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STRATEGIES FOR PERFORMANCE OPTIMIZATION IN SUPERCAPACITOR-BASED ICE STARTING SYSTEMS

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Abstract **– The supercapacitors are recently developed electrical energy storage devices. Among many applications already developed, a promising application is the use of supercapacitors in the starting process of the internal combustion engines (ICE). In the paper three starting startegies are analyzed (maximum energy and maximum power – two cases) combining the supercapacitor and the battery of the vehicle. Experimental results are registered and included in the paper.**

Keywords: *Supercapacitor, battery, energy, power, internal combustion engine (ICE).*

1. INTRODUCTION

The supercapacitors are energy storage devices which can be used for the starting of internal combustion engines [1],[6]. This solution has the following advantages:

- Allows the use of old, out of order or almost depleted batteries which are unable to provide enough current to rotate the starter yet sufficient energy to charge up a supercapacitor.
- Reduces the role of the battery at high discharge currents. Thus, the service life of a battery working combined with a supercapacitor is 2-3 times longer than that of the same battery operating alone [4].
- Reduces the volume of the battery box on the vehicle by 10-30% and reduces battery weight by 25-40%.
- Complies with all environment demands. It emits no harmful substances during operation and storage [5].

This paper analyzes the optimal use of supercapacitors by applying three ICE starting strategies.

2. THE MAXIMIZED ENERGY SUPPLIED USING SUPERCAPACITOR STRATEGY (SC-B.MAXW)

This strategy includes the use of the supercapacitor during the first sequence of ICE starting, then the supercapacitor is disconnected and the battery is connected, when the energy supplied by the supercapacitor W_C equals the estimated starting energy W_P, in accord with the relation

$$W_C = \int_0^{t_C} U_L(t) \cdot I_L(t) \cdot dt = W_P \ ,$$

where $U_L(t)$ is the load voltage, $I_L(t)$ is the load current and t_c is switching time.

In this case, the existing possibilities are shown below:

- The energy supplied by the supercapacitor is sufficient for the starting process, and re-connecting of the battery is not necessary, Fig. 1. It is the case of warm starts, when the start doesn't require much energy;
- The energy supplied by the supercapacitor is insufficient for starting, but very close to the required amount. The additional energy supplied by the battery is negligible and thus the battery is less stressed, Fig. 2;
- For cold starts, the energy supplied by the supercapacitor is less than the required starting energy, Fig. 3. In this case, the battery is intensively used, like when starting without a supercapacitor, therefore the supercapacitor isn't necessary.

Conclusions on this strategy: For the case of cold starting, since the necessary energy to start the engine is greater than supercapacitor's available energy, the maximized energy supplied from supercapacitor strategy is often inadequate for engine starting.

The characteristics of the power supplied by a battery and a supercapacitor on a constant load, working either alone or combined, with the initial voltage on the supercapacitor greater or equal with the battery's open circuit voltage, shown in Figure 4, show the possibility of delivering maximum starting power to the load.

Considering the supercapacitor's low internal resistance, it can easily deliver the power peak required for ICE starting, during the first sequence, (Fig. 4.a).

For supercapacitors with high internal resistance, the power peak must be supplied by the supercapacitor combined with the battery connected in parallel (Fig. 4.b).

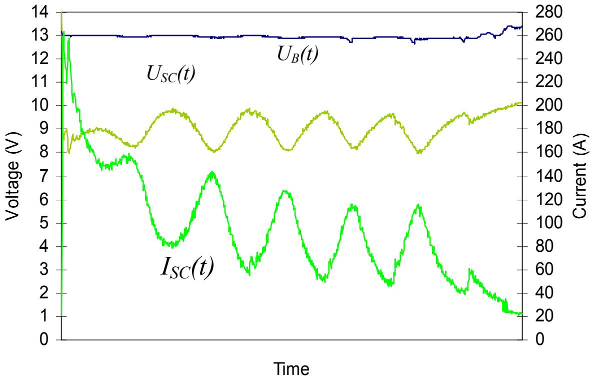

Figure 1: Warm engine starting using the SC-B.MaxW control strategy.

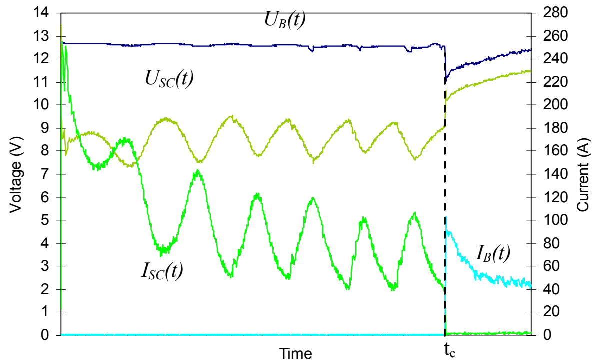

Figure 2: Engine starting when the energy of the supercapacitor is close to estimated starting energy, using SC-B.MaxW control strategy.

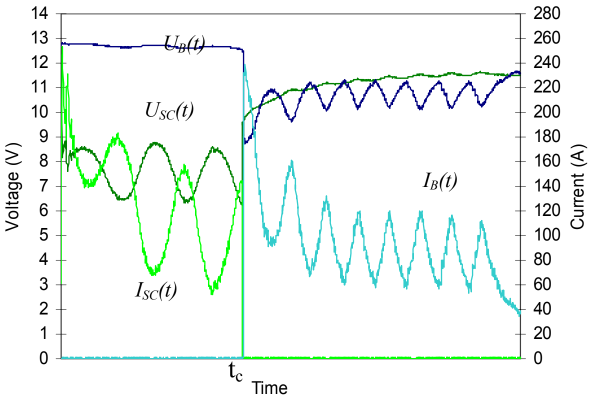

Figure 3: Cold engine starting using SC-B.MaxW control strategy.

3. STRATEGIES FOR MAXIMIZED POWER SUPPLIED TO THE LOAD

3.1. The SC–B.MaxP control strategy

In this case, as illustrated in Fig.4.a, the engine starting process begins with the supercapacitor and next, when the power supplied by the supercapacitor becomes equal with the battery's estimated power, the battery is switched on.

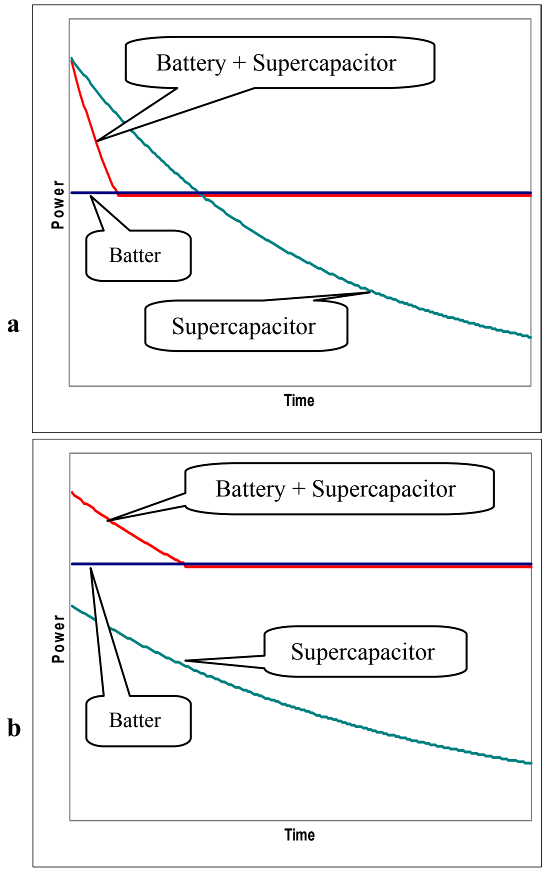

Figure 4: The power supplied to the load;
a) with the supercapacitor in the first sequence;
b) with the supercapacitor and the battery.

Since the power on the load R_L can be written as

$$P_L = R_L I_L^2 = U_L^2 / R_L ,$$

results that the switching time occurs when the voltage on the load $U_L(t)$, implicitly the supercapacitor voltage $U_{SC}(t)$, becomes equal to the battery's estimated voltage $U_{Be}(t)$, or when the current supplied by the supercapacitor $I_{SC}(t)$, implicitly the current through the load $I_L(t)$, becomes equal with the estimated current supplied by the battery.

The usage efficiency of the energy stored in a supercapacitor is the ratio between the supercapacitor energy required to start the engine W_U, and the amount of energy stored by the supercapacitor W_T, in accord with the equation

$$\eta_U = W_U / W_T \cdot 100$$

For constant parameters U_{B0} – battery open terminal voltage, U_{SC0} – initial supercapacitor open terminal voltage, R_L – load, R_{SC} – supercapacitor internal resistance and R_B – battery internal resistance, the estimated voltage is calculated by

$$U_{Be} = R_L \cdot U_{B0} / (R_L + R_B),$$

and the supercapacitor voltage results

$$U_{SC} = R_L \cdot U_{SC0} \cdot \exp\{-t / [(R_L + R_{SC}) \cdot C]\} / (R_L + R_{SC})$$

At the switching time from supercapacitor to battery, these voltages are equal. The supercapacitor open terminal voltage can be calculated using:

$$U_{SCopen} = U_{B0} \cdot (R_L + R_{SC}) / (R_L + R_B).$$

Since the energy supplied by the supercapacitor is $W_C = 1/2 \cdot C \cdot (U_i^2 - U_f^2)$, with U_i the initial supercapacitor open terminal voltage and U_f the final supercapacitor open terminal voltage, the efficiency $\eta_{U,B\text{-}SC}$ can be calculated by using the relation:

$$\eta_U = 100 - 100 \cdot \{(R_L + R_{SC}) \cdot U_{B0} / [(R_L + R_B) \cdot U_{SC0}]\}^2$$

The usage efficiency depends on U_{B0}, U_{SC0}, R_L, R_{SC} and R_B parameters, as shown in Fig. 5.

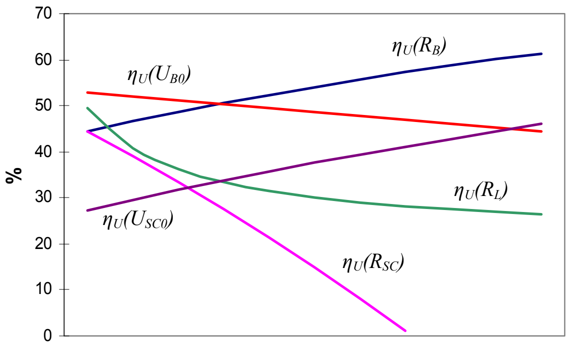

Figure 5: Supercapacitor efficiency during engine starting using the SC-B.MaxP control strategy.

The value of the supercapacitor can be determined by using the equation $W_{SC} = W_P / \eta_U$ where W_{SC} is the energy stored by the supercapacitor and W_P is the required starting energy.

The maximum power ratio supplied by supercapacitor and battery during engine starting can be calculated with the equation

$$rP_{\max,B-SC} = \{U_{SC0} \cdot (R_L + R_B) / [(R_L + R_{SC}) \cdot U_{B0}]\}^2.$$

The maximum power supplied from supercapacitor and the battery working alone is obtained during starter short-circuit regime and its dependence on U_{B0}, U_{SC0}, R_L, R_{SC} and R_B parameters, is shown in Fig. 6.

Conclusions on SC-B.MaxP control strategy: As shown in Figs 5 and 6, the SC-B.MaxP strategy with supercapacitor as the first source of electrical power is adequate in following cases:

- The use of old or depleted batteries working at low temperature, with increased internal resistance;
- The use of almost depleted batteries which have a low open terminal voltage;
- The use of batteries with lower capacity because these are not intensively utilized;
- High voltage charging of supercapacitors.This is the case of frequent starts, when the alternator charging voltage is 14,2V;
- The operation of the starter at, or near the short circuit regime;
- The use of supercapacitors with low internal resistance. Above 15mΩ equivalent series resistance of the supercapacitor, this strategy is impractical.

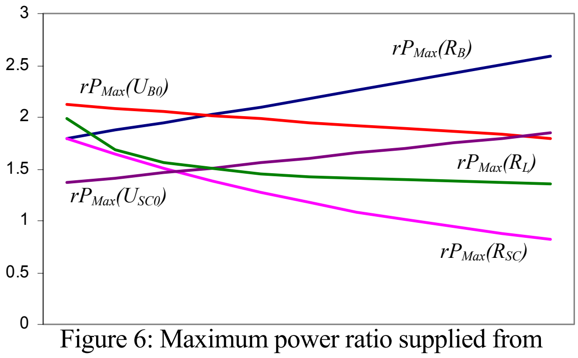

Figure 6: Maximum power ratio supplied from supercapacitor and battery during engine starting.

In the real situation [2], when the evolution over time of the equivalent series resistance (ESR) of the starter is like in Fig.7, the switching time t_c, can be estimated.

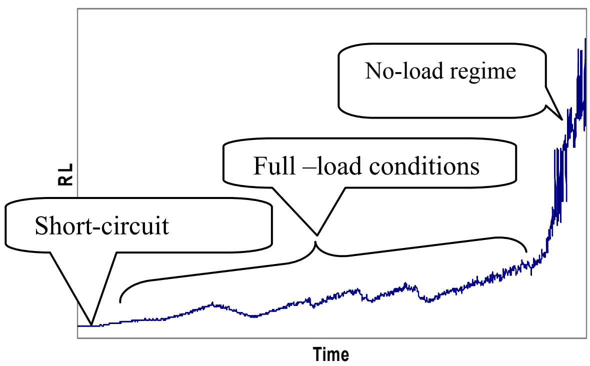

Figure 7: Equivalent resistence of starter (ESR) during starting process.

Since the behavior of the starter - energy source system is similar with the previous, Fig.8, the switching time should occur when the supercapacitor supplied power equals the estimated battery energy, working alone.

The instantaneous starter ESR is given by

$$R_L(t) = U_L(t) / I_L(t),$$

where $U_L(t)$ is the load voltage and $I_L(t)$ is the load current.

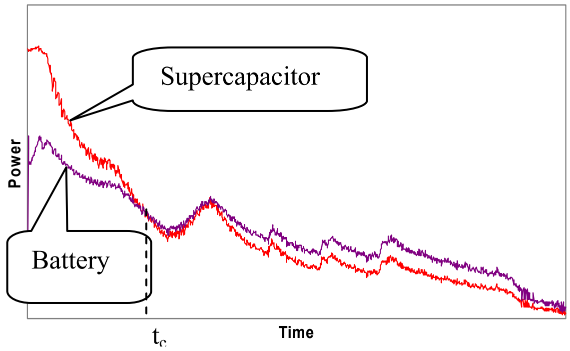

Figure 8: The supplied power of supercapacitor and battery during engine starting.

The estimated battery voltage $U_{Be}(t)$ is given by

$$U_{Be}(t) = U_{B0} - I_{Be}(t) \cdot R_B ,$$

where $I_{Be}(t)$ is the estimated load current supplied by the battery which is calculated by

$$I_{Be}(t) = U_{B0} / \left(R_B + R_L(t)\right).$$

Finally, using equation (1), the current equation results

$$I_{Be}(t) = U_{B0} \cdot I_L(t) / \left(R_B \cdot I_L(t) + U_L(t)\right).$$

3.2. The BSC–B.MaxP control strategy

In this case, as illustrated in Fig.4.b, the engine starting sequence begins when the supercapacitor is connected to the battery then disconnected after discharge. Fig.9 illustrates the evolution of supercapacitor and battery currents during the starting process for constant U_{B0}, U_{SC0}, R_L,, R_{SC} and R_B parameters.

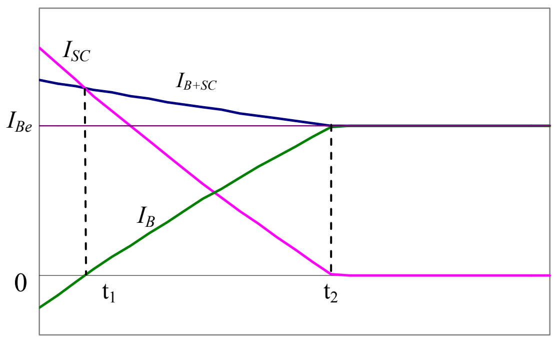

Figure 9: Evolution of supercapacitor and battery currents, working together during the starting process

During the first sequence, between *0* and t_1, the supercapacitor delivers energy to load and battery.
During the second sequence, between t_1 and t_2, both the supercapacitor and the battery are delivering energy to the load.
During the third sequence, after t_2, the battery delivers energy to the load only, since the voltage on the load is equal with the supercapacitor's open terminal voltage. Therefore it is unnecessary to disconnect the supercapacitor.
In real situations, when the load ESR takes values as shown in Fig.7, the supercapacitor must be disconnected since it will draw current from the battery thus diminishing the available power, as presented in Fig. 10.

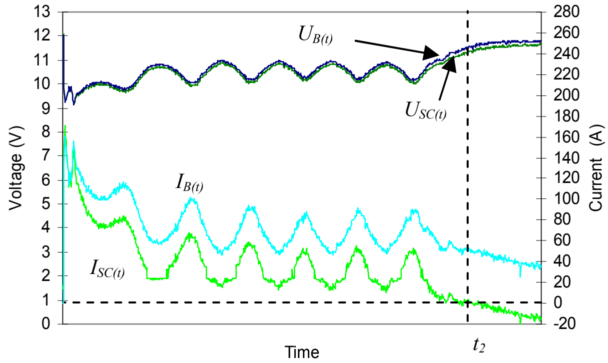

Figure10: The engine starting BSC-B.MaxP strategy, without disconnecting the supercapacitor.

The appropriate time to disconnect the supercapacitor occurs at $I_{SC}(t)=0$.
The usage efficiency for the BSC-B.MaxP strategy is calculated by the equation

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

and the maximum powers ratio supplied is

$$rP_{\max,BSC-B} = \left[(R_L + R_B)/R_L\right]^2 \cdot$$
$$\left\{R_{SC} \parallel R_L / (R_{SC} \parallel R_L + R_B) - U_{SC0} \cdot R_B \parallel R_L / \left[U_{B0} \cdot (R_B \parallel R_L + R_{SC})\right]\right\}^2$$

Conclusions regarding the BSC-B.MaxP strategy: This strategy can be used in the same conditions as the SC-B.MaxP strategy, but with lower usage efficiency and lower maximum powers ratio.
However, for supercapacitors with high internal resistance, the BSC-B.MaxP strategy may be an alternative for the SC-B.MaxP strategy.

4. CONCLUSIONS

All three control strategies were verified under experimental conditions using a LabView platform and an USB 6009 NI acquisition module.
The operating strategy which provides maximum power to the load during starting is an adequate strategy for engine starting and is recommended to be implemented with an embedded microcontroller-based system for controlling the hybrid engine starter system.

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