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Real-time control based on a CAN-bus of hybrid electrical systems

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Abstract: Power management of a one-converter parallel structure with battery and supercapacitor is addressed in this paper. The controller is implemented on a DSP from Microchip and uses a Controller Area Network (CAN) bus communication for data exchange. However, the low data transmission rate of the CAN bus data impacts the performances of regular power management strategies. This paper details an initial strategy with a charge sustaining mode for an application coupling a battery with supercapacitors, in which low performances have been witnessed due to the high sampling time of the CAN bus data. Therefore, a new strategy is proposed to tackle the sample time issue based on a depleting mode. Simulation and experimental results with a dsPIC33EP512MU810 DSP based on a 10 kW hybrid system proves the feasibility of the proposed approach.

Keywords: Hybrid electrical system; power management, battery, supercapacitors; Controller Area Network (CAN), Microchip DSP.)

1. Introduction

Many works based on hybrid electrical transport applications are performed essentially to face environmental issues. Most of the time, three kinds of hybridisation are pointed out: fuel cell (FC)/supercapacitors (SCs), fuel cell/battery (BT) or battery/supercapacitors [1–11] or more sources [12–14]. The connection of the power sources is subject to many power electronic topologies. Each of them has advantages and disadvantages regarding efficiency, flexibility, price, and weight. However, the main topologies are the one-converter or the two-converter hybrid structures. The key-point of such hybrid systems is the suitable energy management allowing a reliable and effective behaviour of the sources [2].

Whatever the power electronic topology (one- or two-converters topology), the most widespread requirement leads to smooth power on the main power source. In the case of a fuel cells (FC)/supercapacitors (SCs) [15] or FC/battery (BT) [16] or BT/SCs [4] associations, the FC or BT are going to operate with low current transients in order to improve the durability of the main power source [17–19].

This work focuses on the one-converter-based hybrid power system associating BT and SCs for civil or military transportation applications and is intended to perform in compliance with real conditions. Batteries have been widely adopted as the main power source for full electric vehicles [20] for their high energy density [21]. In this work, a Lithium Ion Fer Phosphate (LiFePO₄) battery was selected for its safety, good environmental compliance, long lifetime, high discharge current, high power density and cost effectiveness when compared to other mature technologies [22].

However, the high price and heaviness of the battery when compared to supercapacitors justify that batteries and supercapacitors can be interfaced in order to maximize the benefits of the two

34 components, i.e. limit the cost and weight of the battery pack, nevertheless with an increase of the total
35 volume [23]. Therefore, SCs are used as an assistant to the main source to deliver power during fast
36 acceleration or braking, and also allows to limit the battery current and temperature by an appropriate
37 assistance of the SCs during high current and high temperature of the battery pack. Moreover, the
38 operation of the battery at high current needs to be avoid in order to impact positively the durability
39 of the battery [20,24].

40 The implementation of these controllers is generally done with high-performance DSP/ μ C
41 with internal current/voltage controllers, PWM outputs to control the converters and its own
42 current/voltage sensors. In such configuration, the implementation does not introduce issues.
43 Nowadays, embedded and networked automotive bus communication such as the Controller Area
44 Network (CAN) is widely used for vehicle networks. It is used for the communication between the
45 controllers, the sensors and the actuators [25–29]. The controller can retrieve data from each component
46 (i.e. voltage, current, temperature of the BT and SCs) and the DSP send periodic messages necessary to
47 control the DC/DC converter [30–33]. It should be pointed out that the sampling frequency of the data
48 on the CAN bus is relatively low compared to a regular implementation on a DSP/ μ C that use analog
49 inputs and the PWM peripherals [34]. In fact, in the case of a regular implementation, the CPU and the
50 peripherals have a sampling time nearly equal to 100μ s for the inner current loops and nearly equal to
51 1ms for the outter voltage loops. Therefore, the performances of the controllers are not degraded by
52 the sampling (see [3] for more information and [35,36] for theoretical details). In practice, the CAN bus
53 data sampling frequency is defined by the manufacturers of top-of-the-shelf equipment and modifying
54 it in a wide range is not always possible, at least in a range defined by the manufacturer.

55 is not always possible, at least in a defined range. It follows that designers need to face such issue
56 by defining an appropriate controller with low data transmission rate [28]. Therefore, this paper aims
57 to detail experimental knowledge about the power management of a hybrid system controlled by a
58 Controller Area Network (CAN) bus communication where one fundamental issue to be addressed
59 concerns the closed-loop control stability under sampling with such network control [29].

60 The main contribution of this paper is focused on the description of an initial strategy [37] with a
61 charge-sustaining mode. Experimental results show that the proposed controlled [37] failed under high
62 sampling time and quantization of the CAN bus data that deteriorate the closed-loop performances.
63 It is the reason why a new rule-based strategy is proposed in this paper to tackle the sample time
64 issue based on a depleting mode. Experimental results based on a 10 kW hybrid power pack coupling
65 battery and supercapacitors prove the feasibility of the proposed approach.

66 The paper is organized as follows. In section 2, a 10 kW experimental system is detailed.
67 Section 3 details a regular controller for power management of a hybrid electrical system, where the
68 closed-loop controller performance degradations are being emphasised with the CAN bus. Therefore, a
69 sampled-data controller based on a charge depleting mode is described in section 4, where experimental
70 results are presented to show the effectiveness of the proposed controller.

71 2. Hybrid power pack structure

72 The hybrid power pack structure under study dedicated for civil or military applications is
73 composed of a 3,84kWh Lithium battery (LiFePO_4 , 48V, 80Ah) from E4V directly connected on the DC
74 bus and supercapacitors (SCs) from Maxwell (BMOD0063P125B08, 125V, 63F). The SCs equipment
75 is connected to the DC bus by an inverter from VISEDO (PowerBOOSTTM series DC/DC converter
76 PBO-M-250-x, 250kW max at 750V with liquid cooling, set at 12kW max without cooling and low DC
77 voltage). The power electronic components are standard MOSFET modules and the PWM switching
78 frequency is set at 4kHz. The E4V battery have a CAN 2.0A protocol adjustable between 100kbs to
79 500kbs, while the PowerBOOST from VISEDO have CAN 2.0A or B with adjustable baud rate between
80 100kbs to 1Mbs.

81 The battery can provide 1C (80A) during steady state without significant overheating, while 2C
82 (160A) during 10 min and 3C (240A) during 40 s at early life of the battery pack and 23°C operation.

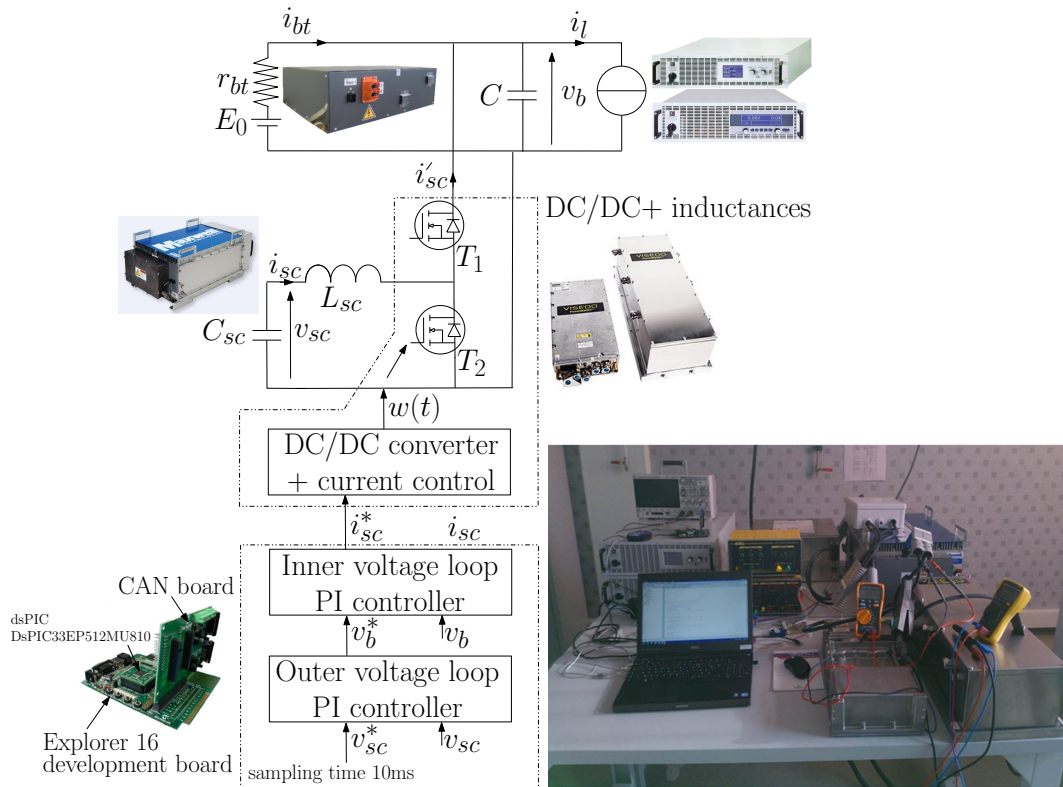


Figure 1. Experimental setup and regular controller of a one-converter hybrid system.

83 As regular batteries, these data decrease over the time due to the cycling and the batterie temperature
 84 [38] and this knowledge can be integrated into the controller for a real-time update of the saturation
 85 functions. On another side, the SCs can provide 140A during few minutes and thus can assist the
 86 battery during over-battery current to limit the battery temperature.

87 A programmable electronic load (EA-ELR 9080-510) and power source (EA-PSI 9080-340) from
 88 EA Elektro-Automatik are connected to the DC bus to emulate a reversible current source, i.e. emulate
 89 traction and regenerative mode. The electronic load has a rated power of 10.5kW, 80V can be obtained
 90 at low current and 510A at low voltage always limited by the maximal nominal output power. The
 91 power source has a rated power of 10kW, 80V-340A, same comment for the current/voltage/power
 92 limitations as the load. Finally, Figure 1 shows the experimental system and Table 1 gives the electric
 93 characteristics of the 10 kW hybrid system.

94 All the control and the monitoring data are transmitted by the battery and PowerBOOST converter
 95 through one CAN bus network. It is worth to mention that the VISEDO inverter integrates an internal
 96 current control loop, where the desired set point current i_{sc}^* of the SCs is transmitted through the CAN
 97 bus. The different nodes involved are the battery pack, the supercapacitors, the DC-DC converter and
 98 the reversible load (parallel coupling of a load and a power supply).

99 The three first variables of table 2 are measurements (DC bus voltage v_b , SCs voltage v_{sc} , battery
 100 current i_{bt}) available on the target test bench. These data are obtained from the CAN bus according
 101 to the indicated features (sampling time, precision, data type). Using these variables regardless
 102 the load power requirement, the controller computes the output control variable of the SCs current
 103 (i_{sc}^*) in order to manage the battery current and the state of charge of the SCs. It is important to
 104 mention that the sampling time, precision and data type of the measurements provided by these top
 105 of the shelf equipments cannot always be changed in a wide range (see table 3). Thus, the behaviour
 106 of a continuous controller under sampling is not always reproducible. In fact, the sampling time
 107 requirement for regular power management controllers are nearly equal to 500 μ s to 2ms (see [3] for

Table 1. Electric characteristics of the 10 kW hybrid system.

E4V Battery pack			
v_n	48 V	E_n	3,84 kWh
C_n	80 Ah	mass	50 kg
Super-capacitors			
v_n	125 V	E_n	140 Wh
C_{SCs}	63 F	mass	61 kg
Electric load			
v_{max}	80 V	P_{max}	10.5 kW
i_{max}	510 A	mass	31 kg
Power supply			
v_{max}	80 V	P_{max}	10 kW
i_{max}	340 A	mass	20 kg
DC-DC converter			
DC bus voltage range	0-800 V	P_n	250 kW
i_n	300 A_{RMS}	mass	15 kg
Switching frequency	4-6 kHz	Operating temperature	-40...105 ⁰ C

Table 2. CAN bus and data characteristics.

Data	Sampling[ms]	Precision	Data type
v_{sc}	54.2	± 0.05 V	8 bits
v_b	109	± 0.01 V	8 bits
i_{bt}	109	± 0.1 A	8 bits
i_{sc}^*	10	± 1 A	8 bits

Table 3. CAN bus and data characteristics.

Baud rate [kps]	Data frames on the CAN bus	Minimum sampling time [Hz]	Maximum sampling time [Hz]
250	10	0.5	10

108 the performances degradation of continuous controllers under sampling). It means that the sampling
 109 time of the data coming from the components to control are nearly 100 times more important than the
 110 desired values. In such industrial case study, authors have face such issues by proposing an adequate
 111 rule-based controller.

112 The choice of the control board was done according to four criteria: portability, scalability,
 113 effectiveness and economical solution. Therefore, an Explorer 16 Development board from
 114 Microchip has been opted that allows to test various (16 or 32 bits) DSP and microcontroller. The
 115 dsPIC33EP512MU810 has been implemented for the reasons cited above associated with a PICtail Plus
 116 card interface for the CAN bus.

117 3. Regular power management

118 3.1. Problem statement

119 Figure 1 represents a parallel power electronic system understudy composed of only one-converter.
 120 The controller is designed to provide a smooth current transition on the source with the lower current
 121 dynamic, namely the battery in this study. Also, the power between the battery and the SCs needs to
 122 be appropriately shared to match the power load requirement. The maximal currents of the battery
 123 and SCs, the state of charge (SoC) of the SCs, the battery temperature must be taken into account as
 124 constraints in the controller design [37]. This regular controller refers to charge-sustaining mode, where

125 SCs assist the battery during power transient and the SoC of the SCs fluctuates but it is maintained at
126 a certain level. Consequently, the control structure is based on three nested loops as shown in Figure 1,
127 namely: (see [37] for details about the controller design):

- 128 • The VISEDO PowerBOOST have its internal current controller and the DSP transmits the
129 supercapacitors current reference through the CAN (Controller Area Network) bus to the DC/DC
130 converter.
- 131 • A PI inner voltage loop controller computes the supercapacitors current reference i_{sc}^* to maintain
132 the DC bus voltage at the desired value.
- 133 • A PI outer voltage controller adjusts the DC bus reference voltage to control the SoC of the SCs
134 and implicitly control the dynamic of the battery current. It is important to mention here that the
135 DC bus of a one-converter structure need to fluctuate in order to change the battery current in
136 comparison with a two-converters structure where the DC bus voltage is constant.

137 Finally, the two PI controllers are sampled at 10 ms which corresponds to the minimum sampling
138 period to transmit the supercapacitors current reference through the CAN bus.

139 3.2. Experimental results

140 Figure 2 shows an experimental result for a nominal operation, i.e. a battery current lower than
141 the maximum values. The battery provides current during the first part of the transient. Later, the SCs
142 react during the second part and let the battery provide energy during the steady state.

143 Figure 3 shows another experimental result when the battery current exceed the maximum values
144 defined by the designer. In that case, the SCs assist the battery during the transient as in Figure 2
145 and continue to sustain the battery as long as the load current is greater (in absolute value) than the
146 acceptable limits of the battery current. Here as an example, the maximum current of the battery have
147 been fixed at -15A during the charge mode (see Figure 3.a) and +15A during the discharge mode (see
148 Figure 3.b). The SCs absorb (or provide) the current that the battery could not absorb (or provide) in
149 order to maintain the battery current at the desired value. As mentionned before, the knowledge of the
150 number of cycling and the batterie temperature (obtained through the CAN bus) can be integrated into
151 the controller to compute in real-time the maximum current of the battery for the saturation functions.

152 Experimental results show that the expected smoothing behaviour of the battery current is not
153 fulfilled as shown in Figures. 2 and 3. Because the battery is connected in parallel to the DC bus
154 without DC/DC converter and the periodic data sampling is too important, it turns out that the battery
155 provide current during the first part of the transient until the SCs reacts. It follows an undesirable
156 behaviour during load current transient. A analysis shows that the high sampling time of the transmit
157 CAN frame data v_{bt} (109ms, see data in Table 2) has been clearly identified as responsible for this
158 unexpected behaviour.

159 3.3. Discussions

160 Experimental results have shown that the control of a one-converter structure with a CAN bus is
161 not suitable and lead to such low performance results. Some of the solutions listed below are feasible:

- 162 • *Components software modifications*: The most effective solution consists on a software update of
163 the sampling time of the data send by all the components at around 1 to 5ms if this option is
164 allowed. This option lead to good performances of the hybrid system.
- 165 • *Additional sensors*: If the first solution is not feasible for top of the self-equipment, additional
166 current and voltage sensors associated with local microcontrollers can be added. This option
167 leads to a flexible solution for the designer but increase the cost and reduce the reliability due to
168 additional materials.
- 169 • *Additional converter*: A two-converters structure is probably an effective solution is such
170 configuration because it allows a separate control of the two current sources and therefore

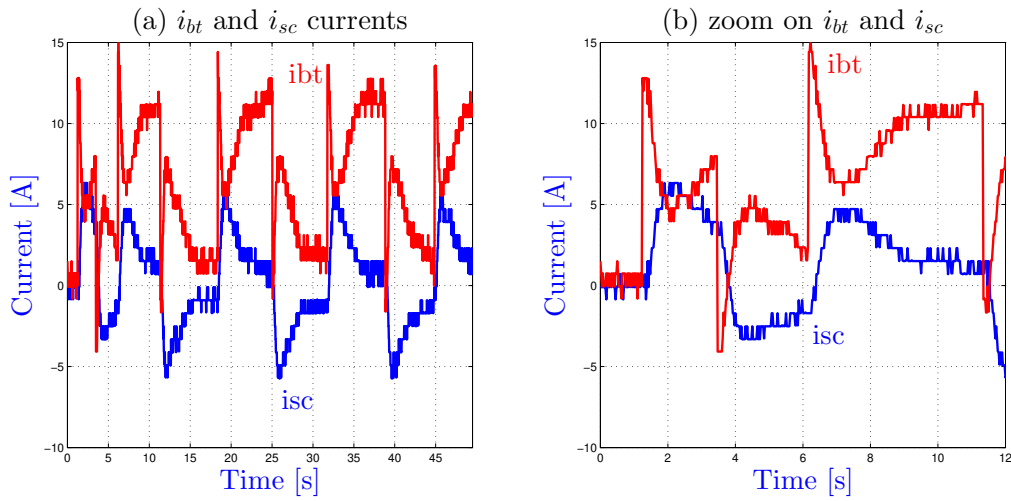


Figure 2. Experimental results with the regular controller - nominal condition.

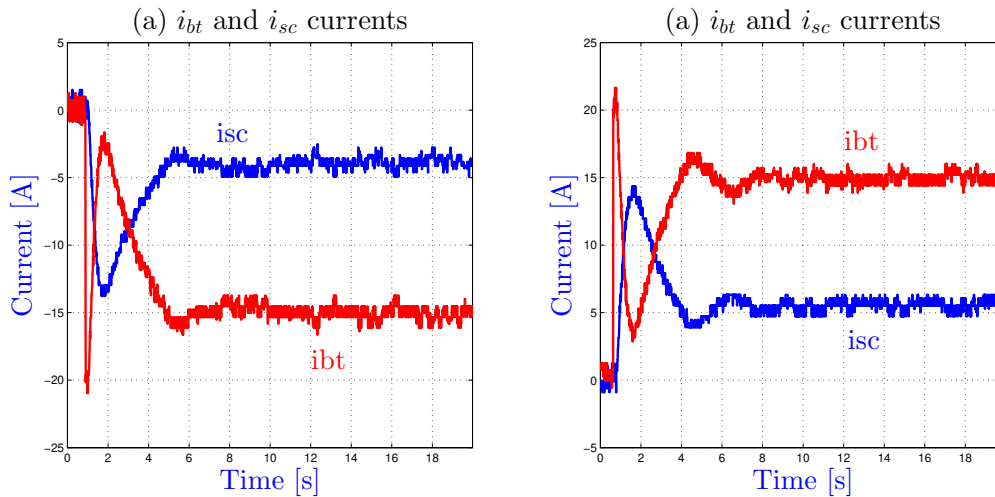


Figure 3. Experimental results with the regular controller - over-battery current.

171 doesn't lead to high battery peak current during load current transient. However, this solution
 172 increases the cost, weight, volume and decrease the efficiency and reliability.
 173 • *Enhanced sampling-time controller*: Papers [3,35,36] have shown that the asymptotic stability of
 174 closed-loop systems could be preserve despite high value of the sampling time of controllers.
 175 This option is strongly interesting but is not under the scope of this work with an industrial point
 176 of view.

177 All the above solutions have been rejected since these top of the self-equipments can not be
 178 updated and the addition of sensors increase the cost and reduce the reliability. Therefore an alternative
 179 controller has been under study base on a rule charge depleting operation.

180 4. Charge depleting mode with SoC recovering of the SCs

181 4.1. Problem statement

182 The proposed controller switch between a charge depleting and a charge-sustaining modes
 183 according to the maximum current allowed for the battery:

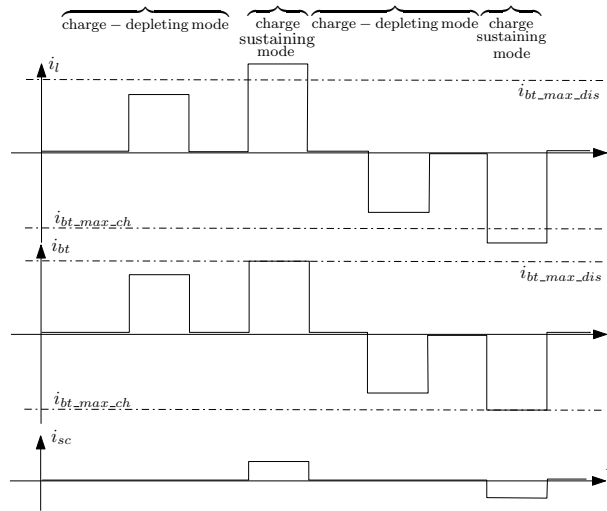


Figure 4. Charge-depleting and Charge-sustaining modes.

- 184 • Whenever the battery pack current remains within the allowable bounds (maximum battery
 185 current during discharge $i_{bt_max_dis}$ and charge $i_{bt_max_ch}$) the batteries satisfy the load power
 186 requirement and the SCs doesn't give any assistance as shown in Figure 4. To recover the SoC
 187 of the SCs and thus the assistance, the controller maintains at a certain level the SoC when the
 188 current battery is in the allowed bounds.
 189 • Whenever the battery current is out of these bounds, the controller switch to charge-sustaining
 190 mode and the surplus current is assigned to the SCs [20,24].

191 It turns out that the control is based on two controllers that are selected according to the operating
 192 conditions, as shown in Figure 5:

- 193 • Controller 1 is activated when the battery current is higher than the threshold $i_{bt_max_dis}$ during a
 194 discharge operation or $i_{bt_max_ch}$ (in absolute value) during a charge operation.
 195 • Controller 2 is activated when the battery current remains in the bounds $[i_{bt_max_dis}, i_{bt_max_ch}]$,
 196 i.e. normal operation of the hybrid system.

197 We need to mention that the thresholds $i_{bt_max_dis}$ and $i_{bt_max_ch}$ can be variable, i.e. function of
 198 the allowed time of overcurrent greater than 1C (see section II) and function of the battery temperature
 199 obtained through the CAN bus.

200 Controller 1 compute the desired current i_{sc}^* in order that the battery current i_{bt} does not exceed
 201 the maximum value, while controller 2 manage the SoC of the SCs. It follows that the decision block is
 202 based on the state machine as shown in Figure 6.

203 4.2. Design of the controller

204 4.2.1. State machine

205 The state machine block depicted Figure 5 is detailed in Figure 6, where states are:

- 206 • State 0: the battery current (i_{bt}) doesn't exceed the maximum value $[i_{bt_max_ch} - \delta i_{bt}, i_{bt_max_dis} +$
 207 $\delta i_{bt}]$ and the SCs voltage is also in the bounds $[v_{sc}^* - \delta v_{sc}, v_{sc}^* + \delta v_{sc}]$, i.e. normal operation of the
 208 hybrid system. Therefore, the SCs is set equal to zero.
 209 • State 1: the battery current (i_{bt}) is higher than a user-defined threshold $i_{bt_max_dis} + \delta i_{bt}$. Therefore,
 210 flag `flag_control_ibt_max_dis` is set to one and controller 1 is activated until the battery current is
 211 lower than $i_{bt_max_dis} - \Delta i_{bt}$.
 212 • State 2: the battery current (i_{bt}) is higher in absolute value than a user-defined threshold
 213 $i_{bt_max_ch} - \delta i_{bt}$. Therefore, flag `flag_control_ibt_max_ch` is set to one and controller 1 is activated
 214 until the battery current is greater than $i_{bt_max_ch} + \Delta i_{bt}$.

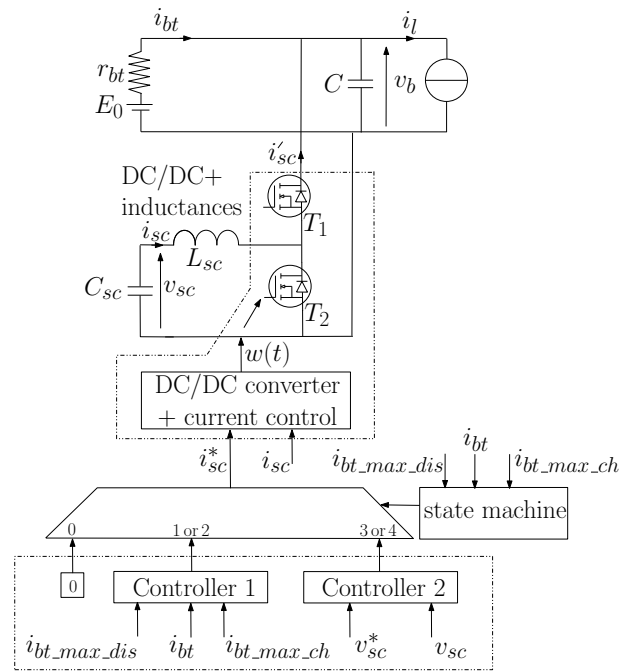


Figure 5. Controllers of the charge depleting mode with SoC recovering of the SCs.

- 215 • State 3: the battery current (i_{bt}) doesn't exceed the maximum value [$i_{bt_max_ch} - \delta i_{bt}, i_{bt_max_dis} +$
 216 δi_{bt}] but the SCs voltage is too high. Therefore, flag `flag_control_vsc` is set to one and controller 2
 217 is engaged, until the SCs voltage remains to the nominal value or the battery current (i_{bt}) exceed
 218 the maximum values [$i_{bt_max_ch} - \delta i_{bt}, i_{bt_max_dis} + \delta i_{bt}$].
 219 • State 4: the battery current (i_{bt}) doesn't exceed the maximum value [$i_{bt_max_ch} - \delta i_{bt}, i_{bt_max_dis} +$
 220 δi_{bt}] but the SCs voltage is too low. Therefore, flag `flag_control_vsc` is set to one and controller 2
 221 is engaged, until the SCs voltage remains to the nominal value or the battery current (i_{bt}) exceed
 222 the maximum values [$i_{bt_max_ch} - \delta i_{bt}, i_{bt_max_dis} + \delta i_{bt}$].

223 It is important to mention that adequate values of the thresholds δi_{bt} and Δi_{bt} need to be adopted
 224 to avoid chattering phenomenon.

225 4.2.2. Controller 1

226 When flags `flag_control_ibt_max_dis` or `flag_control_ibt_max_ch` are set to one, controller 1 base
 227 on a PI is engaged in order to inject or absorb the current that the battery could not inject or absorb.
 228 Figure 7 shows the sampling-time PI controller where i'_{sc} represent the SCs current at the output of the
 229 boost converter.

230 So that the SCs provide current as quickly as possible, the integral action S of the PI-controller is
 231 initialized at a right value, i.e. so that i'_{sc} is equal to $i_{bt} - i_{bt_max_dis}$ or $i_{bt} - i_{bt_max_ch}$ at the initialization
 232 step of the controller:

- 233 • if `flag_control_ibt_max_dis` is set to one, S is set to $i_{bt} - i_{bt_max_dis}$
 234 • if `flag_control_ibt_max_ch` is set to one, S is set to $i_{bt} - i_{bt_max_ch}$

235 Finally, the SCs voltage fluctuates within a range [v_{scL}, v_{scH}]. If the SCs voltage exceeds these
 236 limits, constraints are added to reduce the SCs current during charge or discharge. Figure 8 shows a
 237 specific saturation function that represent the saturation block of Figure 7.

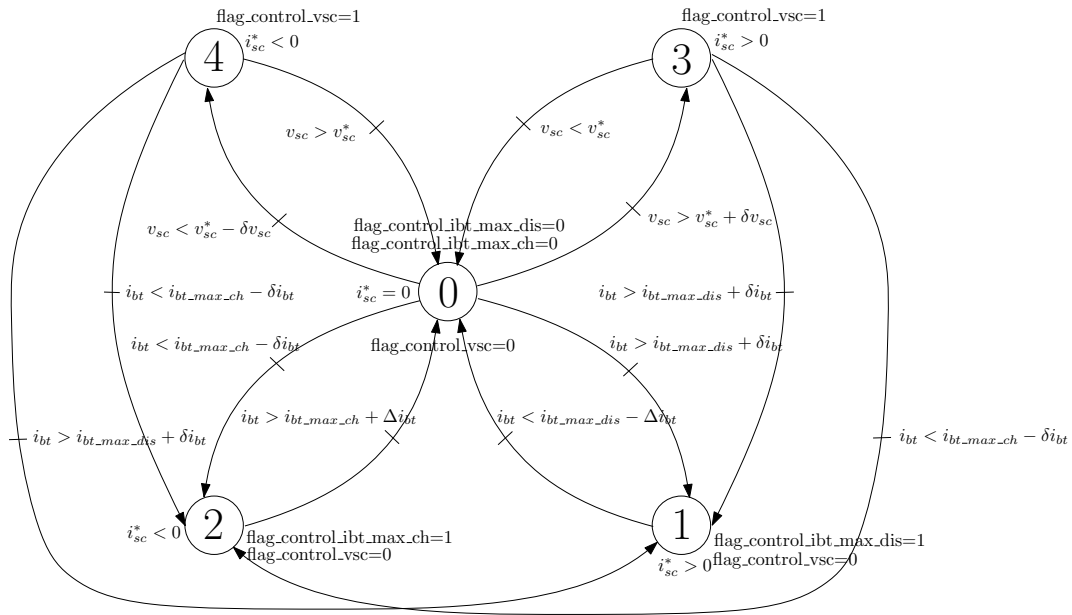


Figure 6. State machine of the controller.

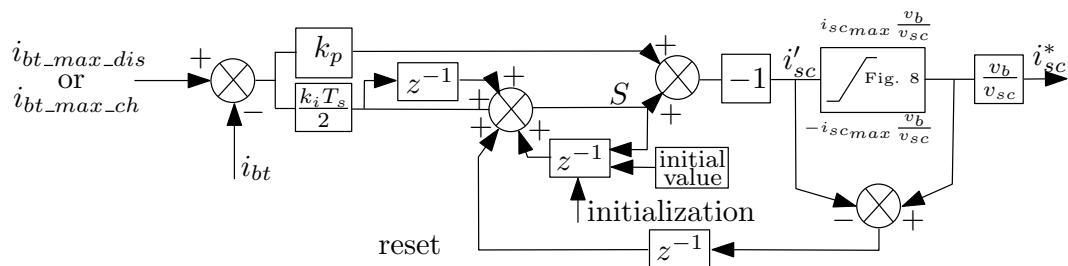


Figure 7. PI controller 1.

238 4.2.3. Controller 2

239 When flag `flag_control_vsc` is set to one (states 3 or 4), the SCs voltage is bring back at its nominal
240 value v_{sc}^* :

- Whenever $v_{sc} \geq v_{sc}^* + \delta v_{sc}$, controller 2 computes a positive value of the SCs current as follows:

$$i_{sc}^* = i_{scmax} \min\left(1, \frac{v_{sc} - v_{sc}^*}{\delta v_{sc}}\right) \quad (1)$$

241 so that the SCs is discharged at the maximum value i_{scmax} as long as $v_{sc} \geq v_{sc}^* + \delta v_{sc}$ and later
242 discharge the SCs by progressively reducing i_{sc}^* until reaching $i_{sc}^* = 0$ when $v_{sc} = v_{sc}^*$. This
243 behaviour is highlighted in the Figure 9.

- Whenever $v_{sc} \leq v_{sc}^* - \delta v_{sc}$, controller 2 computes a negative value of the SCs current as follows:

$$i_{sc}^* = -i_{scmax} \min\left(1, \frac{v_{sc} - v_{sc}^*}{-\delta v_{sc}}\right) \quad (2)$$

244 so that the SCs is charged at the maximum value $-i_{scmax}$ as long as $v_{sc} \leq v_{sc}^* - \delta v_{sc}$ and later
245 charge the SCs by progressively reducing i_{sc}^* until reaching $i_{sc}^* = 0$ when $v_{sc} = v_{sc}^*$.

246 Controller 2 is a static controller based on equations 1 and 2 (see also Fig. 9 for a graphical
247 representation). When the system is in state 3 or 4, the battery provides power to the load and also
248 charge/discharge the SCs function of the state (i.e function of the SCs voltage) with the maximum
249 allowed current of the SCs. It would have been possible to use a regular controller to compute i_{sc}^* but

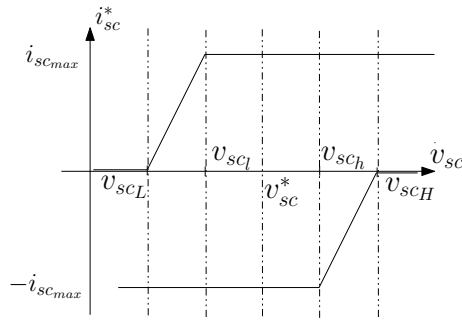


Figure 8. Definition of the maximum SCs current ($i_{sc_{max}}$) according to the SCs voltage for controller 1.

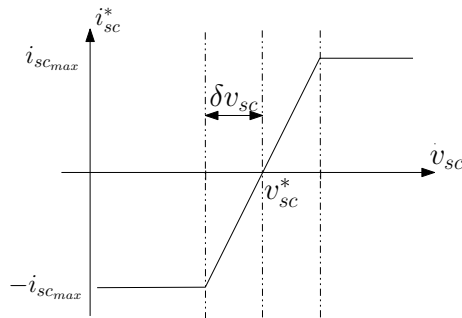


Figure 9. Definition of the SCs current according to the SCs voltage for controller 2.

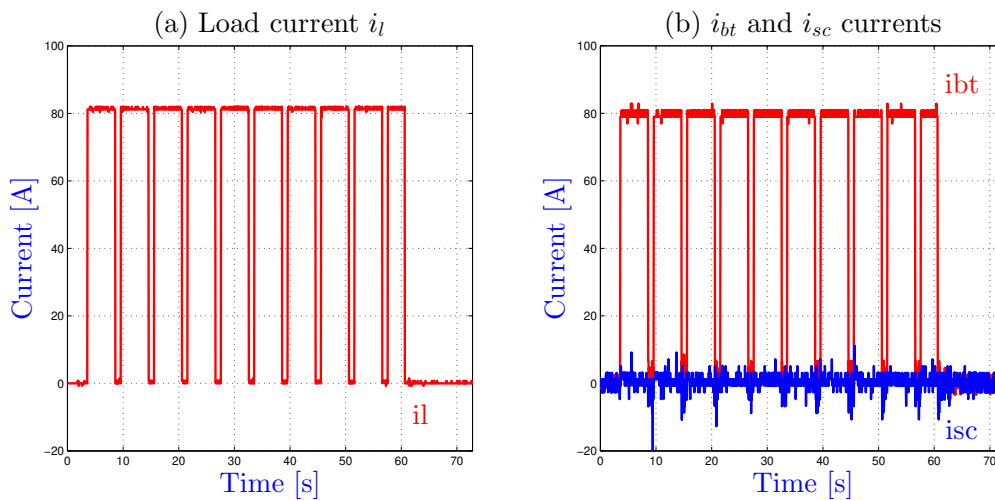


Figure 10. Experimental results during nominal condition - state is equal to 0.

250 the static controller based on equations 1 and 2 is interesting because it charge/discharge the SCs with
 251 the maximum allowed current of the SCs. It reduces the time needed for charging/discharging the
 252 SCs.

253 4.3. Experimental results

254 Experiments have been conducted in the test bench where the battery current has been limited at
 255 90A during charge and discharge of the battery. All the controller parameters are as follows: $\delta i_{bt} = 1A$,
 256 $\Delta i_{bt} = 10A$, $v_{sc}^* = 32V$, $v_{scL} = 27V$, $v_{scI} = 28V$, $v_{scH} = 36V$, $v_{scH} = 37V$, $\delta v_{sc} = 2V$, $i_{sc_{max}} = 100A$,
 257 $k_p = 0.001$ and $k_i = 0.114$. The parameters of the PI controller have been defined empirically. It
 258 is important to mention that the response time of the PI-controller is reduced; this is achieved by

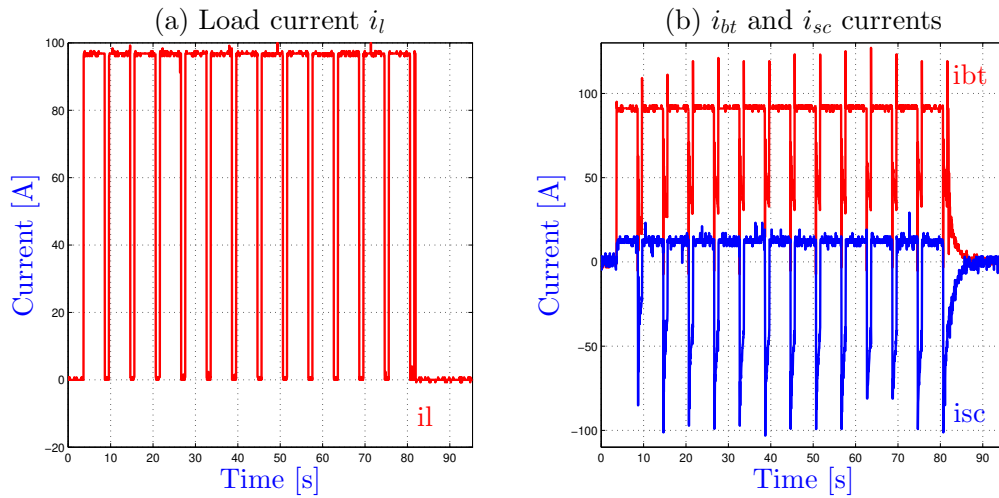


Figure 11. Experimental results during nominal condition.

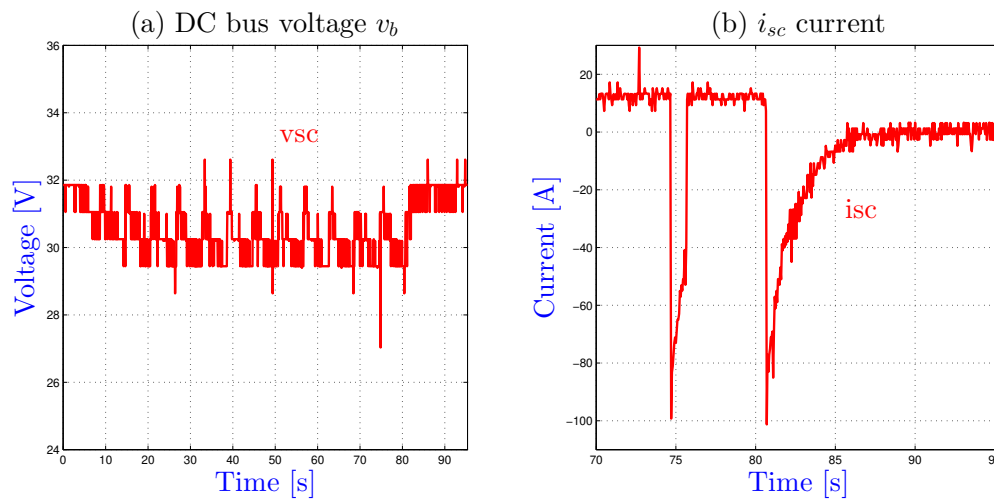


Figure 12. Experimental results during nominal condition.

259 initializing integral term S with an appropriate value that results in the battery current value converging
 260 fast to $i_{bt_max_dis}$ or $i_{bt_max_ch}$.

261 Figure 10 shows an experimental result for a load current profile composed of 5s at 80A
 262 and 1s at zero current, i.e. for operating points where the battery current remains in the bounds
 263 $[i_{bt_max_ch}, i_{bt_max_dis}]$ and the SCs voltage is in the bounds $[v_{sc}^* - \delta v_{sc}, v_{sc}^* + \delta v_{sc}]$ (state 0). As expected,
 264 the SCs current is null and the battery supplied all the energy to the load.

265 Figure 11 shows an experimental result for a load current profile composed of 5s at 95A and 1s
 266 at zero current, i.e. for operating points where the battery current is greater than $i_{bt_max_dis}$ (state 1)
 267 and operating points where the SCs can be recharge (state 3). As expected, the SCs current provides
 268 current to the load for state equal to one. We can notice in Figure 12 that the SCs voltage is regulated at
 269 the desired value v_{sc}^* equal to 32V and that the SCs current is always initialized at a value different
 270 from zero (see comments in section IV.B.2) to improve the convergence of i_{bt} to $i_{bt_max_dis}$.

271 In fact the commutation from controller 2 to controller 1 needs an adequate re-initialization of
 272 the integral term of the PI controller and the commutation from controller 1 to controller 2 doesn't
 273 introduce difficulty. When controller 1 is engaged, thanks to the initialization flag in Figure 7, the

274 integral term S is initialized at $i_{bt} - i_{bt_max_ch}$ or $i_{bt} - i_{bt_max_dis}$ according to the system state. As
275 noticed just above, this reduce the convergence time of i_{bt} to $i_{bt_max_dis}$ or $i_{bt_max_ch}$ through a fast drop
276 of the battery current as shown in Figure 11.b.

277 We can noticed that the results are acceptable despite the important sampling-time of the data
278 and that the current battery remains to the limit current value $i_{bt_max_dis}$ or $i_{bt_max_ch}$ defined by the
279 designer. We have shown that the PI controller (state 1 and 2) have been engaged so that the SCs assist
280 the battery as long as the SoC of the SCs is not too high or low (see Figure 8). Furthermore, every time
281 that the SCs can be charge or discharge (i.e. the battery current i_{bt} doesn't exceed the allowed value),
282 controller 2 is activated.

283 5. Conclusion

284 A single converter-based hybrid system energy management through Controller Area Network
285 (CAN) bus communication has been studied. Experimental results show that charge-sustaining
286 controller have low performances due to the sampling-time of the CAN bus data. Therefore, a
287 rule-based strategy has been proposed in order to tackle with sample-time issue based on a depleting
288 mode, where experimental results based on a 10kW hybrid power pack coupling battery and
289 supercapacitors prove the feasibility of the proposed approach.

290 As mentioned in the paper, the CAN network suffers from the low transmission rate and low
291 quantification of data. In the current scenario, the increasing number of functionalities grows in
292 all type of vehicles because of the decentralization of functions and leads to an over-loaded CAN
293 network. CAN FD and FLEXRAY have emerged as new trend to comply with real-time constraints
294 [34]. However, such adaptation does not seem the solution to control electrical systems with high
295 performances and safety. Therefore the question of centralized/decentralized critical functions in an
296 electrical vehicle need to be further investigated.

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