Bulletin of the *Transilvania* University of Braşov
Series I: Engineering Sciences • Vol. 7 (56) No. 1 - 2014

A NOVEL SYSTEM USED IN THE STARTING PROCESS OF THE DIESEL LOCOMOTIVES

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Abstract: *The paper presents an implementation of an improved starting system of the diesel engine fitted on LDH1250HP locomotives. Using a new system for controlling the starting motor of diesel engine in the paper are detailed the technical aspects related to energy sources - a battery of super capacitors and a lead battery - which are intelligently and successively switched on the starting drive in order to offer a reliable and available starting process in any conditions. It is described the structure of the control system, the component devices, the performance obtained and the future development previewed for this technology of starting systems.*

Key words: *embedded system, energy management, hybrid electrical energy storage system, power-energy density, adaptive control.*

1. Introduction

Nowadays the important changes of the climate at global level and depletion of fossil resources require from the human society a rapid and strong assembly of measures able to determine a drastically reduction of energy consumption. An important step towards this goal consists in the fuel consumption and engine pollutant reductions. The actual locomotive starting system includes huge batteries that offer the pulse current (energy) necessary to start the diesel engine. In order to offer a high reliability and availability level of the system these batteries are over dimensioned. The starting transitory process affect the life time of batteries, and the possible damages produced due to starting shocks are difficult to be evaluated and as consequence this fact determine the reduction of system reliability [8-10]. As a result of nanotechnologies evolution, the parameters of super capacitors become more appropriate to fulfil the requirements related to maximum current, power and energy density and nominal voltage necessary to be provided by starting devices [13].

Combined solutions, batteries plus super capacitors, appear to be the optimum compromise in terms of energy economy, materials, size and cost (including maintenance costs) [1]. While for batteries, starting becomes difficult at low temperatures, by using the combined solution, the battery will be protected and significantly improves ICE (Internal Combustion Engines) starting. By providing intelligent and adaptive switching of the electric starter energy source between super capacitor and battery, the system's response characteristic can be optimized.

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Resuming, the most important demands addressed to locomotive are starting system reliability and availability, low weight, cost and fuel consumption as well as the current tendency of increasing of battery life time due to appropriate operation [7], [11].

2. Starting System Structure

The structure of the starting system is presented as in Figure 1.

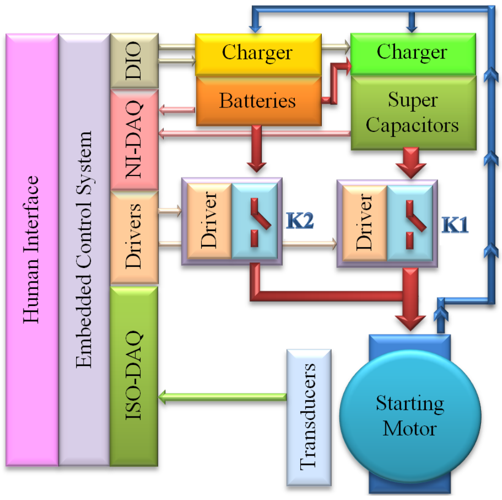


Fig 1. *Structure of the starting system of diesel locomotive LDH1250HP* [6]

The system storage for electrical energy necessary to the starting system includes one battery of 8th series lead acid batteries which provides a capacity of 150 Ah at 96 V (this storage capacity represents less than half of the initial one (360 Ah at 96 V)). Three aqueous stacked super capacitors (SSC) of 12 F at 110 V connected in parallel that means 36 F at 110 V. The technology development for this super capacitors is the Electric Double Layer Capacitors (EDLC) type with aqueous electrolyte, each super capacitors with an equivalent series resistance (ESR) 20 mΩ, and can function correctly in a wide range of temperature (–50 ºC to +80 ºC). The weight of each one was 30 kg, having diameter of 23 cm, length of 42 cm and energy stored of 145 kJ. This kind of stacked EDLC doesn't require any additional balancing system for the elementary cells, being compact and resisting at a mechanical stress (sinusoidal acceleration of 5 g) more than 10.000 hours [2]. The cyclability of this stacked EDLC exceeds 500.000 charging - discharging cycles [14].

For this super capacitors battery's charging process we have used a constant current buck regulator that is able to provide a constant current of 10 A at 160 V. The charging time of the super capacitor is around 180 s (when initial voltage on super capacitors is around 50 V).

For its discharging on starter motor (DC series motor), a SCR thyristor has been used (K1) which is able to switch a current of 4000 A at 1200 V, device produced by PowerEx (TBS702350) [15]. Because, in some cases the energy stored in the super capacitors is not enough for the whole starting process is mandatory to continue this process with energy stored by lead acid batteries. For this cases it was introduced a K2 switch using an IGBT at 1200 V and 600 A nominal current produced by PowerEx (CM600HA) [16].

The data acquisition system (NI-DAQ) is used for acquiring the parameters of the LDH1250HP locomotive from the starting process [4]. The NI-DAQ is based on a National Instruments USB6215 [17] device able to simultaneously acquire 16 analogue data with 20.000 samples/ second having 16 bits resolution. In order to monitor the starting process, the following data were acquired: (i) the voltage on battery, (ii) the voltage on super capacitor, (iii) the voltage and current on starter motor, (iv) temperature variations in the chambers of the batteries, (v) temperature variations at the internal combustion engine (ICE) and (vi) revolution of the ICE. All these data are used to analyse the behaviour of the locomotive in the starting process. In order to be analysed, data is transmitted via USB interface to embedded control system.

In Figure 2 it is presented the prototype of the starting system.

Fig. 2. *The starting system prototype implemented on LDH1250HP* [11]: 1 - *Software interface of the command and control panel;* 2 - *Locomotive, electronic power switching devices and battery of super-capacitors;* 3 - *SSC* (*3 x 12F ≈ 36 F at 110 V*)*;* 4 - *Cockpit and control console of the locomotive*

Figure 3 shows the control sequences implemented by the *Embedded Control System*:

i) The super capacitors are charged at maximum voltage. The process of charging the super capacitors is supplied by the group of accumulators if the locomotive is not running (nominal voltage 96 V) or from the generator - DC series starting motor (nominal voltage 110 V).

ii) At the locomotive mechanic's command, the starting process is preceded by switching on the thyristor K1 that will discharge the group of super capacitors on the DC starting motor; Also in this phase is enabled the NI-DAQ subsystem in order to record the footprint of the starting process.

iii) After a settled delay (around 1 second), in loop is checked both the voltage on the super capacitors battery's and also the trend of the rotational speed of the ICE. If the rotational speed exceeds the preset threshold the start-up process is considered ended successfully and the electronic switch devices are turned off together with data acquisition system.

If the energy respectively voltage from the super capacitors battery's drops below the pre-set threshold the K2 IGBT is switched on. Simultaneously, K1 will be switched off by applying a reverse voltage on its terminals.

iv) The control system will detect when the ICE reaches the base revolution speed and will switch off the K2. In case the ICE does not turn on, the starting process will be automatically interrupted after 10 seconds. Also if the peak current exceeds the preset threshold the embedded control system immediately will interrupt the starting process in order to protect the lead acid batteries.

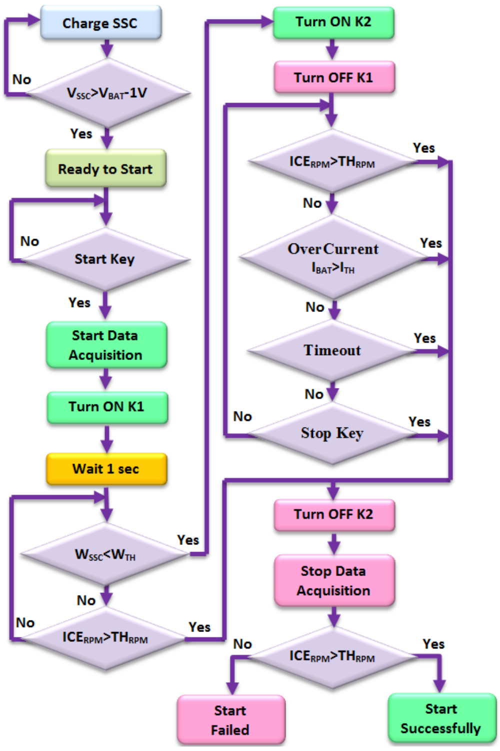


Fig. 3. *The control sequences implemented by the Embedded Control System*

3. System Efficiency

In order to have a more accurate assessment regarding of efficiency of the new starter ICE system, in the CFR depot, from Brasov on the LDH1250HP locomotive, having 80-0479-8 serial number, were performed and self-recorded a number of over 4,000 of starting processes, over three years.

For each starting process following parameters have been recorded: i) temperature on lead-acid battery and the ICE, ii) voltage on lead acid batteries, super capacitors and starter motor, iii) current and rotational speed of the starter motor. Based on these parameters recorded, it was possible to obtain a set of derived parameters useful for evaluation and optimization the starting prototype system. The huge amount experimental data were automatic processed using Data Analysis, software developed in Visual Studio.NET [3], [11].

Figure 4 shows in statistic form, energetic contribution of each element in the starting process. Thus, almost all starting processes, the peak power supplied by super capacitors it was around 333% times higher than peak power supplied by lead acid batteries (1), and ratio of energy provided by these storage elements it was around 430% (2):

$$\gamma_{AvgP} = \frac{P_{AvgSSC}}{P_{AvgBAT}} \approx 333\,\%\,, \tag{1}$$

$$\lambda_{AvgW} = \frac{W_{AvgSSC}}{W_{AvgBAT}} \approx 430\,\%\,. \tag{2}$$

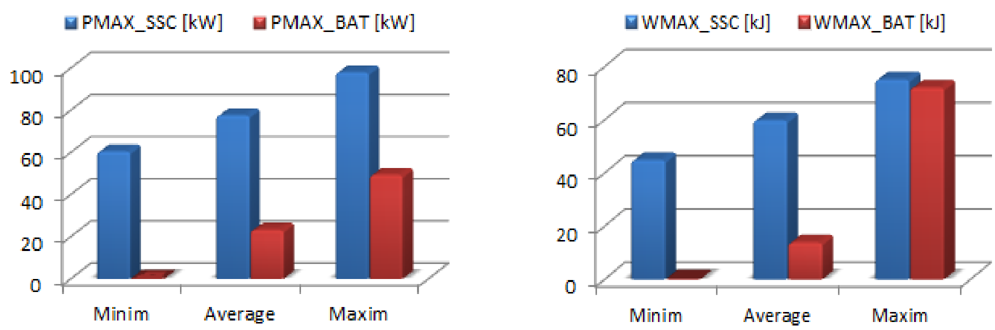
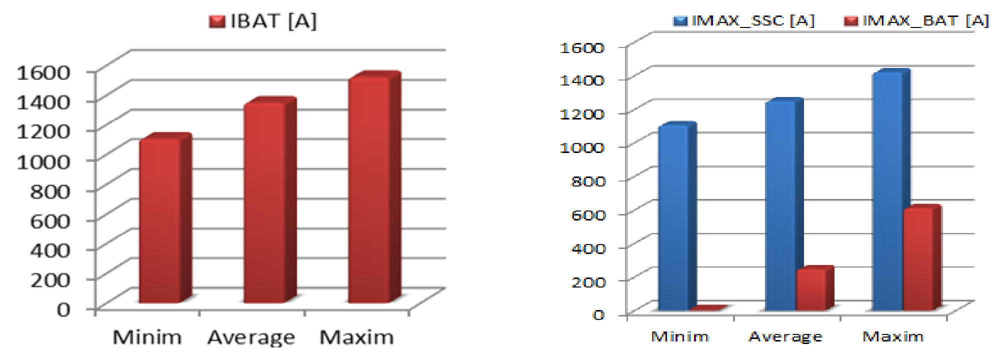


Fig. 4. *Minim/Average/Maxim values for power and energy provided by the SSC and lead acid batteries* [6]



a) b)

Fig. 5. *Minim/Average/Maxim values for current delivered by the lead acid batteries for a) standard and b) hybrid, starting system* [6]

Figure 5 shows few starting processes which were either lightly or heavily, within which the contribution of lead acid batteries was zero or nearly to that of the super capacitors.

Also in Figure 5 it can be seen that in most of starting process the peak current delivered by the lead acid batteries was significantly lower than in classical starting systems (3):

$$\delta_{AvgI} = \frac{I_{AvgSSC}}{I_{AvgBAT}} \approx 506\,\% \,. \qquad (3)$$

In most cases the energy provided by super capacitors has contributed to achieving twelve strokes, these means two revolutions of the crankshaft [12].

4. Conclusions

Although apparently is less important, upgrading the ICE starting system by providing combined energy sources and their optimized operational control in concordance with the ICE, has positive effects, such as:

- the system allows multiple stop and start processes without damaging the batteries thus reducing the fuel consumption, especially for shunting locomotives having positive effects on the environment protection;
- the system improves the reliable and available starting process of the ICE in a large domain of temperature (–30 ºC to +60 ºC) even in low SoC batteries conditions;
- some experiments done have demonstrated that even at 86 V in the conditions when one of batteries was destroyed the locomotive was started;
- super capacitor delivers energy boost in peak current situations (peak load regime);
- battery operation under less demanding conditions (under 25% of the initial maximum current) will increase the lifetime of the battery;
- the prototype system developed raise the availability and reliability of the locomotive;
- the adequate control system improves the performances of the starting process;
- reduces the volume and weight of system by reducing at half the batteries' number.

Savings:

- reduction at more than half the batteries capacity "on-board" the locomotive (360 Ah / 96 V at 150 Ah / 96 V) (the production of the batteries can be reduced significantly);
- increase by more than 70% of the batteries lifespan (estimated result) (the production of the batteries can be reduced significantly);
- a fuel consumption reduction approximated at 50 litres (diesel oil)/day, respectively around 1500 €/month for the shunting locomotives used in railways stations.

The adequate control offered by modifying the time for switch on K1 and K2 electronically can offer an optimal fit of device characteristics of batteries and super capacitors [5], [14]. Making a calculus about the return of investment (ROI) involved by such starting system the recuperation of investments will be produce in maximum two replacing cycles of batteries, which means 3-4 years. Taking into account only the cost of devices without any consideration about the savings it was resulted a 100% reliable start of locomotive demonstrated during more than two years of experiments. The pollution and fuel consumption of locomotive were also reduced because in case of shunting locomotives for the periods when locomotive was not used the driver has switch off the ICE.

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