta_m$, where η_m is the motor efficiency. The storage power (P_s) is sum of the supplied motors powers ($\sum P_m$), divided by the storage efficiency (η_s) and DC converters efficiency(η_c) $P_s=\sum P_m/(\eta_s.\eta_c)$. The total supplied energy by the storage is $E_s=\int P_s.dt$.

An example: supercapacitor storage for vehicle [2]

Figure 4 shows plots of vehicle speed and tested SC current, voltage and power, for an SC supplied electric vehicle, tested on standardized urban drive cycle [3]. The vehicle characteristics are: front surface S [m^2], mass m [kg], and tire pressure p [bar]. The road is characterized by its slope α [rad]. Various vehicle speed mission records (experimental or standardized data sets of vehicle speed v[m/s] versus time t_r[s]), as well as aerodynamic (C_d) and rolling resistance (C_o, C_1, C_2) parameters, can be found in the web [4]. Vehicle forces are caused by: aerodynamic drag: $F_a=\rho.S.C_d.v^2/2$; rolling resistance: $F_r=m.g.(C_o+(C_1+C_2.v^2)/p)$; and gravity: $F_g=m.g.sin(\alpha)$; $\rho=1.2754$ [kg/m^3]; $g=9.81$ [m/s^2]. The inertia effect is $F_i=m.dv/dt$. The driving motor force is $F_m=F_i+F_a+F_r+F_g$. The motor power is $P_m=F_i.v/\eta_m$. The power delivered by the supercapacitor storage is $P_s=P_m/(\eta_s.\ \eta_c)$. The vehicle parameters (and power) are scaled to meet the maximal power which can be delivered by tested cell-sets.

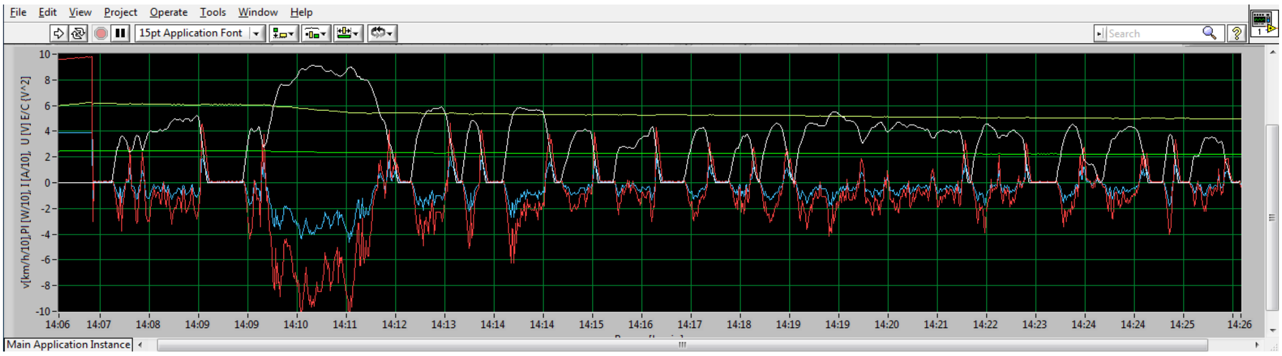

Fig.4 SC cells tests, in emulated vehicle, at FTP-75 driving cycle

5. CONCLUSIONS

A computer controlled system is developed for testing novel systems experimental electrochemical cells. The bidirectional DC-DC converters and application specific software of the system, based on the LabView platform, allows testing and optimization of virtually unrestricted variety of: electric charge/discharge algorithms, control strategies, missions, storage structures and applications: vehicles, robots, power systems, etc. Thus it becomes as a universal environment for development of energy management systems with hybrid storages, by experimental testing and performance optimization with real electrochemical components (batteries, supercapacitors). The platform gives opportunities for determination of the storage power by the mechatronic apparatus (vehicle, robot, etc.) software modeling.

REFERENCES

[1] Trenev V., Mladenov M., Stoyanov L., Veleva S. High-Power Energy Storage with Ni-Zn Batteries and Supercapacitors, Complex Control Systems, ISSN 1310 – 8255, Vol.12, 2013, pp.24-30

[2] Trenev V., Raicheff R., Mladenov M., Electrical Vehicle Oriented Testing and Optimization of Energy Storage Systems with Novel Asymmetric Supercapacitors, XXVI ADP conference, Sozopol, 2017, pp.236-240.

[3] http://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules

[4] http://www.virtual-car.org/wheels/wheels-road-load-calculation.html.