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Embedded System for Start of ICE with Hybrid Battery-Super-capacitor Sources

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***Abstract* — In automotive starting systems the demand for efficient use of energy and environmental protection lead to the use of supercapacitors in combination with traditional starter batteries. The main advantages of the hybrid battery – supercapacitor systems are extended life span of batteries, lower capacity, lower weight and volume as well as meeting the environmental regulations. The control of internal combustion engine (ICE) starting systems values the specific gains in terms of energy of lead acid batteries and supercapacitors, having as final performance indicator the available starter power.**

The paper presents the control strategies of the hybrid battery – supercapacitor system using a micro-controller which efficiently distributes the energy transfer among sources (battery, supercapacitor, alternator) and specific loads (starter and other energy consumers).

***Index Terms* —Algorithms, alternator, battery chargers, microcontroller, starting.**

I. INTRODUCTION TO START OF ICE STRATEGIES

The control strategies for start of ICE with hybrid battery-super-capacitor sources already presented in [1] have the same performance criterion, the maximization of the power delivered to consumers: the first strategy abbreviated *SC-B.MaxP* requires to supply the maximum power on the starter, initially from supercapacitor and then, if necessary, only from the battery; the second strategy abbreviated *BSC-B.MaxP* requires to supply the maximum power on the starter, initially from both battery and supercapacitor and then, if necessary, only from the battery.

In the *SC-B.MaxP* strategy, the switching from supercapacitor to battery is done when the power delivered by supercapacitor is equal to estimated power delivered by battery. This strategy is appropriate for hybrid battery – supercapacitor systems with low capacity batteries, aged or partly discharged, working at low temperatures and so having higher internal resistance and lower voltage and supercapacitors with lower internal resistance, charged at higher voltages.

Unfortunately, the *SC-B.MaxP* strategy is not applicable to supercapacitors with internal resistance higher than *15mΩ* [1]. In this situation, even the supercapacitor energy efficiency and power peak delivered to the load are smaller, it is recommended the use of BSC-B.MaxP strategy. The selection of controlling strategies is done according to stored energy efficiencies ηU,SC-B.MaxP , respectively ηU,BSC-B.MaxP, which are quality indicators depending on energy sources parameters, battery and, respectively supercapacitor, and load: battery internal resistance RB, starter resistance RL, battery open (circuit) voltage UB0, initial voltage on supercapacitor USC0, and in case of SC-B.MaxP strategy, supercapacitor internal resistance RSC.

$$\eta_{U,SC-B.MaxP}=\left[1-\left(\frac{U_{B0}}{U_{SC0}}\cdot\frac{R_L+R_B}{R_L+R_{SC}}\right)^2\right]\cdot 100$$

$$\eta_{U,BSC-B.MaxP}=\left(1-\frac{U_{B0}}{U_{SC0}}\cdot\frac{R_L}{R_L+R_B}\right)^2\cdot 100$$

As battery internal resistance increases with operation time, charge-discharge cycles and temperature decrease and supercapacitor internal resistance has a more drastic increase with operation time and charge-discharge cycles, it is required a permanent supervising of these resistances.

For *SC-B.MaxP* strategy, as starter power has variations due to ICE compression/expansion strokes, the intersection of supercapacitor delivered power plot with battery (estimated) delivered power plot, takes place in several points, (in $t_1 \div t_5$ moments), from Fig.1. The control algorithm will switch from supercapacitor to battery (in t_6 moment) after successive checks done at time intervals equal to load peak intervals. In this diagram: $U_{SC}(t)$ is instant value of voltage on super-capacitor and $I_{SC}(t)$ instant value of current delivered by super-capacitor in case of use the SC-B.MaxP strategy; $U_{Be}(t)$ is instant value of estimated voltage on battery and $I_{Be}(t)$ is instant value of estimated current of battery in case of start with battery only.

For *BSC-B.MaxP* strategy, in order to avoid the premature supercapacitor disconnection (Fig.2.) and then lessen the $\eta_{U,BSC-B.MaxP}$ value, it is required the monitoring of supercapacitor current and switching when it becomes zero. In diagram from Fig.2 $U_{SC}(t)$ and $U_B(t)$ are instant values of super-capacitor and battery voltage powering together the starter; $U_{SCo}(t)$ is open circuit voltage of super-capacitor after it is uncoupled; $I_{SC}(t)$ and $I_B(t)$ are instant values of current delivered of super-capacitor and battery, respectively, in case of the *BSC-B.MaxP* strategy.

In order to have a high quality indicator for both strategies it is necessary to increase the initial supercapacitor voltage.

For example if U_{SC}=16.2V (the voltage on 6 super-capacitors with 2.7V nominal voltage connected in series) it will generate efficiencies $\eta_{U,SC\text{-}B.MaxP}$ = 79% and $\eta_{U,BSC\text{-}B.MaxP}$ = 33%.

II. THE HARDWARE OF THE START OF ICE MANAGEMENT SYSTEM

Figure 3. shows the functional scheme for ICE starting management in which the blocks have the following significance : *SC* – supercapacitor, *B* – battery; *DCDCC* – dc-dc converter (12V-16,2V) for supercapacitor charging based on High Efficiency, Synchronous, 4-Switch Buck-Boost Controller LT3780, *CS* – sensor for the alternator current, *CoC* – conditioning circuits, μC – microcontroller, the system core and the power switches for: K_{start} – the starting of ICE, K_{SC} – the coupling/uncoupling the supercapacitor to/ from the starter, K_B – the coupling/uncoupling the battery to/ from the starter, K_{CB} - the coupling/uncoupling the battery to/ from the alternator, K_P – the starter feed maintaining, K_S – the starter feed break.

The system signals monitored by microcontroller as well as their type and significance are described in table 1.

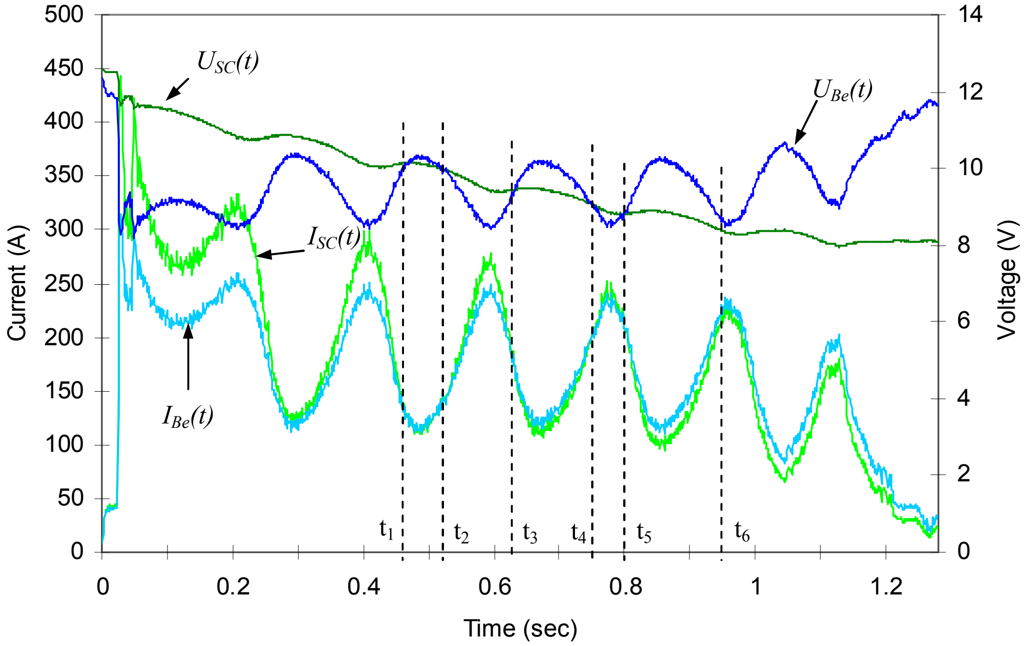

Fig. 1. The $U_{SC}(t)$ and $I_{SC}(t)$ diagrams for *SC-B.MaxP* strategy and $U_{Be}(t)$, $I_{Be}(t)$ for on-battery start of ICE.

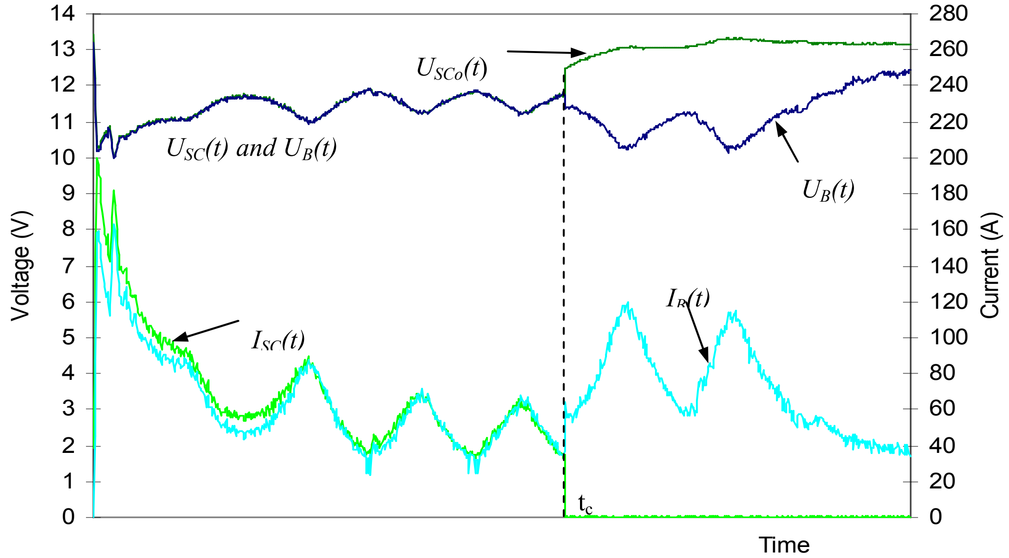

Fig.2. Early switching in the case of *BSC-B.MaxP* strategy.

III. OPERATION THE START OF ICE MANAGEMENT SYSTEM

In system operation there are the following phases (Fig.4.):

Pre-starting, the phase of the system until moment $K_{start}\cdot K_S=ON$; the engine is stopped and the supercapacitor (in τ_m period) is kept loaded at 16.2V through *DCDCC* (*CHARGE=ON*) and K_B and K_{SC} switches are open; during all phase $K_{CB}=ON$.

Starting, the phase of the system when $K_{start}=ON$ (in t_{pk} moment), $K_P=ON$ and $K_S=ON$; the starting time is controlled by K_S, when it is opened, the stating phase being over; for strategy *SC-B.MaxP*, $K_B=OFF$ and $K_{SC}=ON$ and for strategy *BSC-B.MaxP*, $K_B=ON$ and $K_{SC}=ON$, in both cases until the moment t_c, corresponding to switching; from moment t_c, $K_B=ON$ and $K_{SC}=OFF$; at the moment t_{od}, when starter is in no load operation, it is controlled $K_S=OFF$, $K_p=OFF$, $K_B=OFF$ and $K_{SC}=OFF$; during all phase $K_{CB}=ON$.

Post-starting, the phase with engine running and $K_B=K_{SC}=OFF$. The phase has three operation modes:

1. *Normal*, the vehicle runs smoothly at relative constant speed, the accelerator pedal being pushed, *CHARGE=OFF* and $K_{CB}=ON$;
2. *Acceleration*, *CHARGE=OFF* and $K_{CB}=OFF$, battery and supercapacitor are disconnected in order to enhance the engine power;
3. *Recovery*, (in $\tau_{l1,2}$ period) *CHARGE=ON* and $K_{CB}=ON$; the operation mode corresponds to braking or slope descending; the alternator delivers a supplementary current required for supercapacitor charging, the energy being practically recovered;

TABLE 1. SIGNALS MONITORED WITHIN ICE STARTING MANAGEMENT

I/O Type	**Signal abbreviation**	**Significance**
Analog inputs	VI_{SC}	Supercapacitor delivered current
	Usc	Supercapacitor voltage
	VI_B	Battery delivered current
	U_B	Battery voltage
	VI_{Alt}	Alternator delivered current
Analog output	V_{REF}	Reference voltage of *DCDCC* converter which modulates the charger current
Digital input	VK_{start}	Starting switch
Digital outputs	VK_{SC}	Control of switch K_{SC}
	ON/OFF	Control of supercapacitor charging *SC*
	VK_B	Control of switch K_B
	VK_S	Control of switch K_S
	VK_P	Control of switch K_P
	VK_{CB}	Control battery charging from alternator

In Normal and Recovery operation modes, if current instantaneous energy consumers, the supercapacitor charge released by alternator is close to maximum value due to current is controlled to be reduced SC_{St} by modulation of reference voltage V_{REF}.

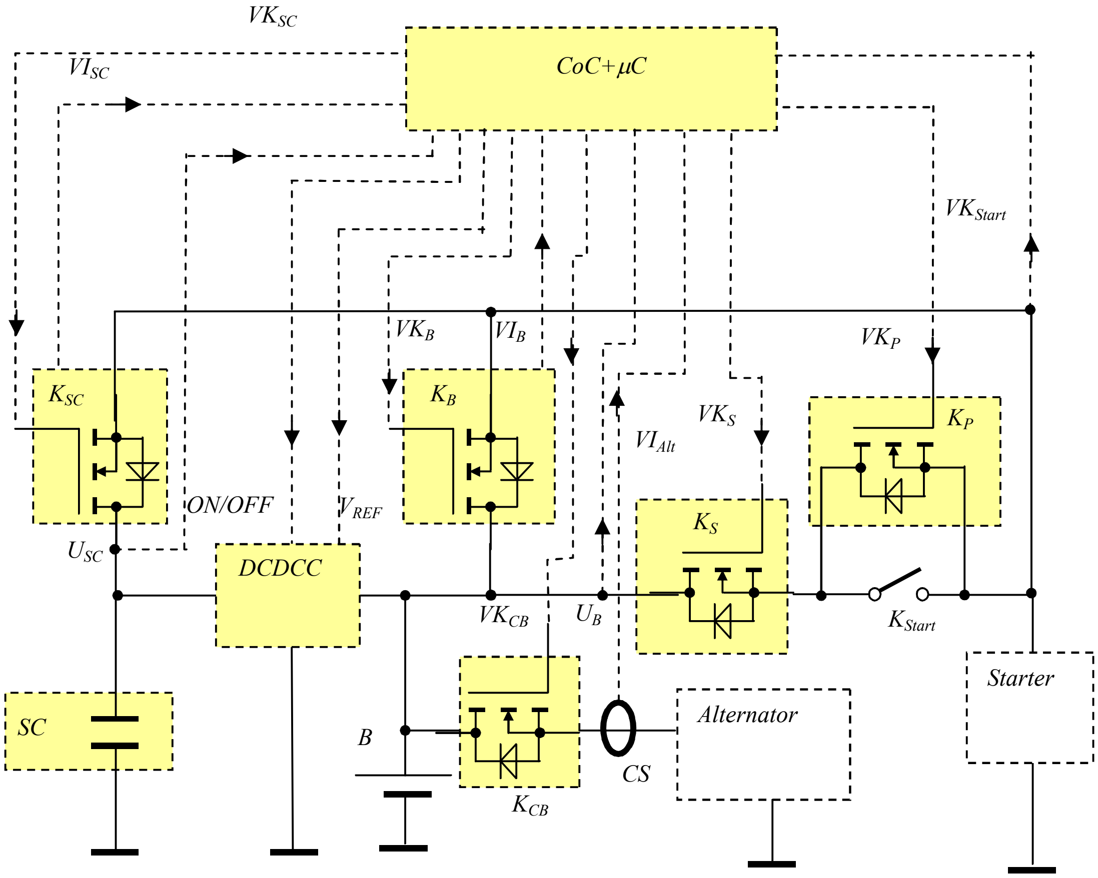

Fig.3. Functional scheme for ICE starting management

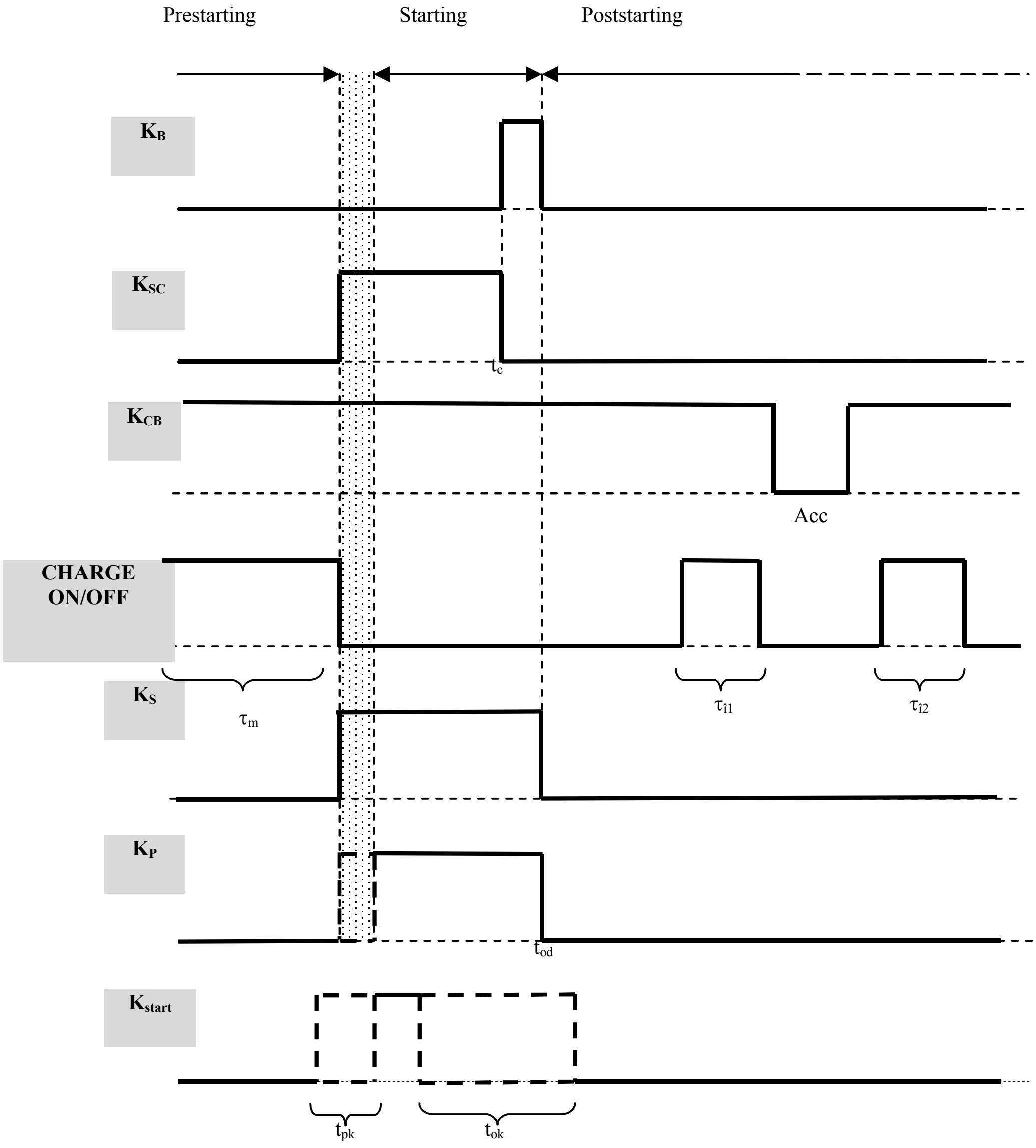

Fig.4. Time diagram for management strategy *SC-B.MaxP*.

The algorithm of the ICE starting system for *SC-B.MaxP* and *BSC-B.MaxP* strategies is described in Fig.5.

IV. Test and Results

The algorithms of the strategies *SC-B.MaxP* and *BSC-B.MaxP* were implemented on an experimental control and data acquisition platform (Fig.6), consisting of NI USB6009 control and data acquisition module, an original conditioning and operation module and a dedicated LabView software.

The data acquisition module NI USB6009 has the following characteristics:

- 8 analog inputs, 14 bits, 48kS/s;
- 2 analog outputs, 12 bits;
- 12 digital inputs/ outputs TTL/CMOS;
- a 32 bit timer at 5MHz;
- The impedance of analog inputs, 144kΩ.

The module connection to PC is done via a serial USB port.

The conditioning and operation module developed turns the analog process signals from 0-15V range into 0-10V range, the digital signals to logic 0V level for False and 5V for True and the switch in circuit of supercapacitor and battery is done using BTS555 (PROFET) transistor - Smart Highside High Current Power Switch Reversave.

The experiments were performed at ambient temperature of 0°C on a passenger car type Dacia 1310Li, fitted with a starter of 1.35HP rated power, 12V rated voltage, 380A short-circuit current [2] and an eight year old, 44Ah lead-acid battery with 15mΩ internal resistance.

The measurements investigated the starting system behavior according to aforementioned strategies.

From real operation data it was emphasized the positive collateral effect of increasing supercapacitor voltage upon dynamical behavior of the starter-ICE system.

Using a 40F supercapacitor with relatively high internal resistance of 20mΩ, loaded at 14.2V, the mean number of in-load compression – expansion cycles was 2.54 and the mean value of consumed energy was 634.23 J (between 2 and 6 compression expansion cycles and consumed energies in range 695.22 J – 1106.23 J) in comparison to ”battery only” starting with the mean number of in-load compression – expansion cycles of 4.57 and the mean value of consumed energy of 968.61 J (between 1 and 4 compression expansion cycles and consumed energies in range 464.59 J – 854.87 J). So, it may be concluded that the starting time was reduced in average with 45% compared with the starting time of the battery itself. Also the consumed energy was lowered with 35% compared to the consumed energy of the battery itself, in the same testing conditions.

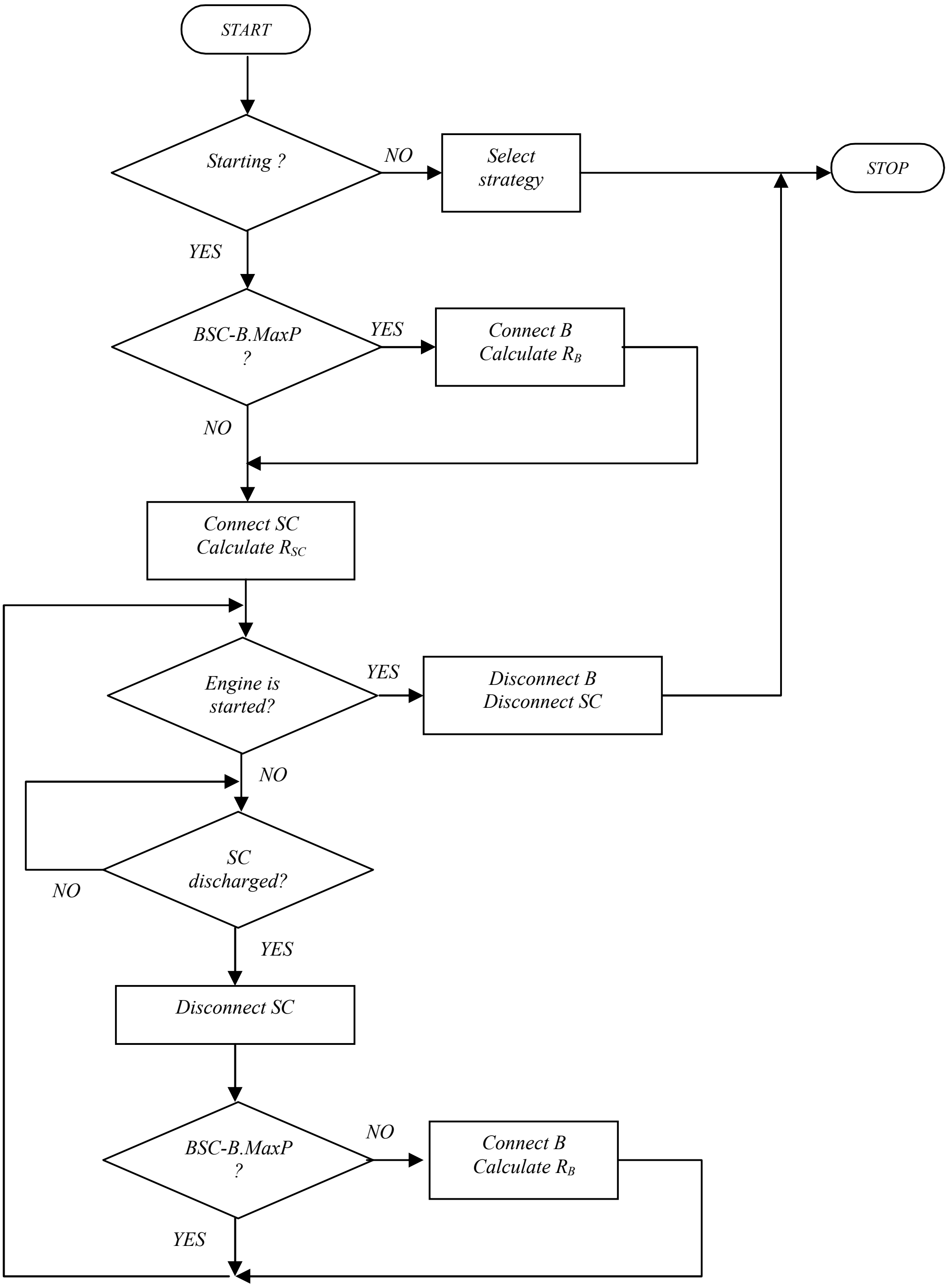

Fig.5. Algorithm of ICE starting system according to strategies SC-B.MaxP and BSC-B-MaxP.

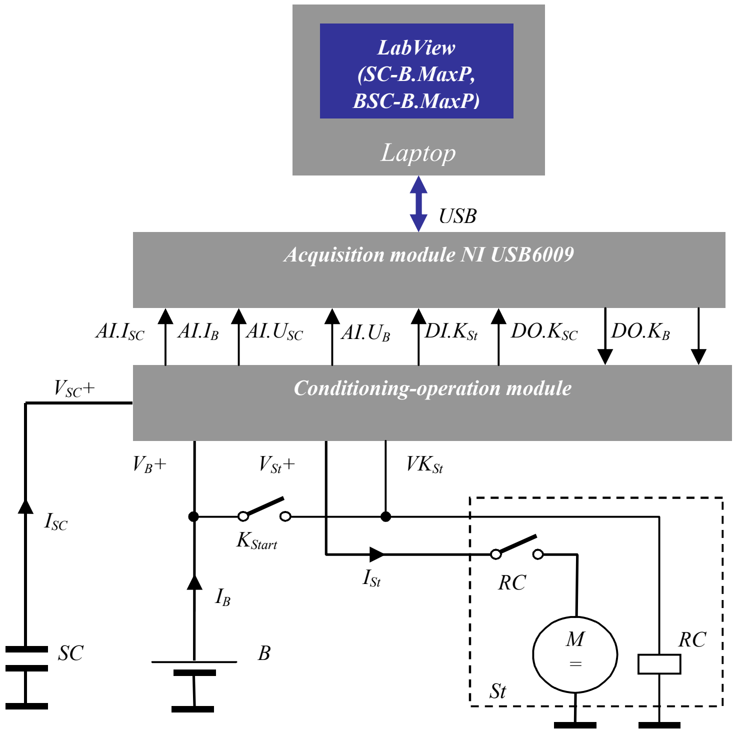

Fig.6. Scheme of data acquisition and control for the starting of hybrid battery – supercapacitor source.

V. CONCLUSIONS

It may be appreciated that the system for ICE starting management satisfies two of the major objectives of contemporary society: increase of energy efficiency and environmental protection through:

significant energy reduction at the ICE starting;

use of recovered energy for engine starting;

reduction of high pollutant potential materials associated to battery production due to increased life span and reduced capacity (also volume and mass) [3], [4], [5];

use of environmentally friendly components (super-capacitors) [6], [7];

Additionally, the system provides:

increased engine power in acceleration operation mode;

optimal operation of the alternator.

In automotive market there are reversible electric motors used as motors in ICE starting phase and as generator in ICE operation phase (post-starting phase) such as B-ISG (Belt-Integrated Starter Generator) manufactured by Integral Powertrain [8]. The extension of the strategies presented in this paper would allow to use the “starter- alternator” as motor and as secondary source of power in acceleration phase, based on recovery energy, thus increasing the vehicle total energy efficiency.

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