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EMBEDDED STRUCTURE USED IN THE STARTING AND REGENERATIVE BRAKING PROCESSES OF A MOBILE SYSTEM

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Abstract: *Reducing the pollutant emissions and increasing the energy efficiency of the mobile systems simultaneously with increasing the driver's comfort represents a priority in the actual researches from the automotive industry. The reason of the research springs from the necessity to optimally adapt different energetic elements located on vehicles, in order to increase their global energy efficiency. In the present paper a hybrid storage and generation device implemented at reduced scale is introduced. Also, the results of the simulations of the hybrid device are illustrated and the results of the experiments are emphasised in order to prove the efficiency of the system and to validate its electrical model.*

Key words: *hybrid device, energy efficiency, Start/Stop system, regenerative braking process.*

1. Introduction

In present, there are two main targets in automotive: reducing the fuel consumption and increasing the energy efficiency.

Among the solutions of the actual constraints it can be identified the transition from the classic vehicles to plug in hybrid electric vehicles (PHEV) and electric vehicles (EV), vehicles less polluting or even non-polluting (zero emission vehicle - ZEV). The field of EV was firstly introduced in 1880s but it was abandoned because of the EV's reduced autonomy [10]. From 1997, the field of HEV and EV has been reopened by Honda and Toyota who introduced models (Honda FCX, Toyota Prius) nominated by U.S Environmental Protection Agency (EPA) and California Air Resources (CARB) as being Partially ZEV and ZEV.

Also, for fulfilling the main targets, there are several aspects that have to be taken into account by the automotive industry, such as: (*i*) the necessity to appropriate and to accommodate the time characteristics of the energetic sources and buffers, (*ii*) the necessity to consider the location of every energetic element in relation with the energy converters (motor/generator - MG) of the vehicles, (*iii*) the finite character of the energetic resources (fundamental

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constraint) that affect the autonomy and the vehicles' transport mission.

Considering the finite nature of the resources, it is rational to pay a special attention at every detail in order to improve mainly the energy efficiency and as consequence the autonomy, dynamicity and the transportation missions. Also, the optimal adaptation of different elements used in vehicles and the above mentioned traits have as result the reduction of waste and of the pollutant emissions. There are two main systems related to these technological approaches and implemented in present on vehicles for reducing the fuel consumption and for increasing the energy efficiency: Start/Stop and regenerative braking systems.

The Start/Stop system was firstly introduced in 1980s by Volkswagen Polo Formel E and Fiat Regata. Researches were abandoned because of the costs of implementation and the driver's safety. In 2000s, reducing the fuel consumption and pollutant emissions became a major issue in the automotive research area and thus Citroen introduced the C3 model with improved Start/Stop system. Researches demonstrated that the fuel consumption can be reduced with up to 0.2 L/100 km and the pollutant emissions with up to 5 g/km [6], [7], [11], [18], [19], [22].

The second implemented system was regenerative braking in correlation with the start booster strategy. The kinetic energy recovered during braking is used in the next acceleration phase to increase the efficiency of the starting process, usually limited by the performances of the storage devices and their time constants. In this process, a major role is played by the rapid release storage devices that have high cyclability and the capacity to store with increase efficiency the energy usually lost into heat.

Also, the technological advance of the PHEV and EV and especially their autonomy and dynamism are deferred by the limitations of the storage and generation devices (SGD). This is more important while considering the aspect of increasing the driver's comfort as a goal that needs to be assessed even in PHEV and EV by adapting systems such as HVAC, GPS, night vision etc. Because increasing the driver's comfort is directly related to increasing the energy consumption, alternatives at the actual storage and generation devices had to be developed and implemented. In present, the technology of the SGD represents a field of major interest both in industry and academy. Moreover, to facilitate the improvements from PHEV and EV, hybrid structures of SGD are researched.

The present paper introduces a hybrid cellular and energetic structure used in the starting process of a MG and in the regenerative braking process. The prototype has the advantage of being modular and of embedding a local microcontroller (μC) able to master the power flow between the elements of the cells. Also, μC ensures the load profile by interconnecting in series or in parallel multiple cells. The prototype was implemented at reduced scale in order to validate the assumption of increasing the energy efficiency in case of the starting and regenerative braking processes. In the present paper the architecture of the hybrid structure is presented. Also, an electric model of the hybrid cellular structure was implemented in Matlab/Simulink in order to simulate the starting process. To validate the model the results of the simulations are compared with the experimental ones.

2. Hybrid Power Supplies Including SGD - State Of The Art

In present, batteries represent the most important SGD used in automotive. Their technology is developing slowly compared to the actual needs because of their major limitations, such as: (*i*) reduced cyclability; (*ii*) lifetime reduced by the high peak power pulses; (*iii*) reduced performances at extreme temperatures; (*iv*) increased self discharge rates etc. These limitations have an important impact on the autonomy of the vehicles (the major limitation of the PHEV and EV) [14].

To eliminate these problems, studies are made on the possibility to implement hybrid structures composed of different SGD characterized by complementary properties and time constants (Figure 1), where *P* = power density, *E* = energy density and τ = time constant.

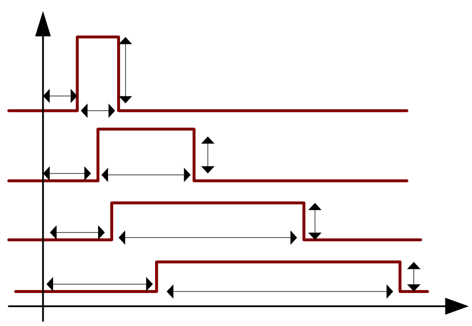

Fig. 1. *Time constants, energy and power density of the storage devices*

By including storage devices with reduced time constants as rapid release devices (supercapacitors - SC), the energy efficiency of the regenerative braking process is increased. Moreover, because the lifetime and performances of a SC are not reduced by the high peak power pulses, using SC is a key element for increasing the lifetime of the battery integrated in the hybrid structure.

In contrast, using SGD with medium and high time constants (batteries and fuel cells) increase the autonomy of the PHEV and EV [1], [3], [5], [9], [12], [13], [17]. For increasing the power, energy density and energy efficiency of the hybrid structures dedicated embedded control systems are developed [2], [7], [8].

In present, the majority of the implementations consider batteries and control systems, but there are researches which considered SC while developing the hybrid structure in order to increase the power density and the life time of the ensemble [2], [4], [5], [8], [18], [21] and also fuel cells for increasing the autonomy of the mobile system [20].

As innovation, the present research considered the possibility to implement a network of hybrid cellular structures, (network of combined energy cells (CEC - Figure 2) composed of different SGD, switches and embedded control system in order to optimize the requirements of the load [4]. An essential aspect considered in the insulated systems was placing the CEC cells in order to reduce the losses from the power excursion. The modular structure has the advantage of being a fundamental aggregation easy to be distributed.

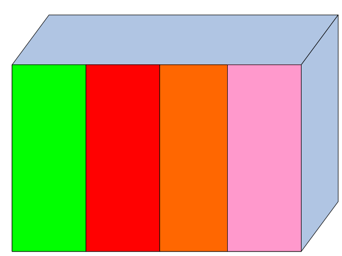

Fig. 2. *CEC cell*

To increase the efficiency of the system, the control was implemented at the cell level and not at the device level. To ensure the optimal load profile, the network of CEC cells was integrated in an embedded system with monitoring, processing and controlling capabilities. Also, the structure was designed to be able to interact with the consumer in order to predict the state of its parameters, its power requirements, to insulate a malfunctioning cell for facilitating the maintenance process and to self adapt its functionalities to ensure the transport mission.

3. Architecture of the Implemented System

During the developing process of the CEC cell, three major aspects were considered: (*i*) selecting the proper SGD, (*ii*) correct sizing of the hybrid structure and (*iii*) the requirements of the final application. For choosing the SGD and for anticipating the behaviour of the hybrid structure, the devices were electrical and thermal characterized [15], [16]. Thus, SC was selected as rapid release SGD and batteries as medium SGD. The sizing process considered factors such as: the overall size of the prototype, the carried weight and the power and energy demands. The final application used the advantages of the SC in the starting and regenerative braking processes.

The architecture (Figure 3) of the implemented reduce scale prototype (1:300 compared with Citroen C0) is composed of: consumer (120 W MG with 0.27 kg·m^2 inertial load - fly wheel), module for current limiting at 5 A, two CEC cells (CEC1 and CEC2), PWM module for controlling the MG, current transducers, voltage sensors, speed monitoring module, data acquisition system (DAQ) and control system (CS).

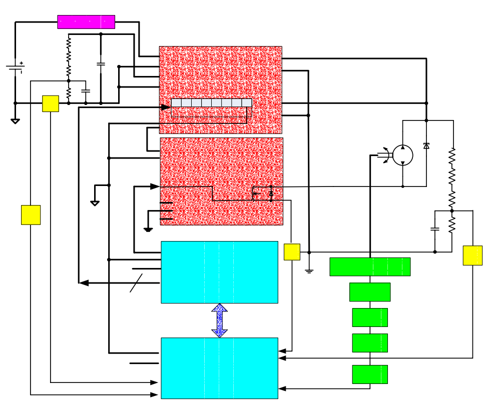

Fig. 3. *Architecture of the implemented system*

The cells CEC1 and CEC2 (Figure 4) are composed of cells of SC, cells of batteries and network of switching devices for ensuring the possibility to interconnect in series or in parallel the cells. The switching devices are controlled by the CS which processes the information of the load acquired by the DAQ. The voltage sensors (ISO124 and analog to digital converter), current sensors (LTSR 25) and revolution sensors (Kubler T8.3700.1138.1024 incremental encoder and frequency to voltage converter) were chosen to ensure the galvanic insulation between the cells.

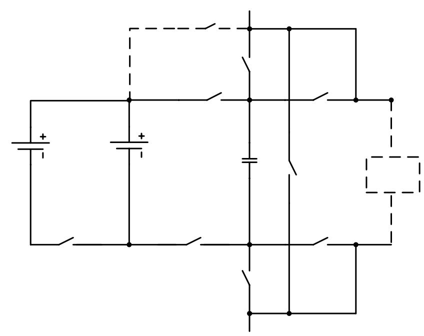

Fig. 4. *CEC cell - architecture*

To increase the energy efficiency of the regenerative braking process, dedicated adjustable buck-boost converters were used (UC2577).

4. Results and Discussions

The experiments were made with one CEC cell and with a network of two CEC cells in order to compare the efficiencies.

4.1. Testing 1 CEC cell

The first implementation consists of one CEC cell controlled by the CS and monitored with DAQ. To facilitate the testing procedure and to observe the behaviour of the CEC system, the testing algorithm was implemented in Visual Basic 6 (VB6). The control of the regenerative braking process depended on the revolution value monitored with DAQ. The experimental results are illustrated in Figure 5.

In the experiments, the SC from the CEC cell was used in the starting process for providing the high peak current pulses which influence the performances of the batteries. The MG was accelerated at four different revolution stages (1320 RPM, 420 RPM, 1080 RPM and 780 RPM). For increasing the energy efficiency, each acceleration stage was followed by a regenerative braking stage.

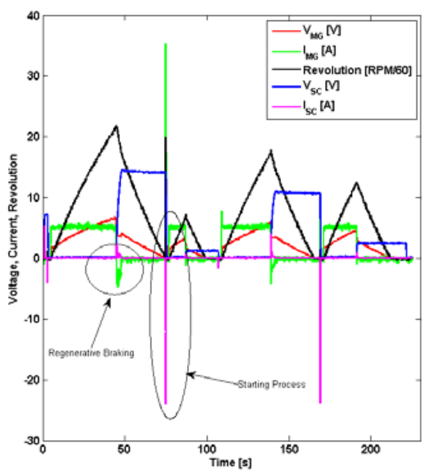

Fig. 5. *Testing 1 CEC cell (experimental results)*

The energy recovered and stored into the SC ($E_{SC} = 1/2\ C \cdot U^2$), 10.78 J, was used in the following starting process thus increasing the overall efficiency with 31%.

4.2. Testing 2 CEC cells: Simulations vs. Experiments

For improving the efficiency, two CEC cells were used in the starting and regenerative braking processes.

The starting process was firstly simulated using Matlab/Simulink tool. The electric model was implemented to simulate the starting process in series connection (SConn) and parallel connection (PConn) between the two SC from the two CEC cells (SC1, SC2).

The parameters considered in the modeling process were: (*i*) equivalent resistance of the switches (R_{ds} = 20 mΩ/cell), (*ii*) internal resistance of SC (R_{SC} = 15 mΩ/cell), (*iii*) wire equivalent resistance (R_{cable} = 15 mΩ/cell), (*iv*) MG inductance (L = 200 μH) and (*v*) MG resistance (R = 0.5 Ω).

The testing algorithm had the following stages: (*i*) charging SC1 and SC2 at the nominal voltage level (V_n = 14 V) and starting MG in SConn, (*ii*) charging S1 and S2 at V_n and starting MG in PConn.

The energy available on both SC1 and SC2 was E_{SC} = 21.56 J. The experimental results are illustrated in Figure 6.

As it can be seen in Figure 6, the voltage level, the equivalent resistance's value, the inertial load and the internal losses of the MG influence the values of the provided current/voltage.

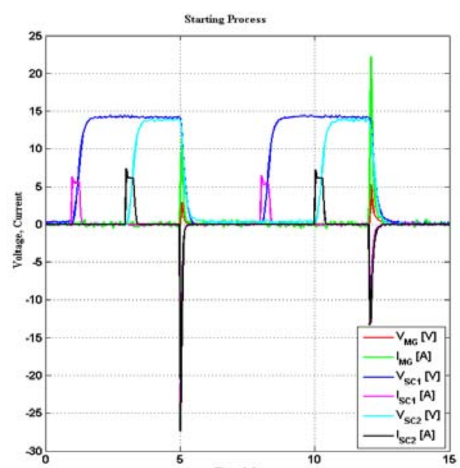

Fig. 6. *Experimental results*

Even so, by embedding SC in the CEC cell and using them in the starting process the efficiency was increased with η = 17.2% in SConn and with 78.35% in PConn.

The experimental results were used in the validating process of the electric model developed. As it can be seen in Figure 7 and Figure 8, the results of the simulations are in agreement with the experimental ones, the only differences appearing due to the ideal model of the considered devices.

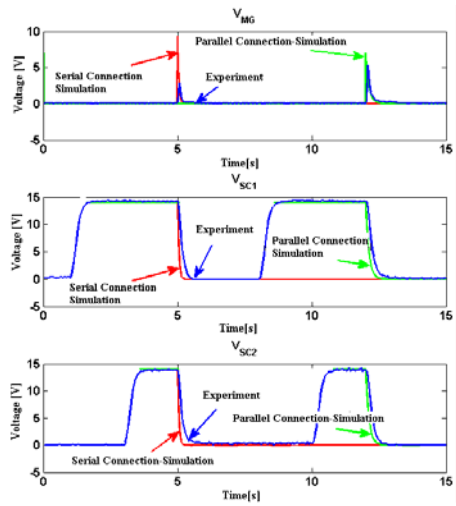

Fig. 7. *Voltage Variation* (*simulation vs. experiment*)

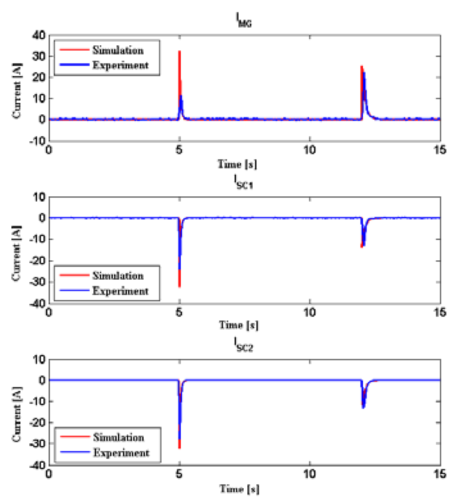

Fig. 8. *Current Variation* (*simulation vs. experiment*)

Moreover, the MG was modelled with an LR circuit and it was not considered the influence of the inertial load attached to the MG.

To optimize the energy efficiency and to ensure increased current and voltage values, two more starting cases were considered: (*i*) SConn for 100 ms and switching on PConn (η = 23.77%), (*ii*) PConn for 100 ms and switching on SConn (η = 66.31%). Depending on the load profile, the optimal switching and supplying strategy can be commanded in the starting process to optimally ensure the load profile and the transport mission.

Also, to observe the behaviour of a hybrid structure composed of two CEC cells in regenerative braking and to facilitate the testing procedure, an algorithm was implemented in VB6. The CS interpreted online data regarding voltage, current on the SC1, SC2, MG and the MG speed, thus taking the decision to switch on regenerative braking process when the monitored speed reached the value of 22.5 m/s (81 km/h). The testing algorithm included a limited 5 A pre-charging of the two SC from the battery in order to ensure the energy of the starting process for the first 500 ms supplied in SConn. After the first 500 ms the supplying system automatically switches on the battery, the system being controlled through the network of switches devices. The supplying process is followed by a regenerative braking process on SC1 and SC2. Using the energy recovered during braking, the MG is supplied in PConn, thus reducing the energy consumption.

In Figure 9 are illustrated the experimental results obtained while testing the starting and regenerative braking processes. The energy recovered during braking was used in the next starting process increasing the efficiency with 68%.

The recovered energy can also be used in the supplying process of the auxiliary loads, such as HVAC, lights, GPS, communications in order to reduce the energy consumption and to increase the overall efficiency of the system.

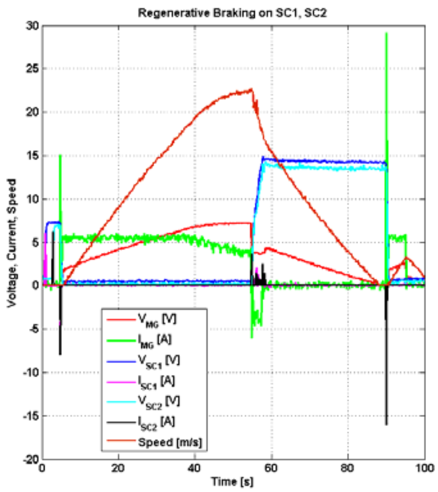

Fig. 9. *Start/Stop and regenerative braking processes using the hybrid structure*

5. Conclusions and Future Work

The paper emphasised the benefits of using a hybrid modular structure (distributed network of CEC cells) in the starting and regenerative braking processes. To increase the energy efficiency, the prototype was integrated in an embedded structure able to switch on series/parallel connection between the cells. The reduced scale prototype was developed and tested. For the staring process an electric model was implemented in Matlab/Simulink and validated by the experimental results. For the regenerative braking process controlling algorithms able to interconnect the cells depending on the transport mission were developed. The experiments proved that the energy efficiency can be increased while using hybrid cellular structures endowed with adequate control strategies. The importance of optimizing the control, crucial if considering the ability to optimize the control based on the energy efficiency, was emphasized. Also, a detailed characterization of each device that influences the mobility process of the vehicle is important to anticipate the behaviour of the device.

As conclusion, the multidimensionality of the actual considered problems is revealed by the present work.

As future development, in accordance with the actual results, cybernetic loops that will intricate the low level control of the dynamic and stationary power flow have to be implemented. The power flow has to be correlated with the transport missions and with the pollution reduction constraints. Also, a real scale prototype has to be implemented and the energy efficiency has to be increased by using switching and storage devices with improved performances.

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