Starter Aiding System Based on Supercapacitors for the LDE2100 Locomotive

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***Abstract**: The paper presents an intelligent embedded system designed for aiding the starting process of the internal combustion engine of the LDE2100 locomotive. The system uses supercapacitors to reduce the strain on the main batteries increasing battery life. The higher charged supercapacitors also offer a higher degree of successful engine starts. Another advantage of the proposed system is the use of solid state relays instead of the electropneumatic ones, greatly reducing transient voltages and current spikes, the main causes of shortened lifespans of traditional engine starting systems.*

1. INTRODUCTION

Vehicle starting systems usually employ lead-acid batteries powering series DC motors connected to the crankshaft of the internal combustion engine. The power demand of these motors spinning the entire engine are very high, conducting to a fast depletion of batteries and shortened lifespan.

The current shocks can destroy or reduce drastically in a single deep discharge cycle the capacity of a lead-acid battery making unusable the whole system [1]. It is essential to find out solutions that can prevent such events.

Nowadays the Electric Double Layers Capacitors (EDLC) became more and more used to improve the control of the transitory processes that need a high energy amount transmitted in very short time to actuators of the electromechanical systems [2]. Comparing with the batteries time characteristics, the EDLCs have a more rapid time response. More than that it is well known that the inner resistance of batteries is strongly dependent of temperature (below 0°C the inner resistance can increase with more than 40-80% in value [3]), whereas EDLCs, especially with aqueous electrolytes, have a very low variation of the inner resistance with temperature. That means supercapacitors can be successfully introduced into energy management systems in vehicles [4].

A such example is done for a small automobile that use for starting of the ICE a combination formed by batteries, supercapacitors and power electronic elements [5]. However starter aiding systems can be employed on higher power vehicles like locomotives as presented in [6].

The main problem with this extension was the difficulty to produce compact "high voltage" devices. The majority of such applications request a large amount of energy ($W_e = \frac{1}{2} C V^2$, where C is the capacitance and V is the voltage). Thinking that the voltage on an elementary capacitor cell is limited by the decomposition voltage of electrolyte [2] – maximum 1.2V for aqueous electrolytes and not more that 3.5V for organic electrolytes - , in order to obtain "high voltage" devices it is necessary to connect in series a lot of them ($C_{equivalent} = \frac{\sum_{i=1}^{k} \prod_{\substack{i=1 \\ i \neq k}}^{k} C_i}{\prod_{i=1}^{k} C_i}$ when $C_1=C_2=..=C_k$) in order to reach the maximum value when all the capacitances are equal. That it is obvious that it is important not only the intrinsic performances of cells but also how these cells are together connected as devices.

This paper presents a starter aiding system based on supercapacitor which was developed for the LDE2100 locomotive, the most used diesel electric locomotive in Romania.

2. Starting the Diesel-Electric Engine

The LDE2100 or 060-DA locomotive employs a diesel-electric engine system, in which an internal combustion engine drives an generator feeding the electric motors on the axes [7]. Starting the internal combustion engine is done by the same generator by connecting this to the batteries.

The electrical system of the LDE2100 locomotive is separated into two parts: a low voltage and a high voltage system. The high voltage system includes the main generator and the traction motors. The voltage generated varies in a range of 800-1200V in order to modify the speed and power provided by the locomotive.

The low voltage system includes the batteries and all other electrical consumers. The battery pack is made up of 12 lead acid battery giving a voltage range of 144-180V. The batteries are charged from a secondary generator installed on the same ax with the main generator.

For safety reasons, these two systems are galvanically insulated from each other and only for the duration of the launching process are connected together so the batteries can drive the generator as an electric motor.

The starting process is very demanding on the batteries due to the high inrush current of the high power generator (as presented on fig. 1.). As a result battery life is much shortened (usually not more than 1.5 year), and the reliability of the starting process is lowered especially when batteries are somewhat depleted and cannot offer the high initial currents. Also the mechanical relays employed for connecting the batteries to the generator suffer from the arcing produced by the high currents and need often replacement.

To reduce the strain on the batteries a supercapacitor based system can be employed to aid

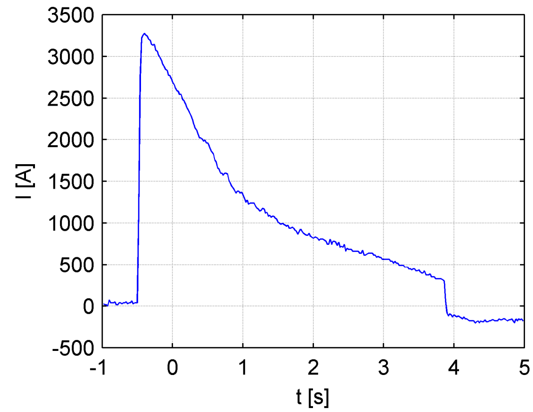

Fig. 1. Current consumption of the launching sequence

the starting process. Such system is presented in [6] for the LDH1250 locomotive. To use a similar system in the LDE2100 locomotive some modifications to the presented solution has to be made. Using the main generator of the LDE2100 as DC motor to start up the engine requires much larger currents and also a galvanic insulation is required between the batteries and the generator after the launching process terminated.

The starter aiding system is permanently connected to the batteries, avoiding the main contactors which have fuses not sufficiently large for the currents demanded by the starting process. However, the low power parts of the system should be turned off when other electrical equipments in the locomotive are disconnected. This means that a modular approach is required separating the system into blocks as presented on fig. 2. This separation is also useful as due to the size of the locomotive parts of the system should be dispersed to the driver cabin and the engine compartment.

The separation between the low power and high power system is also done on a galvanic insulation level, so the two parts can act fully independent as required by the safety regulations. The low power system is the intelligent control panel employing the microcontroller which reads the system parameters and commands the power electronics. The galvanic insulation is realized with fiber optic transmission of the commands and the reading of voltages and currents by the means of Hall effect sensors.

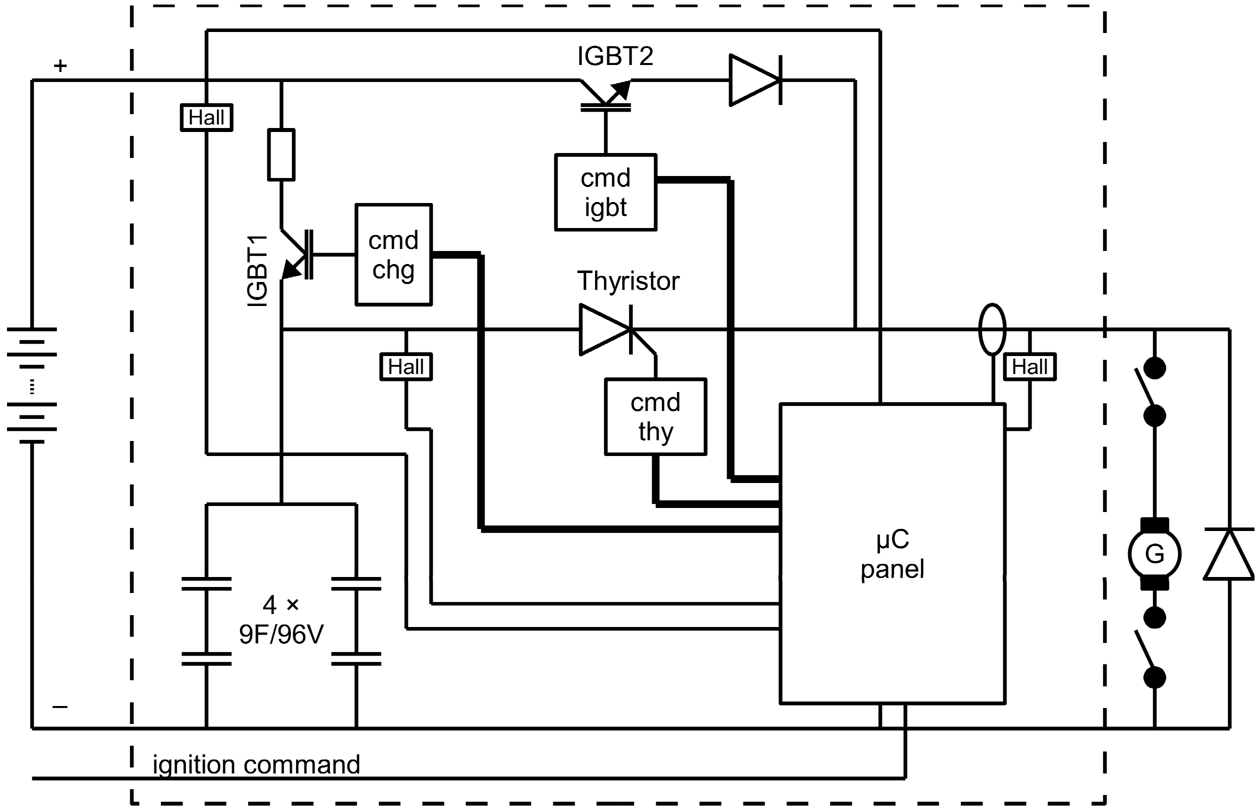

Fig. 2. Block diagram of the starter aiding system

The power system employs the supercapacitors which are charged from the batteries through IGBT1 with a much lower current than required by the generator. Because of this, the charging of the supercapacitors can take longer time, but during this time the other pre-start operations like oiling the engine or pressurizing the pneumatic system can be done, so the startup process is not delayed.

At the effective ignition process, the capacitors are first connected to the batteries through a thyristor and handle the first current spike. After the capacitors are depleted the batteries are connected to the generator through IGBT2 and continue the spinning of the motor with a much lower current requirement. The overall peak current requirement on the batteries are therefore lowered resulting in a longer battery life.

Because of the need of galvanic insulation between the low voltage (batteries) and high voltage (generator) circuits the electropneumatic relays (KEPA) of the original starter system must be kept between the new starter aiding system and the generator. However because the high currents are commanded by the solid state relays, no current will flow through this contactors when they are disconnected, so no arcing is produced, increasing the life of these relays too.

The timing of the whole ignition process is presented on fig. 3. The capacitors are considered already charged before the process starts. In order to avoid a short circuit on main electric circuits the control system provides adequate delays between the commutations electromechanical and power electronic elements. A short pulse turns on the thyristor connecting the supercapacitors to the generator. After this the capacitors start discharging until a threshold is reached. The IGBT2 is turned on to continue feeding the generator from the batteries. This also turns off the thyristor by the higher battery voltage. The IGBT2 is kept on until the engine starts spinning on its own detected by measuring the rotation by the means of the tachogenerator on the motors. Because of the adaptive nature of the IGBT2 command the timing is only estimative.

3. Hardware Implementation

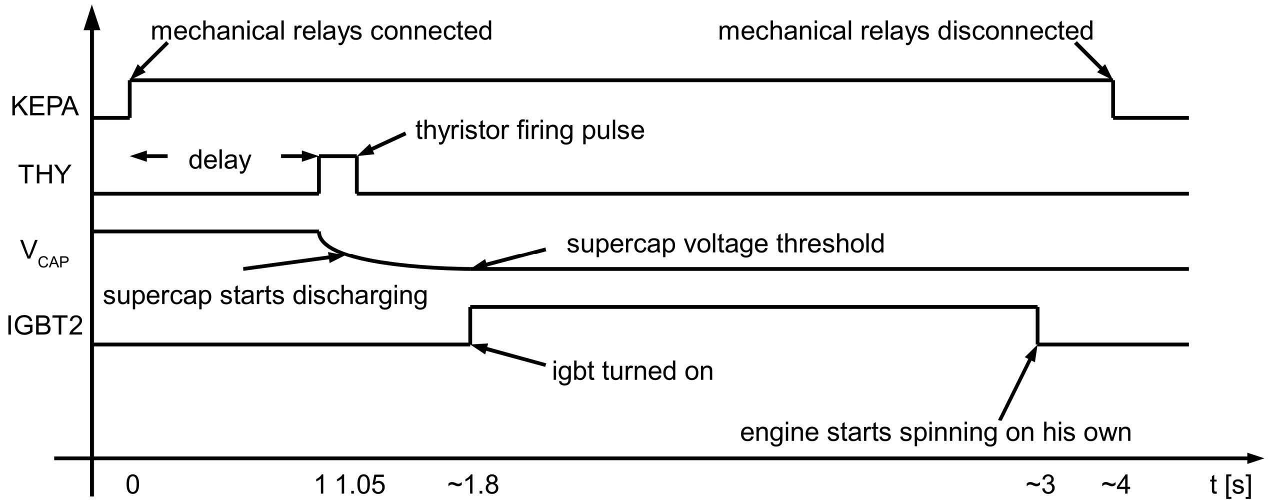

Fig. 3. Time diagram of the launching process

The system is separated in two independent parts: a power part handling the high voltage and high current circuits and a commander unit containing the microcontroller board.

The power part of the system contains the supercapacitors, the mechanical relays, the thyristor and the IGBTs and their commanding circuits.

The power part is located in the engine compartment, between the main generator and the battery pack to minimize power losses on the circuit. The mounted power system is presented on fig. 4.

The stacked aqueous supercapacitors used in the system are 9F/96V ones from ECOND. These supercapacitors (EDLC tupe) are based on activated carbon (AC) having as electrolyte an aqueous KOH solution. Because the lower voltage limit, 4 capacitors are used connected in parallel/series formation to give a total capacity of 9F at 192V above the maximum voltage of 180V of the battery pack. We haven't used balancing elements because the capacitance of each supercapacitor is quite equal.

For connecting the capacitors to the generator during the launching process a T1509 type thyristor is used capable of handling up to 3600A current, suitable for the high inrush current sunk by the generator. After the capacitors are depleted the current needed by the generator has to be taken from the batteries, but this current need is much lower than the initial current. For connecting the batteries to the generator a pack of three CM600HA type IGBTs connected in parallel are used. This type of IGBT is used also for charging the capacitors from the batteries before the launching sequence.

The thyristor and the IGBTs are mounted on the same copper bars that connect the capacitors together to have the lowest power losses possible. The thyristor is commanded by a MOC3020 optotriac and the IGBTs are commanded by TLP250 optocouplers offering a galvanic insulation of the commanding circuit from the high voltage circuits. For safe operation these circuits are connected to the command panel through a fiber optic link using the HFBR1533 – HFBR2533 transmitter-receiver pair. This also insures a galvanic insulation of the command panel and offers a higher reliability due to immunity to electromagnetic noise.

The command panel is located at the driver compartment for easy access and reading of status during the launching process. It is based on a ATmega128 microcontroller and includes and LCD screen and LEDs used as a user interface offering information about the current status of the system, the optical transmitters for connecting to the power system, analog inputs for measuring voltages and currents of the power system and an XPort serial to Ethernet converter for remote monitoring of the whole system.

The prototype of the microcontroller board is presented on fig. 5.

The voltages of the batteries and the capacitors along with the current sunk by the generator are measured using Hall effect sensors, also insuring galvanic insulation of the command panel.

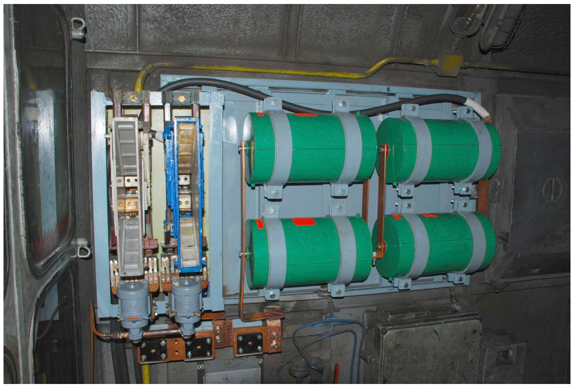

Fig. 4. The power system (supercapacitors, mechanical and solid state relays) mounted in the engine compartment

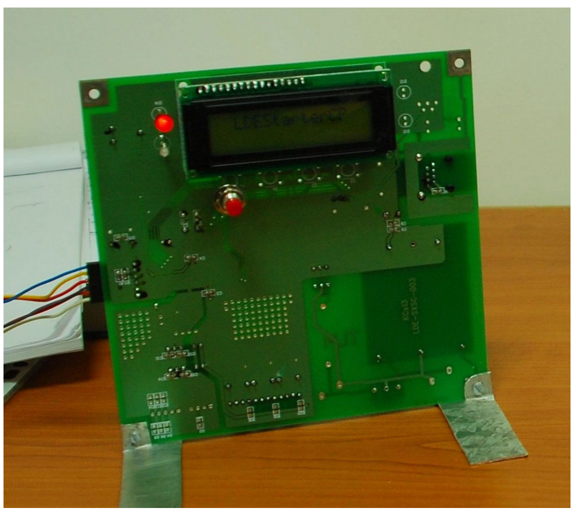

Fig. 5. Prototype of the command panel

4. SOFTWARE IMPLEMENTATION

The microcontroller software is based on a simple event manager, containing a fast response and a slow response event loop. The fast response loop is done in a timer interrupt and manages the state machine handling the launching process. This fast loop has the highest priority making sure the launching is realized in a reliable manner. The other part of the event manager is a slow event loop which handles all the non-critical functions of the system, like displaying information on the LCD and LEDs, self adapting the system based on the voltage and current measurements and handling the communication with the master device for remote monitoring of the starter system.

The state machine controlling the launching process is presented on fig. 6.

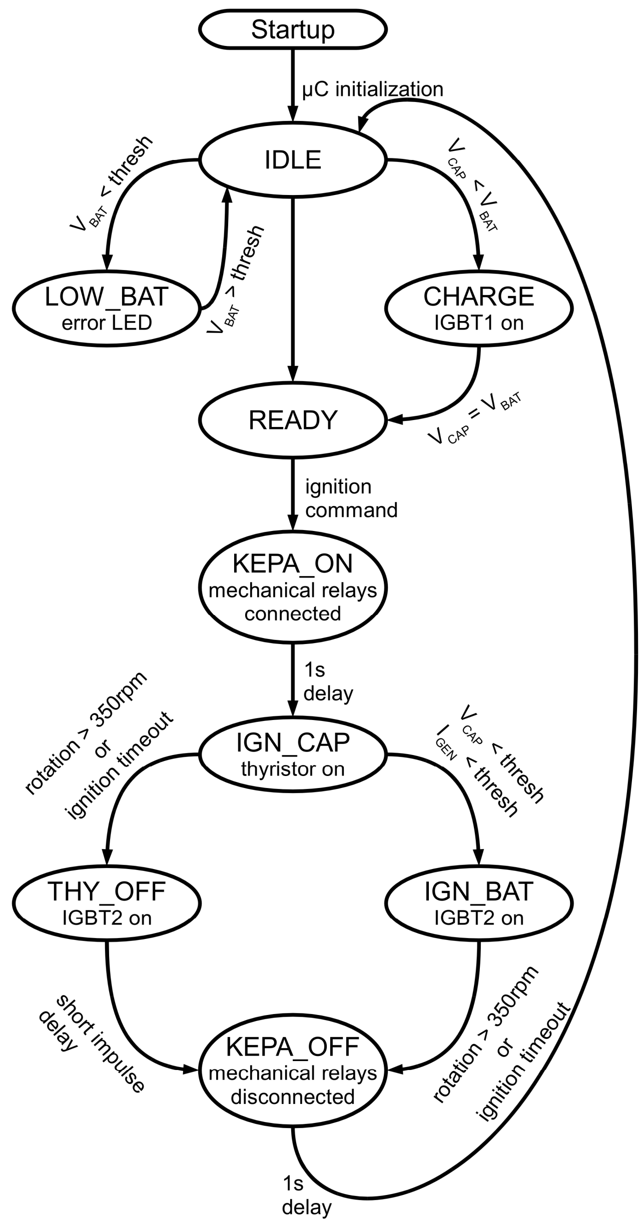

Fig. 6. State machine of the launching process

The whole state machine is controlled in the interrupt of the clock timer with updates at every 1/256 seconds. After the powerup of the microcontroller the state machine enters an IDLE state throughout the initialization process. Based on the voltage measurements the state machine can enter an error state (if battery voltage is too low), a charging state (when the capacitor voltage is lower than the battery voltage) or into the ready state. In the charging stage IGBT1 is turned on until the capacitors are charged to the battery level. After entering the ready state the system waits for the ignition command from the train mechanic to enter the launching process.

The effective launching process starts with turning on the mechanical relays between the low voltage and high voltage circuits. After the contacts are stabilized, the thyristor is turned on, connecting the capacitors to the generator. This is done until the capacitors are depleted (below a certain threshold) or the launching process should be aborted (due to engine spinning up or some errors). In both cases the IGBT2 is turned on connecting the battery to the generator. In the latter case this is done to turn off the thyristor with the higher voltage of the batteries and last for just a short period of time (about 5ms). In the former case the IGBT is kept on until the engine reaches minimum rotation or a timeout occurs indicating failure of the starting process. The exit from both states is a delay during which the mechanical relays are kept connected to avoid sparks at disconnection.

5. CONCLUSIONS

The presented system presents several advantages over the traditional starting system:

- the shaving of current peaks during the starting process reduces the stress on the batteries also increasing their life time
- because the thermal dependance of supercapacitor parameters is reduced the new system improves significantly the performance of the starting system at low temperature allowing to stop anytime the engine without consequences on the health of batteries
- the solid state relays employed in the system offer a much cleaner current switching avoiding arcing and current spikes of the traditional mechanical relays, this can also increase the necessary servicing period of the mechanical components
- the system allows a remote monitoring of the whole starting process giving much more information to the driver about the state of the electrical systems, and by storing the data collected during engine starts an easier servicing of the starting system can be achieved

In the future the long term reliability will be proved by intensive tests. Also the long term stability of the supercapacitors mounted on locomotive will be verified in order to prove the technical viability of present solution.

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