Embedded Intelligent Structures for Energy Management in Vehicles

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Abstract. The present research is focused on developing embedded intelligent structures for energy management in mobile systems. The research introduces a hybrid structure composed of different energy sources and endowed with control systems able to optimize the power flow of the ensemble. In the paper, the architecture of the proposed hybrid system is described. Preliminary simulations were made in order to test the functionality and the advantages of the system. A test bench was implemented in order to characterize the behavior of the implemented system.

Keywords: combined energy sources, energy efficiency, control systems, control algorithms, electric vehicle.

1 Introduction

Lately, the automotive industry has been focused on reducing the fuel consumption, the energy consumption and the pollutant emission while increasing the global efficiency of the vehicle and the passengers' comfort. The new facilities for improving the comfort (GPS, night vision camera, parking assistant etc) increase the energy and fuel consumption thus heating the battery, reducing its lifetime and performances and affecting the environment.

In order to respect the environmental issues, the general trend in the automotive industry is to transit from the classic vehicles toward hybrid electric vehicles (HEV) and electric vehicles (EV), vehicles non-polluting and economics [1].

In the recent years, HEV and EV field has been significantly improved, Honda being one of the companies which opened the gates in this direction by implementing Toyota Prius nominated by U.S. Department of Energy as "zero-emission vehicle".

Our aim is to optimize the energy and fuel consumption of the HEV and EV, the lifetime of the storage devices, to increase the energy efficiency, the autonomy and dynamism of the vehicles and also, to reduce the size of the storage and generation devices by developing embedded intelligent structures for energy management

(EISEM). The EISEM integrates auxiliary energy storage devices and use embedded systems based on microcontrollers (UC) and network of switching devices.

In order to fulfill our aim, the primary goal is to develop the primary elements of the HEV and EV represented by a "combined energy cell - CEC". This is a hybrid system composed of battery, supercapacitor (SC), flywheel and intelligent control elements. A reduced order model was required before a detailed analysis of the components was performed. This paper describes the proposed model of a network of four CEC cells and the results of the simulations. Also, a test bench, the first implemented prototype and some preliminary experimental results are emphasized.

2 Contribution to Sustainability

Nowadays, increasing the energy efficiency represents the main target of any emergent technologies. In the present research, an innovative technique that reflects the fusion between energy and information implemented as a dynamic network of CEC cells is proposed. The CEC is composed of different storage and generation devices with different time constants, all embedded in an intelligent structure with computation abilities (EISEM). This technology could be applied in a lot of actual and also critical applications, from mobile (HEV, EV) to stationary (renewable energy sources (RES), active filters). Active filters represent an important advance of the actual distribution grids by improving the reliability and the quality of the energy provided to the critical loads.

By using EISEM devices, an optimal balance between power and energy density offered is reached. Also, the volume, the wasted energy and the pollution are reduced. Based on the experimental and simulation results, the performances of the EISEM are evaluated and the EISEM model will be integrated as power supply in the overall HEV and EV models. Thinking at the economical aspects, this solution represents a good compromise between performances and prices obtained without major technological efforts. Thus, it is considered an important step toward improving the sustainability of the energetic solutions.

3 Storage Devices Used in Automotive – State of the Art

In present, the lead-acid, NiMH and Li-ion batteries are the most used energy storage devices in automotive [2]. Unfortunately, it was proven that their lifetime, cyclability and performances are drastically affected by the peak current pulses from the starting process [3]. In addition, the high time constant of the battery decreases the performances of the regenerative braking process thus limiting the technological advance in HEV and EV.

To eliminate these disadvantages, three possible solutions can be identified. *The first solution* is the transition to 42 V for EV, thus increasing the energy efficiency of the system. The disadvantage of this solution is related to the high costs of the vehicles' technology translation from 12 V to 42 V. *The second solution* is over sizing the battery, thus increasing the equivalent capacity of the system. The disadvantages are related to increasing the costs and the carried weight of the system and affecting the environment by consuming the non-renewable resources or by polluting through recycling the damaged battery. *The third solution* and the actual trend in automotive is to migrate toward storage and energy device hybridization and also to improve the dynamicity of the vehicles in urban traffic conditions [4], [5], [6], [7], [8], [9].

Because there is no device able to ensure high energy and power densities and increased lifetime at the same time, automotive industry focused its attention on developing embedded control solutions for reducing the fuel consumption and increasing the efficiency [10], [11], [12]. The actual researches use batteries as storage devices but there are also implementations which used SC in order to increase the power densities and the lifetime of the ensemble [3], [13], [14], [15].

Our research presents a hybrid storage and energy device embedded in an intelligent structure. The hybrid system is composed of cells of batteries, SC and fuel cells (FC), sensor networks and intelligent control system able to combine and commute all the storage and generation devices thus optimizing the power flow. The SC has the advantage of being non-polluting and being able to provide and to smooth high peak current pulses thus increasing the lifetime of the battery [16]. A fuel cell can be used in order to increase the autonomy of the vehicles. The main difference between the researched system and the existing ones is the control made at the cell level, instead of the control made at the device level [17].

4 Hybrid Storage Device – Architecture

By connecting in embedded intelligent structures, in a logic way, multiple storage devices (batteries, SC, FC, flywheels) characterized by different time constants and performances to ensure long lifetime and high energy and power density, storage and energy device hybridization is obtained (Fig. 1) [18]. For increasing the performances of the ensemble, the hybrid system was endowed with an intelligent control system able to monitor, control and optimize the energy flow of the vehicle thus improving its performances. The architecture of the hybrid structure is illustrated in Fig. 2.

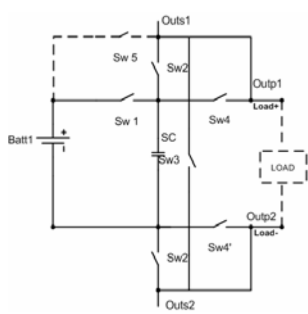


Fig. 1. CEC cell.

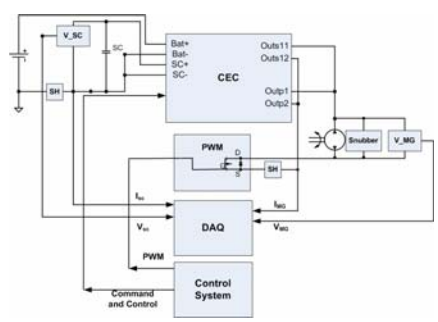


Fig. 2. Architecture of the hybrid structure.

The hybrid structure is composed of EISEM connected to a DC motor/generator (MG) controlled though PWM. The EISEM consists in: (i) CEC: hybrid device composed of cells of storage devices and back to back switches able to ensure the bidirectional power flow (Fig. 1); (ii) Data Acquisition System (DAQ): embedded system based on ATMega128 UC used for acquiring data from the voltage, current and revolution sensors; (iii) Control System: embedded system based on UC for controlling and optimizing the power flow transferred through CEC. Multiple EISEM can be connected in series/parallel to increase the performances of the system (Fig. 3).

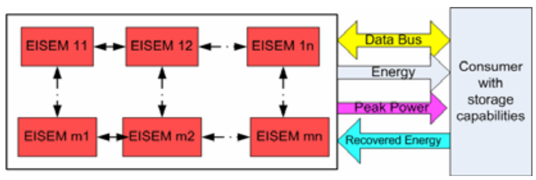


Fig. 3. Network of EISEM.

5 Simulations and Results

The main advantages of a hybrid storage device are related to (i) increasing the lifetime of the battery by supplying the high peak pulses from the SC and (ii) improving the energy efficiency of the system in the regenerative braking process because of its reduced time constants [19].

In order to highlight the performances and the advantages of a network of CEC hybrid devices (Fig. 3), the system was modeled and simulated with Matlab/Simulink tool. The architecture of the modeled system is illustrated in Fig. 4. The simulated network was composed of four CEC cells which can be connected in series and/or in parallel in order to assure the load profile. In the four CEC hybrid devices four 400 F/42 V SC and four 77 Ah/42 V lead acid batteries were used. Also, as an analogy with the inertial storage from HEV and EV, two capacitive loads (*Load1* = 400 F, *Load2* = 200 F) were considered.

The control algorithm (Fig. 5) was implemented to charge the *Load1* from 0 V to 40 V and to supply *Load2* from *Load1*. To control the charging process, voltage transducers were used.

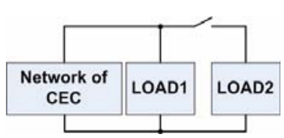


Fig. 4. Simulated system.

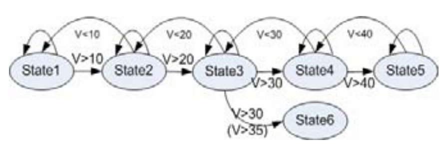
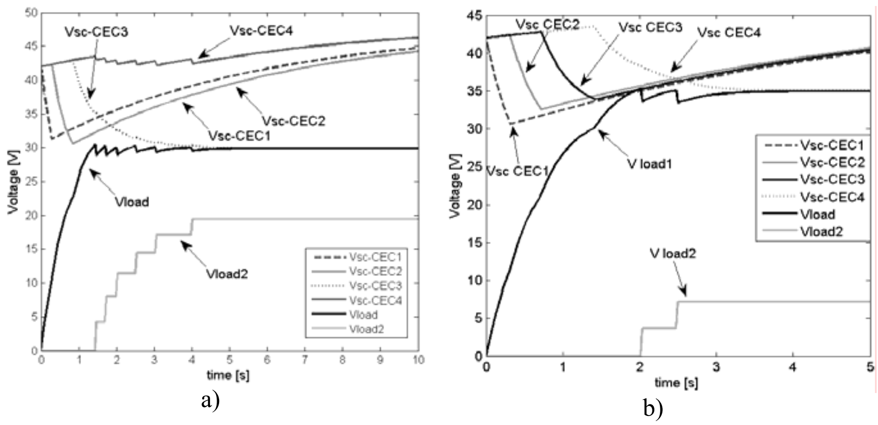


Fig. 5. Control algorithm used in simulations.

The results of the simulations are illustrated in Fig. 6 a), b).



a) b)

Fig. 6. Results of the simulation.

As can be seen, the results of the simulations are in a good agreement with the logic described in the control algorithm (Fig. 5). Thus, depending on the voltage of the load, the network of cells was commuted. *State1* corresponds to charging the *Load1* from SC-CEC1 until the voltage of the *Load1* reaches 10 V. In *State2, Load1* was charged up to 20 V from the SC-CEC2, in *State3* the *Load1* was charged up to 30 V from the SC-CEC3. In *State4* started the stabilization phase. From this state, the algorithm jumped in *State5* and *State6* in order to supply the *Load2* while maintaining the voltage on the *Load1*. Thus, for voltages measured on *Load1* greater than 30 V (Fig. 6 a) and 35 V (Fig. 6 b), the *Load2* was supplied from *Load1*. At the same time, the CEC cells were used for maintaining the 30 V (respectively 35 V) level on *Load1*.

Thus, the simulations proved that a network of CEC hybrid devices endowed with the adequate control strategies can be used for mastering the desired load profile. This embedded system reflects the fusion between the power flow transmitted bidirectional between generator - load and the information that provides the necessary data to the control strategies.

6 Experiments and Results

A single EISEM cell was implemented and tested before the physical implementation of the network of cells. In order to experimentally test the functionality of our prototype (EISEM hybrid device) (Fig. 2) and its efficiency, a first test bench was implemented. The test bench (Fig. 7) is composed of: Device Under Test (DUT), DAQ, Control System and laptop.

The DUT module consists in: CEC hybrid system, MG – electro ventilator with 0.27 kg/m^2 inertia and snubber circuit, Hall sensors for monitoring the values of the MG and capacitor currents, sensors for monitoring the MG and capacitor voltages and optical sensors for monitoring the revolution of the MG. A 0.11 F capacitor was used as generation and storage device in CEC. The battery was replaced with a DC voltage source limited at 5 A.

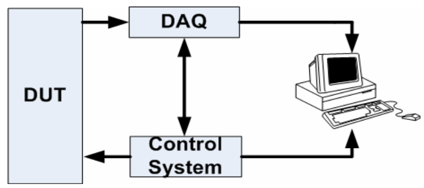


Fig. 7. Test Bench.

The system was implemented to ensure the communication between the modules. Data were acquired with DAQ and were sent to a laptop by using Visual Basic software and UART facilities. Data were locally stored and processed using Matlab tool. DAQ also communicates with the Control System. Based on the information received from DAQ, the Control System interprets the data and controls both modules DAQ and CEC in order to optimize the process.

The first experiments were made while supplying the MG at the maximum power values of 12.5 W (Fig. 8) and 40 W (Fig. 9). In these experiments, while braking, the energy is recovered and stored on the SC without using a DC-DC converter.

If a DC-DC converter and adequate control system are integrated in the tested prototype, the recovered energy can be significantly increased (Fig. 10 and Fig. 11).

In the experiments, the regenerative braking efficiency implemented at reduced scale was tested. The energy recovered and available in the capacitor is:

$$E = (1/2)\cdot C\cdot(U_{max}^2 - U_{min}^2). \quad \mathbf{(1)}$$

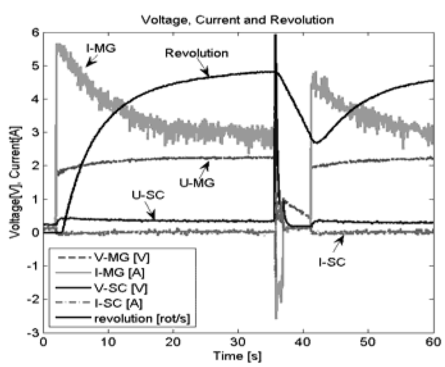


Fig. 8. Experiments at 2.5 V and 5 A.

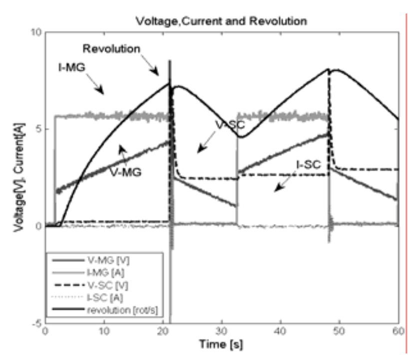


Fig. 9. Experiments at 8 V and 5 A.

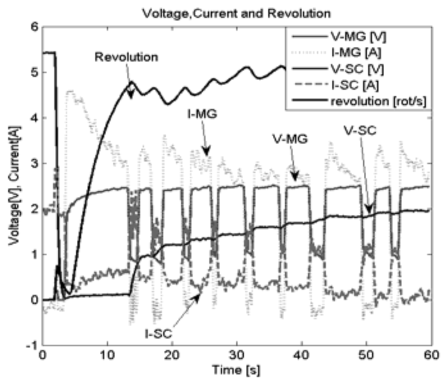


Fig. 10. Experiments at 2.5 V and 5 A.

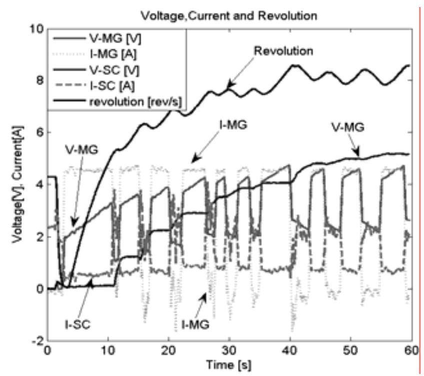


Fig. 11. Experiments at 8 V and 5 A.

By analogy with the urban traffic we have conceived a control strategy that provide by accelerating respectively recuperate by decelerating the energy necessary to move the vehicle.

As it can be seen in Fig. 10 and Fig. 11 the energy recovered in 60 seconds of successively accelerations and breakings while the MG is supplied at 2.5 V/2.5 A is 0.22 J and while the MG is supplied at 8 V/5 A is 1.48 J. Thus, if supplying at 12 V/5 A the energy recovered in 60 seconds is 8 J. For testing a real implementation of regenerative braking on EV, supercapacitors of 400 F/14 V able to recover 39.2 kJ will be used. Thus, the energy efficiency can be significantly increased by recovering the energy usually lost in heat.

7 Conclusions and Future Work

This paper briefly presents the advantages of using embedded intelligent structures for increasing the performances of the EV and HEV.

The paper demonstrates the viability of a cellular concept used for controlling the power flow from the sources toward loads with storage characteristics, as alternative of the batteries systems endowed with step up/down converters. By analogy, this application is similar to the generic control of the HEV and EV where an essential phenomenon consists in recuperating the kinetic energy of the vehicle. The energy efficiency can be increased by replacing the step up/down converters with such a network of cells.

A network of EISEM was introduced and the EISEM hybrid energy storage device was detailed. To observe its behavior, the EISEM firstly was modeled and simulated. The simulations proved that the EISEM not only increase the performances of the ensemble and the lifetime of the batteries, but it also can be endowed with adequate control system in order to optimize and to maintain the load profile.

A first reduced scale prototype of the EISEM hybrid configuration was implemented and its architecture was described. The experimental results proved its efficiency while using it in the regenerative breaking process. Based on these experiments, the corresponding model has to be developed and simulated.

As future work, the network of EISEM cells will be physically implemented. Inside the network, the EISEM cells will have the capability to communicate with a control system and also between them. The control system will have the intelligence to optimally connect the EISEM cells in order to optimize the power flow inside the system. Also, a full scale implementation for EV and HEV has to be done.

References

1. Unnewehr, L. E., Nasar, S.A.: Electric Vehicle Technology. John Wiley, pp. 81--91 (1982)
2. F.A Settle (Editor): Handbook of Instrumental Techniques for Analytical Chemistry. Prentice-Hall, Inc., NJ, USA (1997)
3. P. Borza, A.M. Puşcaş, I. Szekely, G. Nicolae: Energy Management System based on supercapacitors used for starting of internal combustion engines of LDH1250 locomotives and charging their batteries. In: SIITME 2008, Predeal, România, pp. 227--231 (2008)
4. Karden, E., Ploumen, S., Fricke, B., Miller, T., Snyder, K.: Energy storage devices for future hybrid electric vehicles. In: Journal of Power Sources 168, pp. 2--11 (2007)
5. Dobner, D.J., Edward, J.W.: An Electric Vehicle Dynamic Simulation. GM Research Laboratories, pp. 103--115 (1982)
6. Salameh, Z.M., Margaret, A.C., Lynch, W.A.: A Mathematical Model for Lead-Acid Batteries. In: IEEE Transactions on Energy Conversions 7, No. 1, pp. 93--97 (1992)
7. Appelbaum, J., Weiss, R.: Estimation of Battery Charge in Photovoltaic Systems. In: 16th IEEE Photovoltaic Specialists Conference, pp. 513--518 (1982)
8. Baudry, P.: Electro-thermal modelling of polymer lithium batteries for starting period and pulse power. In: Journal of Power Sources 54, pp. 393--396 (1995)
9. Guerrero, M.A. et al.: Overview of Medium Scale Energy Storage Systems. In: Compatibility and Power Electronics, vol. 6 (2009)
10. Fuhs, A. E.: Hybrid vehicles and the Future of Personal Transportation. CRC Press (2009)
11. Carp, M.C. et al: Monitoring system and intelligent control system used in the starting process of a LDH1250HP locomotive. In OPTIM 2010 12th, pp. 551--556 (2010)
12. Mitsubishi Electric Shows Prototypes of Ultracapacitor-Battery Hybrid Energy Storage Device, http://www.greencarcongress.com (2010)
13. Ayad, M.Y., Rael, S., Davat, B.: Hybrid power source using supercapacitors and batteries. In: Proc. IEEE-PESC'03, Acapulco (2003)
14. Cericola, D., et al.: Simulation of a supercapacitor/Li-ion battery hybrid for pulsed applications. In: Journal of Power Sources 195, pp. 2731--2736 (2010)
15. Kötz R., Carlen, M.: Electrochimica Acta 45, pp. 2483--2498 (2000)
16. Conway, B.E.: Electrochemical supercapacitors – scientific fundamentals and technological applications. New York, Kluwer Academic/Plenum Publishers (1999)
17. Borza, P.: Electric Power Cell. Patent EP 1796199 (2007)
18. Brice L., Magali, L.: Automatic vehicle start/stop control method. US Patent 2009/0216430 A1, DAYTON, OH US (2009)
19. Puscas, A.M. et al.: Thermal and Voltage Testing and Characterization of Supercapacitors and Batteries. In OPTIM 12th 2010, Brasov, pp. 125--132 (2010)