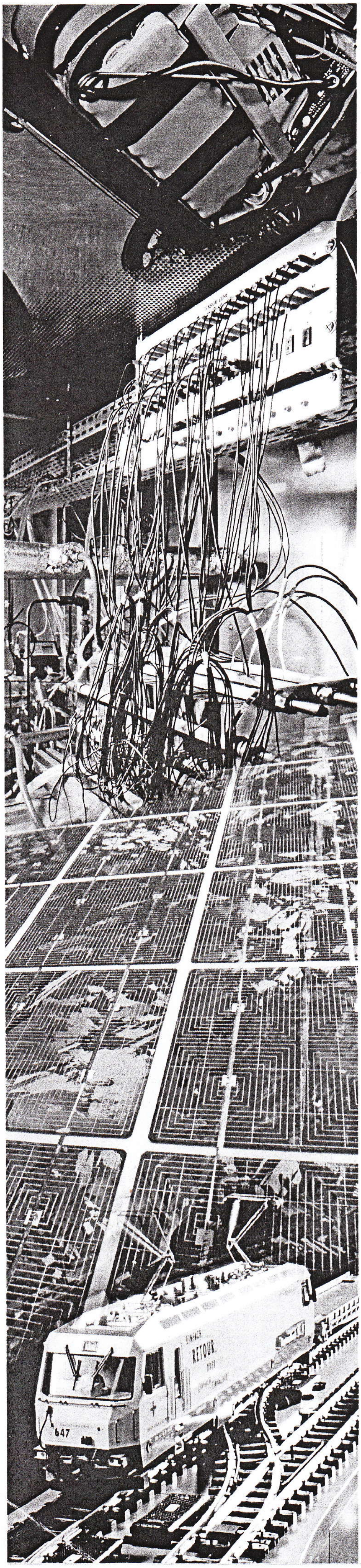

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Supercapacitors and their Applications on Vehicles

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Abstract – The present paper is focused on the supercapacitors technologies applications on vehicles. As complex mechanical and electrical systems, vehicles applications are the ideal field of application for mobile power supplies and for storage devices (supercapacitors) which are attached at these. In the paper we have made an overview of the main types of the supercapacitors and their characteristics. We have described a test bench for these devices, in order to illustrate the measured characteristics of the aqueous, "stacked", electric double layer supercapacitors (EDLC). Also, two applications of supercapacitors: a starting system for locomotive and an energy management system were described. We have also described some advantages of a composed solution that uses power electronic systems and a combination between batteries and supercapacitors in order to assure energy and cost efficient system solutions.

***Index Terms*:** aqueous, EDLC, energy management, ICE, "stacked", vehicle.

I. INTRODUCTION

Nowadays, among the challenging targets for the vehicles designers are: increase energy efficiency and performance of vehicles, avoidance of the air and soil pollution, and preservation of a clean environment. For vehicles, a lot of phenomena's are represented by an exchange of different form of energy and, in this case, the role of the storage devices became crucial toward the increase of the energy efficiency. The progresses of nano-technologies lead to the possibility to think about the feasibility and the reliability of the electrical storage solutions by using supercapacitor technology.

In all the domains where the form of the energy is converted from electrical to mechanical or chemical, and vice versa, the storage elements with rapid release of energy have a crucial role by assuring the required power reserve necessary to reach an optimal regime for energy converters. In particular, the vehicles can include such storage devices for ICE starting systems, start booster, recuperative breaking and electric energy management systems.

Supercapacitor technology has not reached yet its technical or market potential due to the limitations of the high-voltage solutions currently available on the market: cost, reliability, operating temperature range, and environmental concerns. In addition, the broad dissemination of the technology has been limited due to the lack of knowledge regarding the prediction of the supercapacitors' behavior under actual field conditions and the lack of experience with their system integration.

Combined solutions, L-A batteries and supercapacitors, can be considered as an optimum compromise in terms of energy economy, materials, size and cost (including maintenance costs)[9]. While for batteries the starting process is difficult at low temperatures, by using the combined solution, the battery will be protected and this fact significantly improves the ICE's starting process. By providing intelligent and adaptive switching of the electric starter and of the energy source composed by a supercapacitor and a battery, the response of the starting system can be optimized. Also, afterward, the charging process of the batteries can be better controlled with consequences on battery's reliability and life time.

II. STORAGE DEVICE USED FOR THE COMBINED ENERGY SOURCE

The breakthrough of the widespread application of the supercapacitor technology will only be possible when appropriate high-voltage supercapacitor solutions will be developed to fulfill requirements such as voltage level, cost, reliability, operating temperature range and environmental concerns. The solutions involve not only an improvement of the cell performances but also to think about assembly of the cells that will form the supercapacitor devices.

This comparison of "high-voltage" assemblies should include at least the following topics: energy density, power density, inner resistance, temperature range of operation, geometry of elementary cells, type of package (used to create the device including the case material that influence the shocks and vibration resistance), form factor that determine the symmetry degree of the electrical and thermal field inside the device influencing the reliability performance, aging, and environmental effects (relating to operation and end- of-life disposal).

The basis of the most high-voltage solutions available on the market nowadays is wound-cell supercapacitors in combination with organic electrolytes. A range of organic electrolytes are currently in use, such as acetonitrile, ionic liquids or propylene-carbonate (PC). In a single supercapacitor cell level, this approach has an important advantage: it enables a higher level of energy density in comparison to aqueous based electrolytes. But, by connecting in series the cells, the differences between cells need an implementation of a balancing system for the high voltage device. Inherently, this makes it vulnerable from the following point of views: reliability, thermal constraints and stability of the obtained high voltage device. Moreover, the advantage of the implementation of the organic electrolyte in respect to the energy density on systems level becomes noticeably smaller and can be estimated to be reduced at least by a factor of 1.5 – 2, with lower reliability and higher cost [9]. In addition, organic electrolyte materials such as acetonitrile can cause environmental concerns, and have significant constraints regarding the range of the operating temperature.

TABLE I
COMPARATIVE TABLE BETWEEN ORGANIC AND AQUEOUS ELECTROLYTE SUPERCAPACITORS

Feature	Organic Electrolyte	Aqueous based electrolyte
Energy Density	Higher for single cells.	Lower level for single cells.
Power Density	Higher	Lower
Internal resistance	Higher	Lower – suitable for high-frequency, prolonged cycling
RC time constant	Higher	Lower
Environmental concerns	Could generate poisoned vapours	No
Recycling phase	Need special procedures	Any special
Temperature range	Upper limit 80°C boiling point of acetonitrile PC high viscosity at low temperature	Range: -40°C - +70°C
Reliability	Negatively influenced by balancing system	Don't need a balancing system
State of the art of manufacturing technology	Highly developed	Moderately developed
Price of electrodes	High	Low
Price of electrolytes	High	Low
Price of "high voltage device"	High	Low

Aqueous-based electrolytes represent a feasible alternative to the organic electrolyte materials. Obviously, the voltage level and consequently the level of the energy density on the single supercapacitor cell level are lower when aqueous-based electrolytes are used, due to the lower level of their decomposition potential. But they cost much less, have a lower level of inner resistance, have potentially a quite wide range of operating temperature, and are completely free from any environmental concerns. By connecting the cells in series in a "stacked" structure the volume, stability and power density of devices became interesting for "high voltage" applications.

TABLE II
COMPARISON BATTERIES-SUPERCAPACITOR PERFORMANCES

Feature	Supercapacitor	Battery (L-A)
Energy density	Low (1-30KJ/kg)	High (>100KJ/Kg)
Specific Power density	High (5-20KW/Kg)	Low (<1KW/Kg)
Cyclability	High (>500.000 cycles)	Low (<500-1000 cycles)
Deep discharge	Allowed (till 0V)	Not allowed (DoD <20%)
RC time constant	Low	High
Temperature range	Large	Limited special for low temperatures

Also, the chemical and dynamical stability of the devices are very good. Due to the form factor and packaging technology these "high voltage" devices don't need additional balancing systems and present a high symmetry that avoid the local thermal or electrical stress, determining a high reliability and cyclability of the devices.

In table I it is given a comparative image [10] of the main two supercapacitor technologies, with organic or inorganic electrolytes.

Thinking at the entire system, which is organized in levels and is specially designed for vehicles applications none of the actual supercapacitor technologies offer a real solution from the high energy and power density point of view. Thus, for vehicles, a composed supply (battery and supercapacitor) with the appropriate power electronic and control can offer energy and cost efficient solution for a specific application. In table II, a comparison of the main features of the batteries and supercapacitors is made [9].

In order to build up the composed sources we determined the current-voltage characteristics of the batteries and supercapacitors. For that, we designed and implemented a test bench dedicated to the batteries and supercapacitors. This includes the following elements: a laptop necessary to integrate and control all the elements respectively: the power supply driven by PC (charge profile) used to control the charging process of the device under test and to control the voltage and/or the current provided.

The measurement system was built around the NI 6215 data acquisition card, linked to PC by USB bus, with 16th isolated analog inputs, each of them having 16 bits resolution-250KS/s. Two of the input channels are dedicated to the acquisition of the current and voltage provided by two Hall current and voltage sensors. The discharging process is implemented using a digital controlled active charge applied to the terminals of the device under test. Also, it is able to control the discharge parameters – current and voltage variation following a pre-defined profile. In Fig. 1 we presented the structure of the test bench. In both cases, the commutation devices function in PWM regime in order to minimize the commutation losses.

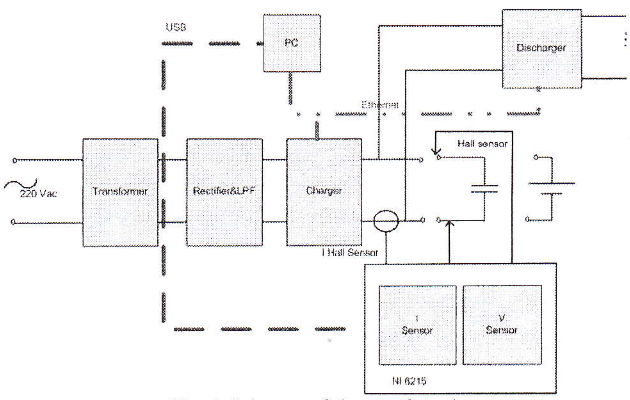

Fig. 1 Scheme of the test bench

The parameters of the test bench system are: nominal power 1KW, maximum frequency 10Hz, maximum voltage 18V, and maximum current 55A. Also, the test bench accepts a pre-defined current/voltage/ charge or a user defined profile for charge/discharge process.

As device under test we used a supercapacitor at 350F/14V produced by ECOD – Russia. For this supercapacitor it was measured the self discharge characteristic at different maximum voltages, respectively at 17.5V (125% V_N), 16V (114%V_N), 14V (100% V_N) and at 12V (85% V_N). These characteristics are presented in Fig. 2.

As a result of the testing carried out, we can conclude that the super capacitor will provide an accurate response to the energy management system if the voltage applied on it is less than 115% of its nominal value. The response provided by the supercapacitor is assured without any damages or significant degradation of its quality of voltage regulation.

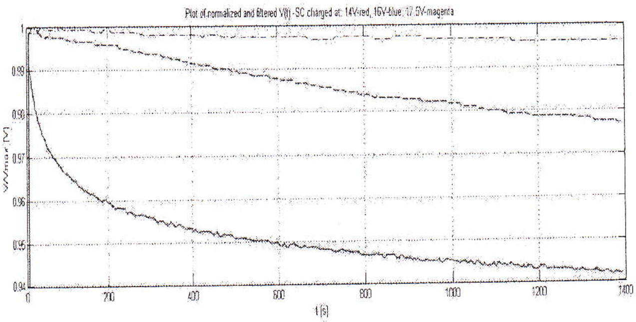

Fig. 2 SC's characteristics at125% of V_N, 115% of V_N and at V_N

III. Case Study: Energy Management System for Shunting Diesel Hydraulic Locomotives

We have developed an energy management system as a case study in order to illustrate the feasibility of the combined power supplies solutions as possible energy sources on vehicles - in our case a diesel hydraulic shunting locomotive solution.

The system developed implements three main functions: optimize de starting process of the ICE, stabilize the voltage provided by the locomotive power generator and optimize the charging process of the existing batteries from the locomotive. We can mention the following advantages of the system: reduction in both capital and operating costs, improved reliability and availability, and extended temperature range of operation.

To meet the functional requirements, a combined energy storage system should include an appropriate energy management system.

A prototype of a supercapacitor-based starting system for a diesel hydraulic locomotive was developed in the frame of the network of several partners from the COST Action 542. The starting system was based on a high-voltage supercapacitor with aqueous-based electrolyte and a purpose-built energy management system. The starting system was successfully tested on a diesel hydraulic shunting locomotive, LDH1250 model. Finally, the developed system was integrated into the energy management system illustrated in Fig. 3.

Thus our system includes four sub-systems, all of them implementing specific tasks.

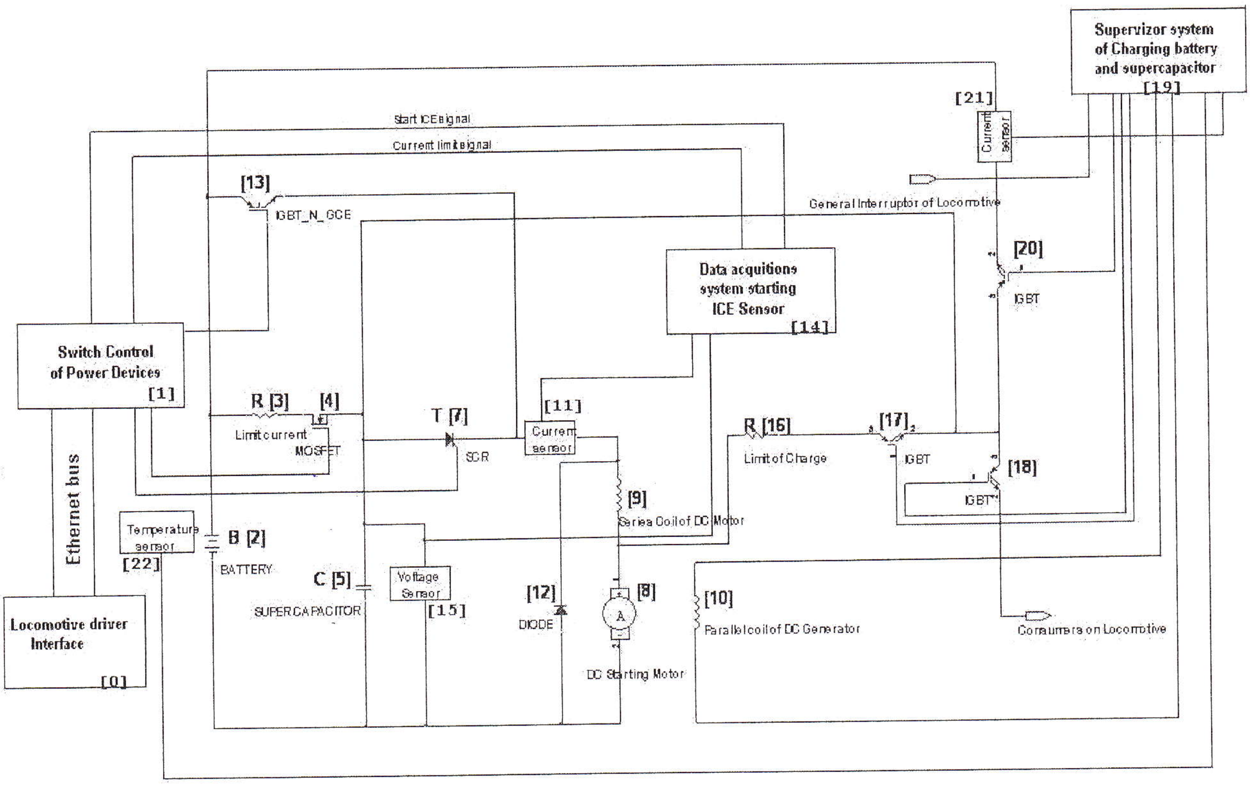

Fig. 3 Scheme of energy management system mounted on locomotive LDH1250HP

The *first sub-system* (1) assures the control of the ICE's starting process. This can be possible by controlling the switching power devices in order to charge the supercapacitor at the beginning of the process. After that, under the guidance of the locomotive operator the sub-system has to supply the DC starting motor from the supercapacitor and afterward from the batteries.

The *second sub-system* (0) is used by the locomotive operator in order to initiate the starting process of the ICE by transmitting the command to the sub-system (1). As we mentioned above this is possible by successively switching, first the supercapacitors and then the batteries in the DC starting motor circuit. During this process, the *third sub-system* (14) monitors the current and voltage on the DC starting circuit. It also adjusts the delays between the exchange of the different power supplies in the DC motor circuit depending on the starting conditions, such as the voltage level of the batteries and their State of Charge (SoC), ambient temperature and temperature of the cooling water of the ICE, oil pressure, produced by pumps inside of the ICE.

The *fourth sub-system* (19) is used to manage the charging process of the batteries exiting on locomotive after the start of the diesel engine was made.

Synchronously with the switching on of the batteries in the DC starting circuit, the sub-system monitors the rotational speed of the ICE and also the oil pressure created at the level of the locomotive speed regulator. These actions are undertaken to detect when a stable regime for the ICE has been reached, to switch off the batteries in the circuit of the DC starting motor and to end the starting process, thereby obtaining an optimal ICE start control.

The components of the energy management system, respectively the panel PC (0), the ATmeaga128 microcontroller based sub-systems (1), (19) and the AVR32UC3 based sub-system (14), are together connected by an Ethernet bus where it also was inserted a switch that is not drawn in above mentioned figure. This system is adequate to the data flow transmitting process because it assures the galvanic insulation of the all sub-systems and the effective protection from all electro-magnetic disturbances that could appear. The bus supports the transfer of the telegrams between the sub-system components in accordance with their specific time constants.

When the ICE of the locomotive is active (running), the role of the energy management system is changed.

The sub-systems (19) and (14) serve to coordinate the battery charging process. Using the Coulomb method [2], [3] the microcontroller accurately measures all the currents related to the battery system.

SoC is defined as the percentage of the full capacity of a battery that is still available for further discharge [4]. The Open Circuit Voltage (OCV) method, developed by Christianson et al [5], is based on measuring the battery voltage (V_{bat}) with high accuracy and the internal resistance (R) at a measured current (I):

$$OCV = V_{bat} + I \cdot R \tag{1}$$

In Lead Acid (LA) batteries the dependency between the OCV and the SoC is quasi linear. The combination of the OCV method with the Coulomb method (based on the integration of current absorbed or provided by batteries) enables the validation of a SoC value at any time with a good accuracy.

$$Q(t) = \frac{1}{R}\int_0^t i(\tau)\cdot d\tau \tag{2}$$

The microcontroller stores the values corresponding ı the maximum charge stored on batteries. Also, it enabl the determination of the real value of SoC according to tl above mentioned relationships [6].

To measure the Electro Motive Force (EMF), tl "voltage relaxation" method was used. This involves tl measurement of the battery voltage relaxation in relation ı the EMF value after current interruption. Th measurement may take a long time, especially if the batte is almost empty, if ambient temperatures are low, or aft the implementation of a high discharge current rate [7], [8]

Before mounting the batteries on the locomotive, a Lool UP Table (LUT) analysis was carried out using the EM values for different SoC. These values were obtained l using the results from preliminary trials. To calculate tl actual value of the SoC, the interpolation formula was use

$$SoC = SoC_l + \frac{EMF - V_l}{V_h - V_l}\cdot(SoC_h - SoC_l) \quad ($$

where (V_h,SoC_h) and (V_l,SoC_l) represent two poin corresponding into the LUT that includes tl characteristics of the battery which was used. Based on tl measured EMF values, the SoC has been calculated l means of the linear interpolation. Accordingly, tl following switches were introduced: (17) which insulat the generator in order to enable high-precisic determination of the voltage generated by (8); and (18) th represents the main switch for the electrical servic provided on the locomotive. The circuit switch (2 (including a high precision current sensor in this circui insulates the battery in order to measure and to monitor i voltage, the relaxation time and implicitly its State (Charge (SoC) with high accuracy. The sampling rate f SoC is very low (between 5- to 60-min. periods) and adapted from the values obtained and stored in the LUT.

In order to preset the charging current for tl supercapacitors it is mandatory to determine their So Also, this is required in order to ensure suitable conditio for starting the locomotive's ICE. The microcontroller sul system (19) it also takes into account the temperature fro the room of the batteries as threshold signal to prote them against overheating.

IV. Implementation

For the new starting system LA batteries 150Ah/96 were used - this corresponds to less than half the capaci of the batteries that the locomotive initially ha (360Ah/110V). The batteries were combined with supercapacitors 12F/110V connected in parallel (provide by ECOND Company). These stacked supercapacitors wi aqueous-based electrolyte have an Equivalent Seri Resistance (ESR) of 20mΩ. Their temperature operatic range is situated between -40°C to +60°C, their weight about 40 kg each, and the energy stored on each is 72K The total resistance of the wires that connect tl supercapacitor and the starting motor was about 10-15mΩ For the charging process of the supercapacitors, a switchir device (4), consisting of a CMOS transistor (82A/150V was used. After the charging phase, the thyristor (controlled by the sub-system (1), will discharge tl supercapacitors directly on the DC series motor (Thyrist parameters 3500A/1200V produced by EUPEC). Tl switching device (13) is an IGBT at 600A/1200V fro

POWEREX. This device applies the voltage from a battery on DC series motor (8) in the second phase of the starting process of the ICE (see Fig. 3), at the optimal moment, under the control of the sub-system (1). Since the tacho-generator of the locomotive provides data on the actual speed of the ICE it has been used as a rotational speed sensor.

The control sequence implemented by the control power switching system (1) is shown in Fig. 4.

[4]				
[7]				
[13]				
ICE				

Fig. 4 The sequence of devices commutation in time (X axis) is controlled by the starting system (1)

The sub-system (0) is implemented using a panel PC with a 1GHz Celeron microprocessor touch screen and two Ethernet interfaces (100Mbps). Sub-systems (1) and (19) are single board computers (SBC) based on ATmega 128 microcontrollers endowed with Ethernet controllers.

Sub-system (14) is implemented using an AVR32UC3 controller and it is also connected to the Ethernet bus by a specific controller. A switch is used between the above mentioned elements in order to interconnect them in a local network.

V. EXPERIMENTAL RESULTS

To compare both starting systems – the old-fashioned one with the new one, which has half-sized batteries combined with supercapacitors—the voltage and current variation during the starting process were measured and analyzed. Hall sensors for voltage and current were used for measurement (accuracy 0.2%). The blue line represents the mentioned parameters for the old-fashioned starting system and the red line represents the new starting system including supercapacitors.

The variation of the voltage during the starting process (X-axis represents the time, Y-axis represents the voltage variation) is shown in Fig. 5. This shows that due to the implementation of the supercapacitors the voltage drop of the batteries during the starting process was reduced by more than 5 times; it means that the lifespan of the batteries and their efficiency will be considerably improved as a result. As shown in Fig. 5 , when the new starting system is used the ICE engine reaches the "idle speed" (minimum stable revolution speed) in less than 200ms. Nevertheless, due to the existing speed regulator which needs a longer time to allow the ICE to reach a stable speed (due to its old fashion design), it was necessary to supply a DC starting motor. (If a more modern/efficient/accurate speed regulator is used, it is likely possible that the supercapacitors and batteries would be sufficient to achieve a stable running performance without needing the DC starting motor.)

The variation of the current during the starting process is presented on the Fig. 6 (X axis represents time; Y axis represents current variation). The variation of the current at the beginning of the starting process is clearly different between the old and new systems. The supercapacitor energy impulsion provided to the DC series motor will also

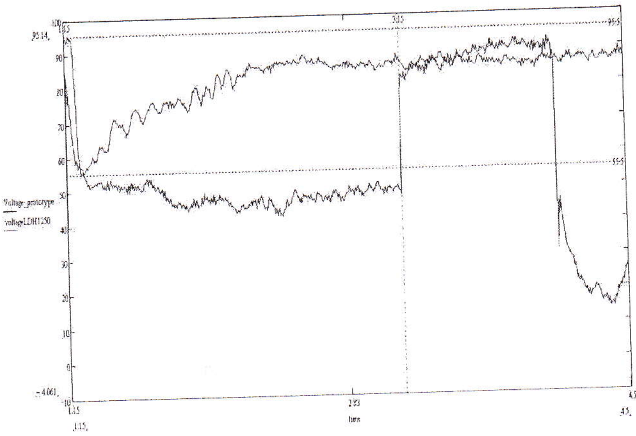

Fig. 5 Voltage variation during the starting process for the LDH1250HP (blue), and the voltage variation (red) during the starting process for the prototype LDH1250 endowed with the new energy management system

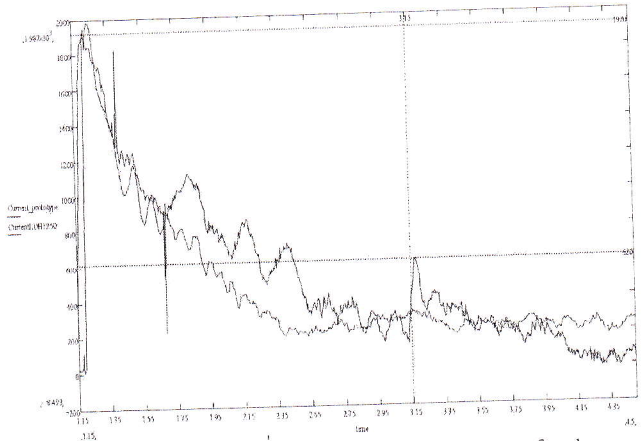

Fig. 6 Current variation during the starting process for the LDH1250HP (blue), and the current variation (red) during the starting process for the prototype LDH1250 endowed with the new energy management system

improve the dynamic response of the system in a similar fashion to a crank. In situations in which there are successive starting processes the remaining energy from the previous process can reduce the charging time of the super-capacitors.

The energy management system which was developed allows the switching process between the two energy sources (supercapacitors and batteries) to occur automatically, depending on the temperature and oil pressure within the ICE.

The importance of having a power supply with a very low level of the ESR at the beginning of the process should be emphasized (see Fig. 7).

In accordance with the characteristics of a DC series excited motor, the designed system leads to an improvement in the "crank effect" for the ICE. Simultaneously the system protects the batteries from the negative impact of peak current, which is a main reason for reducing their lifespan.

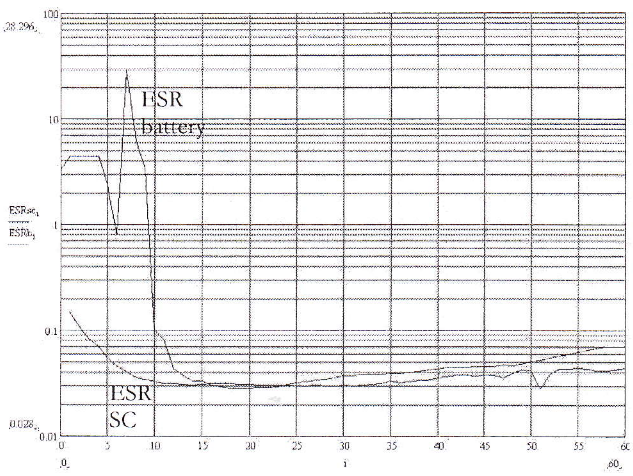

Fig. 7 Short time variation of ESR during the first 600 ms after begin of the starting process with logarithmic scale on Y axis - (blue represents ESR variation in time for batteries and red represent the ESR variation in time for supercapacitors – the measurement was obtained using a shunt with 60mΩ resistance)

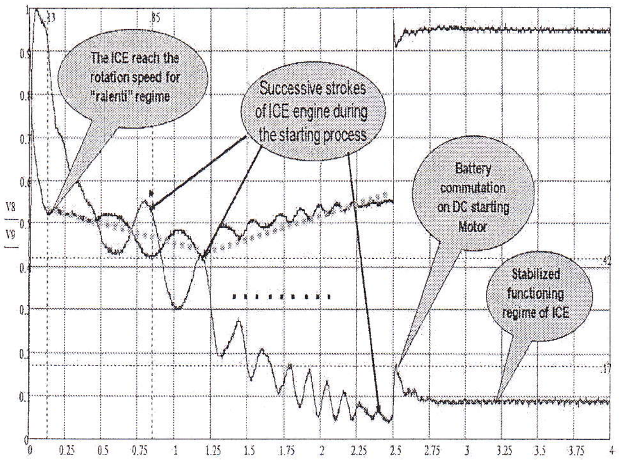

Fig. 8 Current and Voltage variation during the starting process (X axis: time is measured in seconds)

By monitoring the current and voltage variation during the starting process as shown Fig. 8, the sub-system (14) will sense when the energy stored on supercapacitors is insufficient to accelerate the ICE engine (the end of the energy that can be transmitted to the DC motor from supercapacitors). This is possible by measuring the period variation between two successive current extreme points in correlation with the measured voltage. After that, the sub-system (14) will send to the sub-system (1) the command to switch-on the IGBT (13). Thus, in the first phase of the starting process (14), the system acts as an optimal and automatic adaptive control system.

VI. Conclusions

The new starting system, implemented with stacked supercapacitors with aqueous-based electrolyte material and 150Ah/96V batteries instead of 360Ah/96V, designed for the LDH1250HP locomotive, possesses the following advantages:

- A reliable and available starting process of the ICE in a large range of temperatures from -30°C to +60 °C and also in weak SoC conditions for batteries;
- The rate between the initial current provided by th batteries –in case of the initial LDH1250HI locomotive and the current supplied from th batteries on the prototype is 5.5 times less than th initial value. This means that the stress of th batteries was substantially reduced, even if th capacity of the batteries was less than half of th initial value.
- The duration of the starting process was also reduce from 7, to 10 seconds (the initial situation) to 4, to 4. seconds. This leads to a reasonable reduction for bot operational and capital costs due to the reduced fue consumption (approximate savings for the shuntin locomotive LDH1250: 56 l Diesel fuel/da respectively more than 1500€/month);
- Extension of the remaining batteries' lifespan b more than 70% (estimated). The suggested lifespa of the supercapacitors is about 10 years;
- Using supercapacitors as temporary buffer of energ provided by generator on locomotive allows to use more precise and simple algorithm for the chargin system of the batteries integrated into the combine energy storage system and, as consequence, a extension of batteries' lifespan.

The starting system described in the present paper wa successfully tested over one-year period in collaboratio with Romanian Railways. The successfully results of th tests, with implications for increased reliability and reduce costs, encourage the application of the stacke supercapacitors using aqueous-based electrolyte to improv the starting systems of the diesel locomotives and of th other diesel engine vehicles.

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