Hybrid storage systems and dynamic adapting topologies for vehicle applications

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Abstract - **The present paper emphasizes the benefits of using supercapacitors in vehicle applications. The paper basically presents the supercapacitor technology and the advantages of using such novel devices in automotive applications. A comparative image of two implementations is described: (i) Start/Stop system implemented on a diesel locomotive, which illustrates an optimal hybrid storage solution and (ii) a regenerative braking system implemented on a reduced scale electric vehicle demonstrator, as an illustration of a dynamic storage multi-element adapting topology. The hardware architectures and implementations, the control systems and data acquisition systems are detailed. The experimental results are interpreted and the corresponding electrical parameters are determined in order to emphasize the increase in energy efficiency. Also, the advantages of using hybrid storage systems and dynamic adapting topologies for vehicle applications are emphasized.**

I. INTRODUCTION

Researching and implementing innovative systems for increasing the energy efficiency of the mobile systems became a major interest in automotive field. The first systems considered in the automotive field were Start/Stop and regenerative braking systems. These systems can be implemented on classic vehicles, electric vehicles (EV), hybrid electric vehicles (HEV) and all self drive structures, including locomotives. At present, the majority of the automotive companies try to improve the energy efficiency of both systems concomitantly with reducing fuel consumption and pollution.

The *Start/Stop* system is used in automotive industry for reducing fuel consumption and pollution by automatically stopping the vehicle's engine while it is being stopped at lights traffic and automatically restarting it while a pre-defined succession of commands is identified. Research studies have proved that the fuel consumption can be reduced up to 20 % and the pollution with up to 5 g / km [1], [2].

For increasing the energy efficiency, the current research studies have considered the regenerative braking system, able to recover a part of the kinetic/potential energy usually lost into heat [3]. Additionally, the researches made in 2006 on the first vehicles that used regenerative braking systems proved that the pollutant emissions can be reduced with up to 1.5 % - 4 % by using regenerative braking systems [4], [5].

The disadvantages of the current Start/Stop and regenerative barking implementations are related to the battery, used in the starting and traction processes. In the starting process, the battery is affected by the high peak current pulses, thus reducing its lifetime. This process is amplified in the case of the Start/Stop process, the lifetime being reduced with up to 50 % [1]. Also, the performances of the battery are reduced while functioning at extreme reduced temperatures, especially in winter conditions [6]. Another limitation of the implemented systems is represented by the high time constants (seconds) of the battery, which reduce the efficiency of the regenerative barking system.

To compensate these limitations, additional control systems can be used. Another trend is to integrate a battery with other storage and generation devices, with complementary performances. At present, to reduce the fuel consumption and pollution and to increase the energy efficiency of the application, hybrid systems composed of supercapacitors, fuel cells, fly wheels and batteries are researched.

The present paper presents the Start/Stop system implemented on a diesel locomotive. In addition to the previous results [1], new software for determining and analyzing the performances and the efficiencies of the implemented prototype were developed and tested. Also, a regenerative braking system was implemented and tested on a reduced scale EV demonstrator. The paper details the dedicated control systems of the implemented prototype and demonstrator and the corresponding data acquisition systems. A dynamic adapting topology was implemented for the demonstrator in order to increase the energy efficiency of the regenerative braking system. The experimental results are emphasized and interpreted to identify the corresponding electrical parameters of the analyzed processes.

II. STORAGE AND GENERATION DEVICES

Nowadays, the main storage and generation devices used in automotive are: batteries, supercapacitors, fuel cells and fly wheels.

Batteries are the most common storage and generation devices used in automotive. They are characterized by medium power density and high storage capabilities. As disadvantages, batteries are irreversibly affected by repeated charge/discharge cycles and can have their capacities reduced if they are overcharged and/or deep discharged. While improperly using, overcharging or deep discharging, the lifetime of the battery can not be correctly estimated. Additionally, the performances of the batteries are reduced while working at reduced temperatures [7], [8]. As a consequence, to guarantee the reliability of the applications, additional redundant systems have to be designed and implemented.

Supercapacitors (SC) are storage and generation devices characterized by high power density and limited storage capability. These elements are completely reversible and have high efficiencies, up to 98 ÷ 99 %. Supercapacitors are characterized by increased number of charge/discharge cycles, 500.000 ÷ 1.000.000, depending on their types [9]. It can be identified two main types of SC, depending on the electrolyte: organic and inorganic. The organic SC are characterized by higher energy density than the inorganic SC but their performances are more reduced at extreme high temperatures (>70 ^{o}C), where the risk of explosion can appear [10]. Instead, the inorganic SC are characterized by high power density and reduced risk of explosion at temperatures of 70 ^{o}C [11].

Fuel cells (FC) are electrochemical storage and generation devices characterized by high energy density and high time constants (minutes-hours). Because of its internal chemical structure, a fuel cell can be considered a complex energy storage element. The main disadvantage of the FC is related to their irreversibility. To eliminate this inconvenient, reversible FC (PEM – Proton Exchange Membrane) were implemented with high manufacturing costs [12].

Fly wheels are devices which can store mechanical energy during braking and are characterized by high energy density, high latency and reduced time constant (miliseconds), depending on the reversible motor-generator (MG) electrical engine.

Such devices can be combined in hybrid structures in order to improve the performances of the final application, related to energy density, power density, time constants [13]. Such a hybrid structure can be used to balance the static/dynamic characteristic of the application, thus ensuring a flat time response (as in the locomotive prototype case). Also, a combined hybrid structure is easily to be distributed in a network of such structures able to dynamically modify their topology to adapt the characteristics of the application and to increase its performances (as in the reduced scale demonstrator case). The power electronics and the system's intelligence ensure a permanent adapting of the system's characteristics, depending on the application's requirements.

III. Applications with Supercapacitors: Stating System Implemented on a Locomotive

To demonstrate the advantages of using aqueous stacked inorganic supercapacitors, Start/Stop and regenerative braking processes were implemented and tested.

The Start/Stop process was implemented on a LDH1250HP diesel locomotive and the regenerative braking process on a reduced scale 100 W EV demonstrator.

Hardware architecture of the locomotive's Start/Stop system

To implement the Start/Stop system on the locomotive, a resizing process of the storage devices was firstly made. To correctly use the stored energy, the energy provided by the battery was determined by using (1).

$$W_{BAT} = \sum_{i=1}^{n} \left(\int_{t_i}^{t_i+d_i} u_{BAT}(t) \cdot i_{BAT}(t) \cdot dt \right) \Bigg|_{t°C} \qquad (1)$$

where:

W_{bat}: energy provided by the battery; n: minimum number of admitted failed re-starts; t_i: time period of a "i" number of starting process; d_i: necessary time period of the "i" starting process.

The original storage system of the locomotive consisted of a package of 16 batteries/12 V/180 Ah.

Because the batteries were used in series / parallel configurations to ensure the voltage and current levels of the locomotive starting process, a strict and permanent monitoring process (voltage, State of Charge – *SoC*, State of Health - *SoH*) of the batteries had to be implemented, thus increasing the maintenance costs. Moreover, if a battery is damaged, the performances of the all package of batteries are drastically reduced by the supplementary energetic stress.

To diminish these problems, by taking into consideration (1), it was experimentally identified that the capacity of the battery (360 Ah) can be reduced at its half size, by introducing an equivalent capacity of 36 F/110 V (3 aqueous stacked inorganic ECOND SC 12 F/110 V). Thus, the weight was reduced with 31.25 %, which triggers the reduction of the fuel consumption, pollutant emissions and recycling costs.

The hardware architecture of the locomotive's starting system is illustrated in Fig. 1.

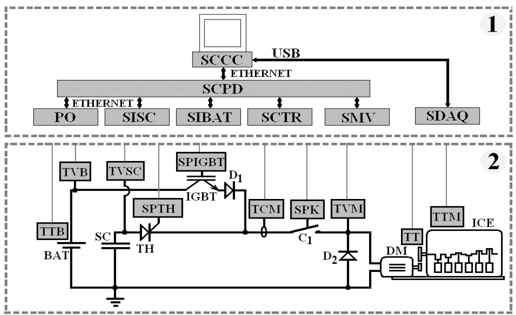

Fig. 1. Architecture of the starting system for LDG1250HP locomotive.

The locomotive's starting system is composed of: control system (1) and energy storage and transfer system (2).

The control system consists of the following subsystems: SCCC: central control system, SCPD: data transfer system, PO: operating panel, SISC: SC charging system, SIBAT: battery charging system, SCTR: real time control system, SMV: battery voltage monitoring system, SDAQ: signal acquisition system.

The energy storage and transfer system consists of the following subsystems: TTB: temperature sensor, TVB:

battery voltage sensor, TVSC: SC voltage sensor, SPTH: thyristor driver, SPIGBT: IGBT driver, TCM: current transducer of the internal combustion engine (ICE), SPK: switch driver, TVM: ICE voltage transducer, TT: revolution transducer, TTM: ICE temperature sensor.

The physical implementation of the Start/Stop process is illustrated in Fig. 2.

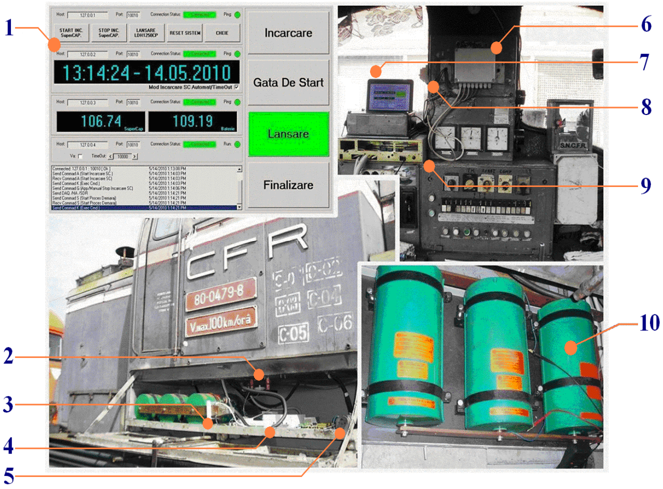

Fig. 2. LDH1250HP locomotive – prototype.

The physical implantation consists of: 1: software for controlling the starting process of the ICE engine; 2: IGBT and its driver; 3: thyristor and its driver; 4: SCTR, SMV; 5: SISC; 6: SCPD; 7: SCCC; 8: PO; 9: SDAQ; 10: SC.

Software Architecture: The control of the locomotive's Start/Stop system

The management of the starting locomotive's ICE process interacts with its hardware configuration by using the TCP/IP data communication protocol. The main issues managed by the current application are:

- acquiring and interpreting the commands of the human operator (HO);
- configuring and synchronizing the data acquisition system (DAQ);
- triggering and controlling the charging process of the batteries and SC;
- managing the starting system by conditioning the initiating and suspending time;
- triggering and initiating the starting process;
- providing a user friendly interface for the HO, in order to facilitate the diagnosis process and to inform the HO in real time about the status of the starting process.

The software configuration of the control system and data acquisition system used for controlling the starting process of the locomotive is illustrated in Fig. 3.

HO can visualize information about the starting system such as: 1: IP/PORT address of the OP; 2: IP/PORT address of the SCTR; 3: IP/PORT address of the SMV; 4: IP/PORT address of the SDAQ; 5: interface for visualization of the starting events; 6: voltage on SC/BAT; 7: the current phase of the starting process; 8: status of the physical link between the subsystems; 9: status of the data links between the installed subsystems.

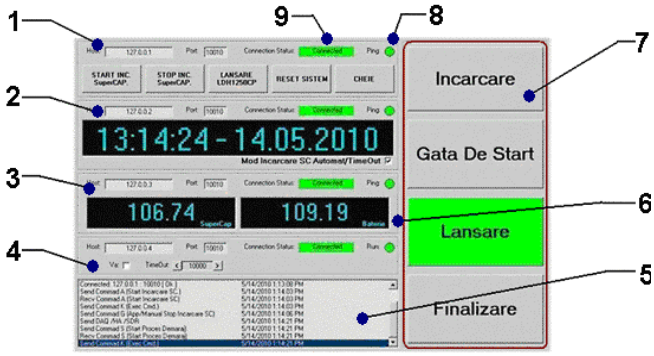

Fig. 3. Software interface of the locomotive.

To reduce the risk of failure of the starting processes, the HO can only supervise the process, this being automatically controlled by the implemented software. To have a better view of the starting process, HO can visualize all the electrical signals and parameters received from the storage devices and ICE (voltage, current, speed, temperature).

The implemented automatic control strategy firstly verifies the availability of the all electronic hardware components used in the starting process. After that, the *SoC* and *SoH* of the storage devices (batteries, SC) are verified. The system's control parameters are voltage, current and velocity. If the voltage measured at the SC terminals level is below the threshold voltage ($V_{min} < V_{batt}$ - 2 V), the charging process of the SC from the battery is activated (where V_{batt} is the voltage measured at the terminals of the lead acid battery). In order to increase the lifetime of the battery, the charging process of the SC from the battery is activated only if the voltage measured at the battery's terminals is grater than 90 V. After the voltage measured at the SC terminals level reaches a preset threshold value (V_{thSC} >= V_{batt} - 2 V), the charging process is completed and the software signalizes that the starting process can be initiated by the HO. When the HO initiate the starting process, the control system commands the ICE to be supplied from the SC and interprets the data (voltage, current, speed) measured in real time by the DAQ. The supplying process of the ICE from the SC is commuted on the battery when the voltage measured on the SC reaches a minimum preset threshold value (V_{start_min} = 60 V) and the revolution of the ICE is under a predefined value. If the revolution of the ICE is above the predefined value, the supplying process does not commute on the battery and it is stopped, considering that the starting process was successfully finalized by using the energy stored into the SC. When the supplying process is commuted by the control system on the battery, the current value of the battery is monitored; if its value is above a threshold value, the supplying process is stopped in order to protect the battery from the deep discharge process [14].

Additionally, to increase the accuracy of the starting process, the control strategy monitors the ICE's speed and the HO actions related to the correctness of the starting process.

For facilitating the HO action and for protecting the battery, in the control strategy a timeout in which a starting process has to be successfully made was defined. Otherwise, after the timeout, the starting process is automatically interrupted and marked as a failure.

If a starting process is successfully made and the locomotive is running, both storage devices (batteries and SC) are being charged at 110 V from the ICE. The charging process is managed by the control system which uses a controlled current hardware implementation.

The advantage of the repeated starting processes is related to the possibility to complete a new starting process by using only the energy stored into the SC while the locomotive was running in the above described situation. In this case, the control strategy skips the pre-charging process of the SC from the battery, thus reducing the energy consumption, the energetic stress of the battery and increasing its lifetime.

IV. Applications with Supercapacitors: Regenerative Braking System Implemented on a Reduce Scale EV Demonstrator

Hardware architecture of the reduced scale 100 W EV demonstrator with regenerative braking system

To test the efficiency of the regenerative braking process, a reduced scale EV demonstrator, illustrated in Fig. 4 was designed and implemented.

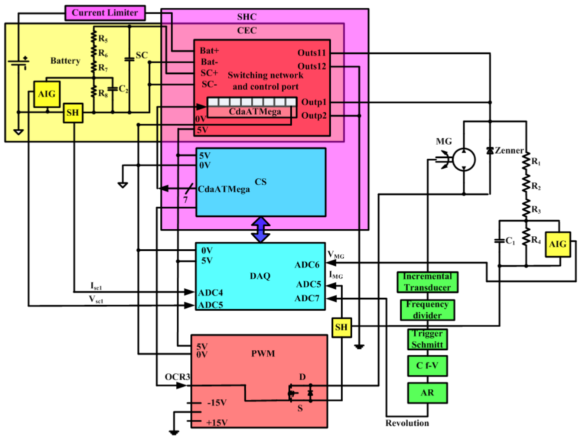

Fig. 4. Reduced scale 100 W EV demonstrator: Hardware Implementation.

The demonstrator consists in: (i) hybrid structures (SHC): two cells of storage and generation devices (each composed of 12 V/7 Ah selead Lead-Acid batteries and 9 F/96 V aqueous stacked inorganic SC), network of electronic power switches (NEPW), control system (CS) and data acquisition system (DAQ); (ii) pulse width modulation system (PWM), current transducer for battery, SC and MG, voltage transducer for battery, SC and MG, speed monitoring system.

The test bench of the physical implementation is illustrated in Fig. 5.

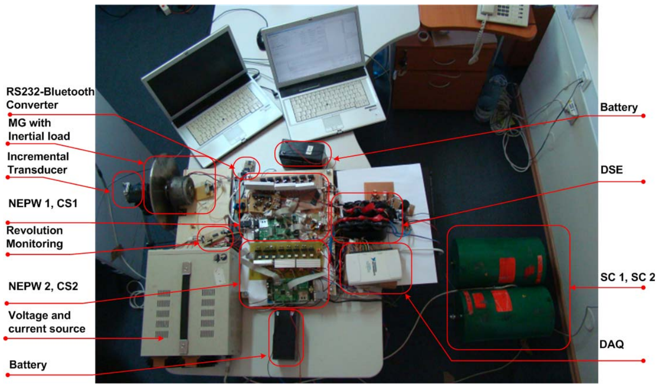

Fig. 5. Reduced scale 100 W EV demonstrator: Hardware Implementation.

Each cell of the storage and generation device is connected to a CS and DAQ based on AtMega128 microcontroller. The CS ensures the load requirements by commanding in a dynamic way the network of switches thus to connect in series and/or in parallel configuration the two cells of batteries and SC. The parallel or series configurations are chosen depending on the load's requirements. For optimizing the energy flow depending on the load's transitory requirements, the dynamic adapting topology was ensured by implementation. The hardware implementation allows a dynamic switching between the series/parallel configurations of the cells in order to ensure optimum voltage and current levels thus increasing the energy efficiency both at the cell level and application level. To improve the control strategy, predictive algorithms can be applied.

Software architecture of the reduced scale 100 W EV demonstrator with regenerative braking system

The regenerative braking system was tested on a reduced scale 100 W EV demonstrator, by using multiple driving cycles implemented in Microsoft Visual Studio software. One of the implemented driving cycles is illustrated in Fig. 6.

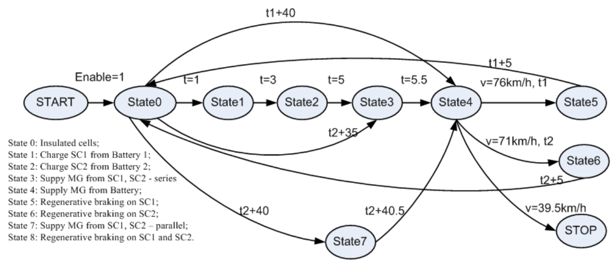

Fig. 6. Testing two hybrid cellular structures in the process of starting and regenerative braking.

The testing driving cycle starts from an insulated state (State 0) and is followed by a pre-charging state of the SC1 (State 1) and SC2 (State 2) from the corresponding batteries. After that, the load (MG) is supplied from the two SC connected in series configuration. The voltage of the two SC is monitored and after it reaches a minimum threshold, the supply system is commuted on the two batteries from the SHC. Meanwhile, the speed of the MG with inertial load is monitored and after it reaches a speed threshold (>70 km/h), the regenerative braking system is activated and the recovered energy is stored on the two SC. The following starting process is made in parallel configuration from the two SC by using the energy recovered during braking.

For facilitating the control and monitoring systems (CS DAQ), a graphical interface was developed in Microsoft Visual Studio and it is illustrated in Fig. 7.

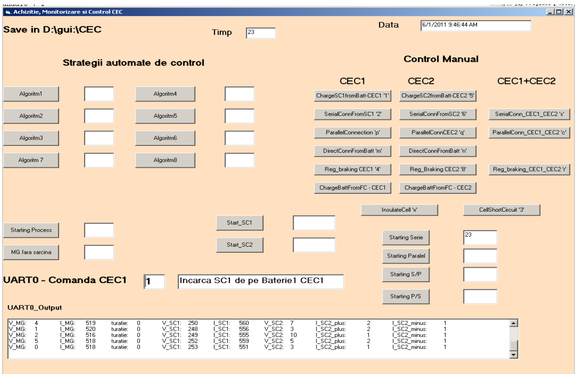

Fig. 7. Graphical interface used for controlling and monitoring the demonstrator.

CS was used to commute between the storage and generation devices to ensure the maximum efficiency of the regenerative braking system. DAQ was used to monitor the status of the used devices: battery, SC, MG (voltage, current, speed).

V. Experiments and Results

a. *Locomotive's starting process*

The starting experiments were made while supplying the locomotive in a classical configuration (from battery) and in the new hybrid configuration (battery and supercapacitor).

The first experiments made on a classic starting process, illustrated in Fig. 8 and Fig. 9, consisted in monitoring the current and the voltage of the battery pack with a Fluke 198B scope-meter.

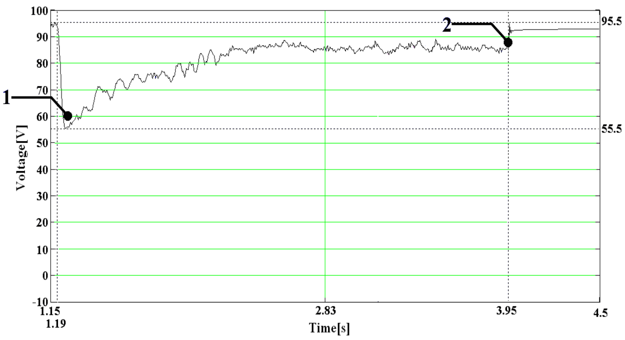

Fig. 8. $u_{MOT}(t)$ variation monitored at the starter terminals, during the classic starting process [6], [15].

where: 1 – minimum voltage value; 2 – maximum voltage value. The voltage values were monitored during the classic starting process, at the starter terminals of the diesel locomotive.

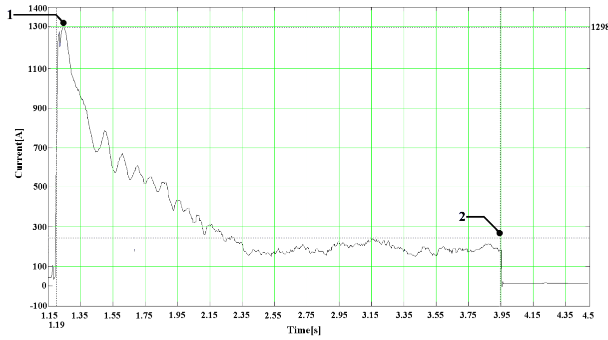

Fig. 9. $i_{MOT}(t)$ variation monitored at the starter terminals, during the classic starting process [6], [15].

where: 1 – the maximum current value; 2 – minimum current value. The current values were monitored during the classic starting process, at the starter terminals of the diesel locomotive.

The experimental data were analyzed and the statistic of the specific electrical measures was made. To acquire and store the huge amount of experimental data, a software interface (Data Analysis) was implemented in Visual Studio .NET. According to the diagram illustrated in Fig. 10, the experimental data were taken online from the SCCC, stored on a server in MySQL database and processed.

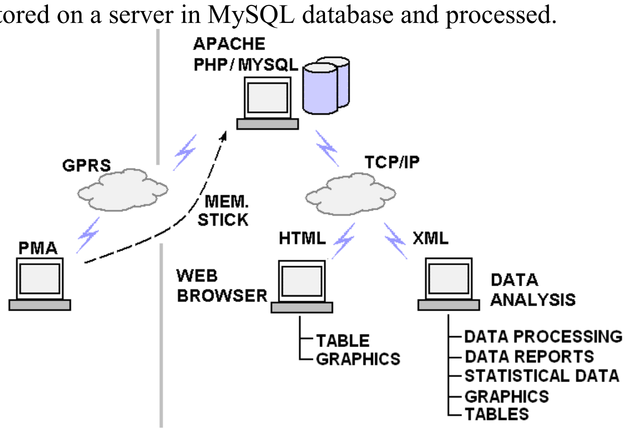

Fig. 10. The architecture of the data analyzing process.

The software architecture consists of:

- *PMA*: diesel locomotive and its corresponding embedded systems.
- *Web server (apache)*: used for exchanging the records between the SCCC and Data Analysis. PHP commands interpreter: used for (i) database statements; (ii) XML data formatting; (iii) data processing for web visualizing. MySql database: used for records management.
- For the *web browser* a "Data Viewer" software was developed. Its advantages are related to ensuring the possibility to quickly analyze the starting process (currents, voltages, maximum power delivered by the starter, maximum amount of energy) of the locomotive, by providing the corresponding wave forms. The user can analyze on-line the experimental results and can extract them in tables for off-line processing.

- *Data Analysis*: software application for advanced data analyzing, processing and interpreting.

By using Data Analysis software application, the experimental results from the starting process were interpreted, as it is illustrated in Fig 11.

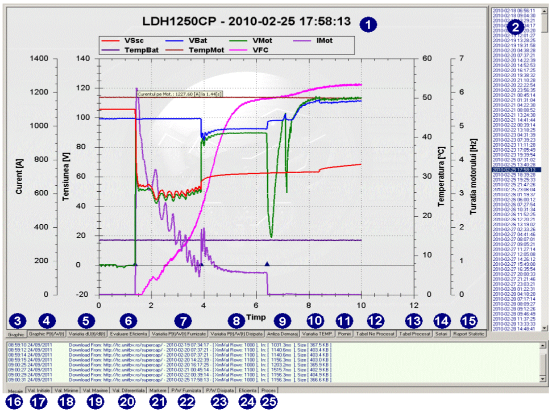

Fig. 11. Graphical user interface for “Data Analysis”.

Where:

1: Main data wave form analysis.

2: Available records of the stored starting processes.

3-15: wave forms with the processed records. The values monitored at the battery, supercapacitor and ICE level (current, voltage, revolution, temperature, energy density, power density) were analyzed to obtain their minimum and maximum values. The quality of the starting processes was determined, by considering the dispersion, standard deviation and inter-correlation between the analyzed records. To identify the accuracy of the implemented system statistics of the records were made, thus quantifying the efficiency of such an embedded starting system. This kind of representation is useful for quick diagnoses.

16-25: the experimental data illustrated as numerical values and stored into data bases, useful for offline processing.

The experimental results where obtained and interpreted by using the Data Analysis software platform. The statistic of the starting process was made by using more than 1500 starts.

In the experiment illustrated in Fig. 12, the classic starting process made only from the battery is analyzed and interpreted. The experiments were made using a 96 V/360 Ah fully charged lead-acid battery.

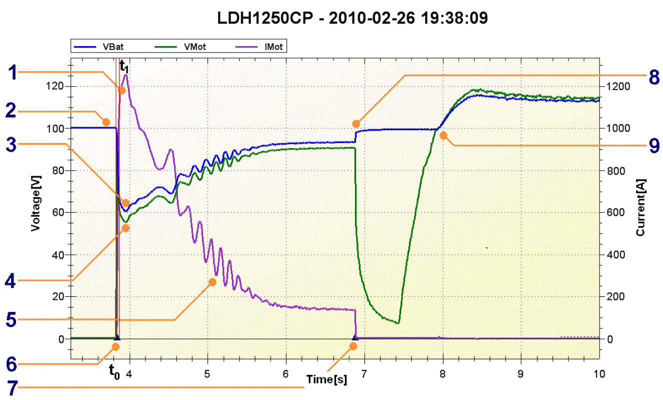

Fig. 12. Experimental results

where: 1: I_{bat} – battery current; 2: $V_{bat}(t_0)$ – initial voltage monitored at the battery level; 3: $V_{bat}(t_1)$ – voltage measured at the battery terminals after 50 ms after the starting process was initiated; 4: voltage monitored on the starter terminals during the starting process ($v_{MOT}(t)$); 5: current variation monitored at the battery’s terminals; 6: initial phase of the starting process; 7: final phase of the starting process; 8: voltage monitored at the battery terminals at the final phase of the starting process; 9: initial phase of the starting process.

The evaluation process of the classic system took in consideration the following parameters: V_{bat}, $v_{MOT}(t)$, $i_{MOT}(t)$ – current absorbed by the starter.

The electrical parameters determined while interpreting the experimental data are illustrated in Tabel I.

TABLE I

ELECTRICAL PARAMETERS - EXPERIMENTALLY DETERMINED

Parameter	Value	Unit
Voltage drop on the battery’s ESR	35.5	V
Electric circuit voltage drop	3.41	V
Maximum current provided by the battery	1255.02	A
Battery’s ESR	0.0307	Ω
Duration of the stating process	3.05	s
Maximum power absorbed by the starter	69450	W
Maximum energy consumed by the starter	94658	J
Maximum power dissipated on the battery’s ESR	47252	W
Energy dissipated on the battery’s ESR	27908	J
Maximum power dissipated on the electric circuit	6626.73	W
Energy dissipated on the electric circuit	5380.17	J

As it can be seen from Table I, the maximum value of the current reaches 1255 A. To reduce the power losses, a good understanding of the electric circuit designing has to be accomplished.

The time evolution of the power and energy used in the classic starting process of the diesel engine is illustrated in Fig. 13.

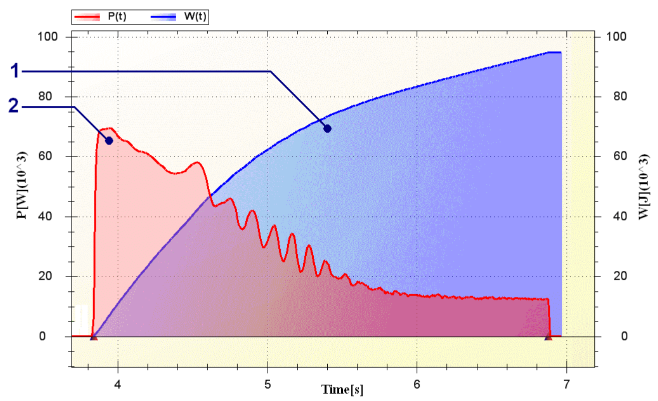

Fig. 13. Time variation of the energy and power consumed by the starter in the classic starting process of the diesel locomotive.

where: 1 – energy consumed by the starter; 2 – power absorbed by the starter.

In the experiment illustrated in Fig. 14, the starting process made from the supercapacitor and battery is analyzed and interpreted. The experiments were made using a pack of 36 F / 110 V ECOND aqueous supercapacitors and a pack of lead-acid batteries of 96 V/360 Ah.

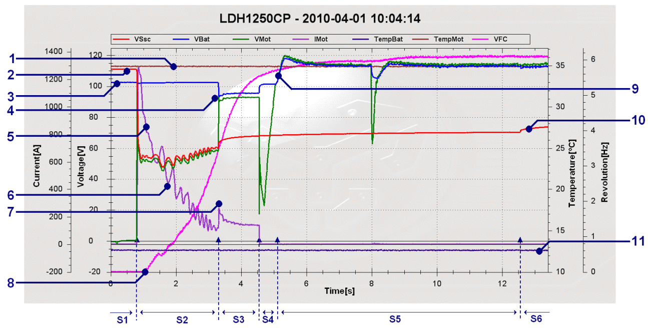

Fig. 14. Electrical parameters variation during the starting process made from the hybrid battery-supercapacitor system.

The experiment was made at a temperature of ≈34.8°C.

Where: 2 - SC voltage (112.7 V); 3 - Battery voltage (103.1 V); 4 - Switching battery voltage (93.4 V), ICE voltage at switching phase (90.1 V); 5 - Maximum current provided by the SSC (1290.5 A); 6 - Strokes in the starting process (11); 7 - Maximum current provided by the battery (260.9 A); 8 - ICE velocity; 9,10 – starting the charging process of the battery and SSC; 11 – temperature monitored on the battery (≈ 12.6°C).

In the starting process, six phases were identified: S1 – ICE stopped; S2 – initiating the starting process from the SSC (W_U≈60.75kJ, t ≈ 2.5s); S3 – maintaining the starting process by using the energy stored on the pack of batteries (W_U≈18.3kJ, t ≈ 1.2s); S4 – ICE idle phase (stabilization phase); S5, S6 – charging phase of the batteries and SSC.

The main electrical parameters acquired during the experiments facilitated the extension of the analyzing domain of the developed embedded system's energy efficiency.

The time evolution of the power and energy used in the starting process of the diesel engine made from the hybrid SC-battery system is illustrated in Fig. 15.

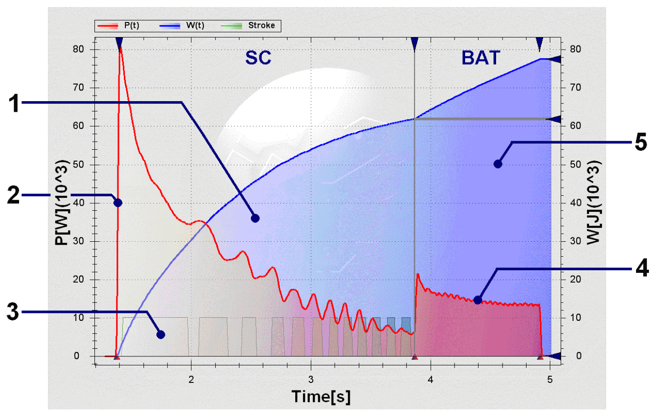

Fig. 15. Time variation of the energy and power consumed by the starter in the starting process of the diesel locomotive, made from battery and SC.

where: 1 – electric energy provided by the SC for supplying the starter; 2 – power absorbed by the starter from the SC; 3 – strokes generated using the energy provided from the SC; 4 – electrical power provided by the battery to the starter; 5 – energy absorbed by the starter from the battery for maintaining the starting process.

Using the experiments, a statistic analyze of the starting process was made and the statistic's results are illustrated in Table II.

TABLE II
MINIM/AVERAGE/MAXIM VALUES FOR ENERGY AND POWER PROVIDED BY THE SSC AND BATTERY

	P_{MAX_SSC} [kW]	P_{MAX_Bat} [kW]	W_{MAX_SSC} [kJ]	W_{MAX_Bat} [kJ]
Minim	60.48	0.05	44.86	0.005
Average	77.56	23.24	59.79	13.87
Maxim	97.97	49.31	75.14	72.06

The efficiency of the two storage and generation devices used in the starting process was analyzed by using (2) and (3).

$$\gamma_{Med} = \frac{P_{MedSC}}{P_{MedBAT}} = \frac{77.56}{23.24} \approx 3.33 \qquad (2)$$

$$\lambda_{Med} = \frac{W_{MedSC}}{W_{MedBAT}} = \frac{59.79}{13.87} \approx 4.30 \qquad (3)$$

As it was demonstrated, the power contribution of the SC in the starting process is with 3.33 grater than the one of the battery and the energy contribution with 4.30 greater. By using such a hybrid system in the starting process, the electrochemical solicitation of the battery is reduced, thus increasing its lifetime and the recycling costs.

b. EV reduced scale demonstrator: starting and regenerative braking processes

To increase the energy efficiency of the vehicle by recovering kinetic and/or potential energy during braking, a hybrid battery-supercapacitor system can be used. To identify the advantages of using such a hybrid system, the demonstrator illustrated in Fig. 5 was tested. The energy recovered during braking was used in the starting process. The testing process made with the hybrid storage battery-SC system consisted of monitoring the current and the voltage of the battery packs and SC with intelligent embedded systems. The results of the experiments are illustrated in Fig 16.

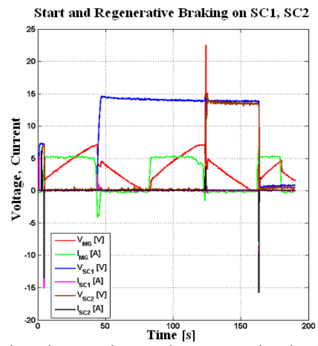

Fig. 16. Testing the starting and regenerative braking systems.

As it can be see from Fig 16, the regenerative braking process increases the energy efficiency of the vehicle by ensuring the energy amount in the following starting process, thus reducing the energy consumption, fuel consumption and increasing the battery's lifetime.

By interpreting the experimental results, a 40 % efficiency was identified in the case of starting the MG in series configuration of the SC, which used the recovered energy during braking. The power losses appear because of the connection lines and internal SC resistor. In contrast, in the case of the parallel configuration, an improving of the energy efficiency was identified (90 %). Also, the energy recovering process was limited by the number of the SC cells. By interpreting the experimental results, it was calculated that the energy recovered during a braking process can be used to charge up to 50 cells of SC, depending on the demonstrator's velocity.

In conclusion, such a hybrid battery-supercapacitor system can be used in the starting process to increase the battery's lifetime and in the regenerative braking process to increase the energy efficiency of the vehicle.

VI. Conclusions And Future Work

The focus of the research studies made in hybrid energy storage and generation devices field is developing novel systems for increasing the energy efficiency of the automotive applications.

The present paper presents two applications with hybrid storage battery-supercapacitor systems: a start/stop system implemented on a diesel locomotive and a regenerative braking system implemented and tested on a reduced scale electric vehicle demonstrator.

The starting system developed and implemented on the diesel locomotive had the advantage of dividing the energy flow used in the classic starting system in two (from battery and from SC), in order to reduce the electrochemical solicitation of the battery and to increase the quality of the starting process. As consequence, the first energetic flow is ensured by the SC and the second one is ensured by the battery, thus reducing the power that has to be ensured by the battery. Moreover, using such a hybrid battery-SC system in the starting process has as result reducing the fuel consumption (with around 50 l/day) and the pollutant emissions. Also, such a system allows a re-dimensioning process of the battery, by replacing half of its capacity with a pack of supercapacitors, lighter than the batteries. Thus, the overall weight of the storage devices was reduced at almost half of its initial weight.

The regenerative braking system was used to increase the energy efficiency of the reduced scale EV demonstrator by recovering a part of the kinetic energy during braking. The small time constants of the supercapacitors increase the efficiency of the regenerative braking system.

Moreover, the dynamic adapting of the hybrid system's topology can be used to increase the energy efficiency of the vehicle application by identifying and self adapting into the optimal configuration type, depending on the load's requirements.

The results obtained and presented in the present paper facilitate the understanding process of the energy flow transferred inside a vehicle.

As future work, the starting process prototype can be used as a model for developing new starting systems used in EV and HEV and also in heavy vehicles. The regenerative braking system has to be designed at real scale and implemented on real EV and HEV and also, can be adapted to be used on the diesel locomotive.

VII. References

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