Experimental test on a fuel cell – supercapacitor hybrid power supply for a digital still camera

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Abstract – **Today, the consumer market calls for high-performance power supply systems. Existing sources and technologies are not abreast of portable electronics trends, thus pressing both the academic and industrial research to focus on innovative technologies. Customers' requirements lead to a growing interest in longer-lasting power, fast transient response power supply systems and a minimization of system weight, volume and cost. In this paper, a fuel cell–supercapacitor hybrid power supply for a Digital Camera is proposed, although the control algorithm can be efficiently applied to any portable device. The power management system also provides the load levelling function, optimizing the hydrogen consumption. The stack current is directly controlled and a multiple-steady-state control technique is implemented, optimizing the hybrid source performances. The hybrid power supply is neither affected by the fuel cell transient response nor by the supercapacitor bank runtime. Experimental results on a laboratory prototype, powering a Fujifilm S5500 digital camera, are shown.**

Index terms- fuel cell, modeling, control systems, DC-DC power conversion, consumer electronics, transient analysis, power supplies, power system modeling, power electronics.

I. INTRODUCTION

Today, the consumer market calls for high-performance power supplies. Existing sources and technologies are not abreast of portable electronics trends, thus pressing both the academic and industrial research to focus on innovative technologies. In each category, i.e. notebook, cellular phones, digital cameras, the leader product is stated by higher running times, lower size, weight and cost. At the same time, due to the increasing complexity of available functions, higher and higher power capability is required by manufacturers. A trade-off between pressing and conflicting requirements on power supply design is brought about. Among emerging technologies, fuel cells are considered the most promising choice to replace lithium ion and other rechargeable battery systems in many hand-held devices [1-4]. Fuel cells potentially ensure unlimited running times. Fuel cell powered devices should not be connected to the electrical grid for recharge and fuel cartridge replacement enables full portability. Due to manufacturing items, keeping low the fuel cell cost, size and weight results in a limited power capability and the use as stand-alone sources for portable devices is thus forbidden. In the last few years, hybrid power sources have received a great deal of attention and they are considered the most promising source of energy for portable applications. Two basic sources are coupled to form a hybrid power source: a high energy density and a high power density source. The goal is to optimize the power and energy performances of the composite power source. Each basic source supplies the load current under a specific working condition, as steady state or transient, according to its own stand-alone performances. If properly controlled, the hybrid source is neither affected by the transient response of the high energy density basic source nor by the runtime of the high power density basic source. If compared with stand-alone basic sources, the hybrid source demonstrates longer running time, faster transient response, higher power and energy density [5-8]. Adding a DC/DC converter between the basic sources leads to several advantages. The DC-DC converter plays an important role in regulating the output voltage and managing the power sharing between the two elements. A detailed comparative analysis of a battery/supercapacitor hybrid in passive and active configuration is reported in [9] and the active hybrid configuration ensures an increase in power capability, a better regulation of the output voltage, a minimization of the current ripple and a reduction of the system weight and volume. Yet, in literature, all described hybrid systems are designed and tested with regular pulsed load, characterized by a square wave current profile whose frequency and width are stated as design ratings. The parameters knowledge and the periodicity of load power consumption are usually assumed as design ratings by control algorithms, even if these assumptions are not verified by commercial devices. If tested with commercial devices, in the worst case these algorithms lead to an accidental turning-off or alternatively to a weak optimization of the hybrid power source in terms of both running time and power capability.

In this paper, a fuel cell–supercapacitor hybrid power supply for a Digital Camera is proposed and the control algorithm can be efficiently applied to any portable device. Like any other portable device, the digital still camera (DSC) behaviours as a pulsed load, whose power consumption profile is strictly dependent on the user-selected function and thus unpredictable. Unlike the others, the DSC power consumption profile is characterized by three possible stand-by modes (playback, photography and movie mode) each one requiring a different average current value. Consequently, the DSC represents the worst-case load for hybrid power supply design and optimization. No assumptions are made on DSC working and useful information about the DSC state is

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reconstructed by sampling the output voltage, thus optimizing the hybrid source performances. Even under stress, an accidental turning-off is avoided. A digital camera simulation model has been defined to avoid experimental failure. The load model provides a user interface allowing the selection of the desired function under system level simulation, thus emulating the effective device working and the unpredictability of the user command. The digital camera model ensures system simulation as closely as possible to the effective working conditions. The importance of load device modelling is also confirmed by simulation and experimental results matching.

The power management system also provides the load levelling function, optimizing the hydrogen consumption. The hybrid power supply is neither affected by the fuel cell transient response nor by the supercapacitor bank runtime. Experimental results on a laboratory prototype, powering a Fujifilm S5500 digital camera, are shown.

II. HYBRID POWER SUPPLY DESIGN

A fuel cell – supercapacitor active hybrid power supply, powering a Fujifilm S5500 digital camera has been designed and tested. The control loop provides a load levelling function, keeping the fuel cell current constant under load transients. The stack current is directly controlled and an innovative multiple-steady-state control technique is implemented, optimizing the hybrid source performances. The fuel cell supplies the standby current of each available mode of the digital camera, as playback, photography and movie mode. The supercapacitor meets the load transient power demand, required for each function running, as taking picture, bracketing, zoom and so on. A recharge state is provided to avoid accidental digital camera turn-off. Due to the innovative control algorithm, the hybrid power supply is neither affected by the poor transient response of the fuel cell nor by the short supercapacitor bank runtime. To ensure system level simulation, each component is accurately modelled. Fig. 1 shows the active hybrid source. The Fuel cell is connected in series with a buck converter and the supercapacitor bank. The buck converter ensures an input current lower than the output current, thus optimizing the fuel cell current value corresponding to each DSC state. The supercapacitor value has been designed to ensure system working under the worst-case. Even under the worst-case scenario, the supercapacitor should supply the load current under function transients avoiding the accidental turning-off of the electronic device. By the load power consumption profile analysis, the worst-case function has been detected. The load nominal voltage is 6V while turning-off voltage is 4.2V. The supercapacitor value has been designed to ensure a negligible supercapacitor discharge under the worst-case function, obtaining a 4.6F value. Since the maximum value of the supercapacitor voltage is 2.5V, three supercapacitors should be connected in series to match the load nominal voltage.

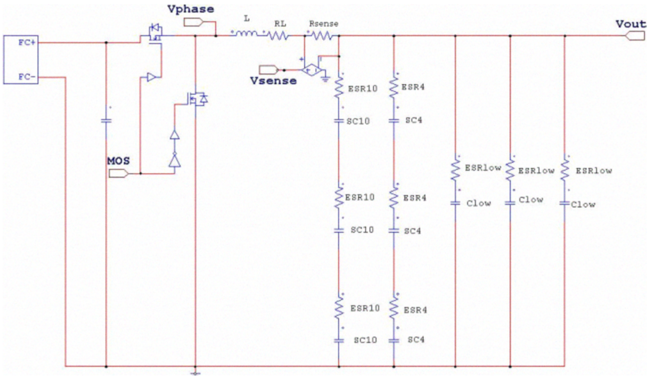


Fig.1. Active hybrid source model.

Two parallel branch of Maxwell PC5 and PC10supercapacitors are connected. A charge balancing circuit is provided on the experimental prototype.

An accurate digital camera model, reproducing the Fujifilm S5500 power consumption profile, has been implemented in MATLAB/Simulink [10]. A static and dynamic fuel cell model, including temperature effects, has been defined in PSIM and used for system level simulation [11]. The control system is modelled in PSIM. The MATLAB/Simulink-PSIM co-simulation tool is used to simulate the entire system as closely as possible to the effective working conditions.

The goal is to maintain fuel cell current constant under load current changes. The DSC has three standby modes: playback, photography and movie mode. Each mode can be maintained indefinitely active without any function running (as taking picture, frame viewing etc.) and each one is characterized by different power consumption: 220mA for playback mode, 330mA for photography mode and 410mA for movie mode. To avoid accidental turning-off, each stand-by mode power requirement is supplied by the fuel cell and each available function is supplied by the supercapacitor. The fuel cell current is thus kept constant except for DSC stand-by mode changes. After all, the control loop optimizes the hybrid source performance by keeping constant at the minimum value, turning-off risk and DSC mode permitting.

A. *Control system design*

The multiple steady-state working control requires a current loop voltage reference management subsystem which adapts the reference value according to the actual DSC mode. The reference subsystem reconstructs the necessary information by sampling the power supply output voltage. In Fig. 2 the simulation model of the control section is shown. The error amplifiers of voltage and current loop are modelled by transconductance amplifiers (OTA) using PSIM library components: a summer generating the differential error signal, a multiplier modelling the OTA gain, a signal limiter modelling the OTA linearity range, a voltage controlled current source generating the OTA output current signal, a resistance Ro modelling the output and load resistance of the OTA.

The RfCf network is introduced as compensation network and the PWM control is implemented. The diode D makes the voltage loop a continuous working loop and the current loop a pulsed working loop. Current loop interferes under a function transient only.

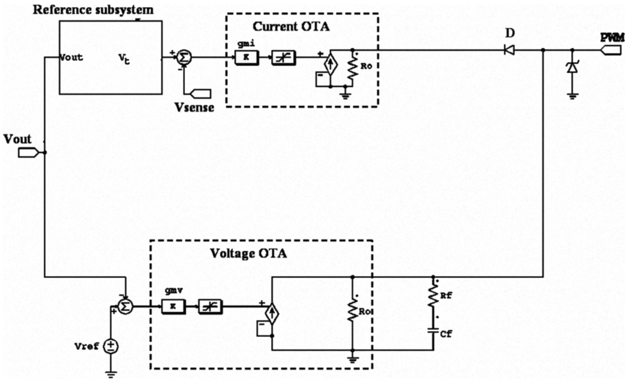


Fig. 2. The control loop simulation model implemented on PSIM.

The control loop parameters are determined by the frequency domain analysis and by the analysis of the non-linear interface between the voltage and current loop. The interface diode turns on under the condition:

$$I_I \cdot R_0 \leq I_V \cdot R_0 - V_\gamma \tag{1}$$

where V_γ is the diode threshold voltage, I_I is the current OTA output signal, I_v is the voltage OTA output signal. The turn on condition can be also expressed as:

$$g_{mI} \cdot e_I \cdot R_0 \leq g_{mV} \cdot e_V \cdot R_0 - V_\gamma \tag{2}$$

where e_V and e_I are the voltage and current differential input signal, respectively, while g_{mI} and g_{mV} are the current and voltage OTA gains, respectively. The current loop action should prevail over the voltage loop action even if the voltage loop is completely upsetted so ensuring the load leveling function. The diode turning-on condition can be expressed as:

$$g_{mI} \cdot e_{I,\min} \cdot R_0 \leq I_{LIM} \cdot R_0 - V_\gamma \tag{3}$$

where I_{LIM} is the voltage loop OTA maximum output current and $e_{I,\min}$ is the desired tolerance on current control. By choosing a current OTA gain that verifies the (3) for a minimum current error value equal to one half the steady-state inductor current ripple, a peak current control is achieved. If the instantaneous inductor current overcomes the current reference value, the interface diode will turn on, the current loop will prevail over the voltage loop and the inductor current will be kept constant to the current reference value, achieving the load leveling function. Under a load transient with constant reference value, if the required load current I_{LOAD} exceeds the reference value $I_{L,th}$, the inductor current will be regulated at $I_{L,th}$ value and the current $I=I_{LOAD}-I_{L,th}$ will be supplied by the supercapacitor until the end of load transient or a reference value change. Consequently, under a load transient the fuel cell current is maintained constant for hybrid power source optimization algorithm: the fuel cell supplies a constant load except for reference value changes. The voltage OTA gain is chosen by frequency domain analysis to ensure system stability and an adequate bandwidth.

B. *Reference Management Algorithm*

The proposed control technique maintains constant the fuel cell load except for DSC standby mode changes. The reference subsystem outputs the current reference signal evaluating the actual DSC working mode by sampling the output voltage only. Therefore, the subsystem should detect load transients but above all the subsystem should mark function and mode transients. As a result of function transients, the voltage reference value of the current loop should be kept constant. As a result of mode transients, the voltage reference of the current loop should be adapted to the reconstructed DSC mode average current value. Note that function transients show a limited execution time while mode transients could be maintained indefinitely active. By choosing a reference subsystem clock period longer than the highest running time of available functions, the control algorithm is not sensitive to function transients. According to the reconstructed information, the subsystem acts on the current loop reference value by increasing, decreasing or keeping it constant. Four possible steady-states, coded by two bits, are provided: 200mA, corresponding to DSC playback mode standby power consumption, 350mA, corresponding to DSC photography mode standby power consumption, 440mA, corresponding to DSC movie mode standby power consumption, 700mA, corresponding to a safety state, reached if an excessive supercapacitor discharge occurs to prevail an accidental DSC turning-off. Four possible actions, coded by two bits, are provided: increase by one, increase by two, decrease by one and keep constant the reference voltage. The action is decided by the subsystem algorithm. Fig.3 shows the reference subsystem model, digitally implemented by logic gates.

The output voltage sample is compared with two threshold levels, accurately designed to prevent an excessive discharge, to obtain information about the instantaneous charge state of the supercapacitor bank. Up, mid and down are binary signal coding the output voltage sample: up is active if the output voltage is over both levels, mid if the sample is in the middle, down if the output voltage is lower than the lowest level. By comparing the two last samples of binary signals, the charge process is monitored and the DSC state can be evaluated. The subsystem decides which action should be performed on the voltage reference, coded by *a* and *b* bits. The new voltage reference bits are determined by the old reference bits and by the action bits. The reference bits feed a digital-to-analog converter which outputs the analog voltage reference value. In Table I the action decision algorithm is summed up and in

Table II the action coding algorithm is shown. The proposed algorithm reproduces information about the DSC state by monitoring the charge and discharge profile of the supercapacitor bank.

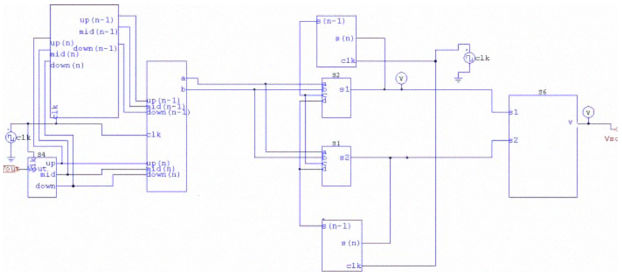


Fig. 3. Reference subsystem simulation model.

TABLE I
ACTION DECISION ALGORITHM

(n-1) Active Sample	(n) Active Sample	Action
Up	Up	Keep constant
Up	Mid	Increase by one
Up	Down	Increase by two
Mid	Up	Keep constant
Mid	Mid	Increase by one
Mid	Down	Increase by two
Down	Up	Keep constant
Down	Mid	Keep constant
Down	Down	Increase by two

TABLE II
ACTION CODING BITS

a bit	*b* bit	Coded Action
0	0	Keep constant
0	1	Increase by one
1	0	Increase by two
1	1	Decrease by one

III. EXPERIMENTAL RESULTS

A laboratory prototype has been realized to test the efficiency of the innovative control loop. The experimental test has been performed in the worst case, stressing the DSC working, for example under multiple and consecutive function running. As an example, Fig. 4 shows voltage and current waveforms under taking picture function without flash. The load current (in violet) under taking picture function is characterized by an impulsive profile and the peak current value is 720mA, while the average current value is 443mA.

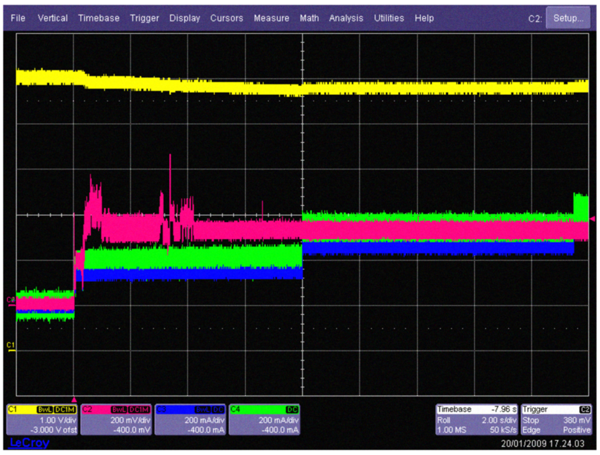
Fig. 4 .The inductor current (in green), the load current (in violet), the fuel cell current (in blue) and the output voltage (in yellow) under taking picture function.

Fig. 5 shows voltage and current waveforms under turning-on in playback mode. System starts at playback mode state. The load current (in violet) is characterized by an impulsive profile. The inductor current (in green) is limited to the playback stand-by mode. The supercapacitor supplies the impulsive current to the load.

Fig. 5 .The inductor current (in green), the load current (in violet), the fuel cell current (in blue) and the output voltage (in yellow) under turning-on in playback mode.

The inductor current (in green) is limited to the photography stand-by mode. The supercapacitor supplies the impulsive current to the load. Fig. 6 shows voltage and current waveforms under turning on in photography mode while system starts at playback mode state. The supercapacitor supplies the load with the difference between the load current and playback mode stand-by current. Due to the supercapacitor discharge, the reference subsystem recognizes the effective DSC stand-by mode and increases the current limit value up to the photography stand-by mode. The supercapacitor state of charge is kept constant but the output voltage is lower than the nominal load voltage.

Consequently, the control system increases by one the voltage reference, avoiding an accidental turning-off and allowing a supercapacitor recharge. When the nominal value is reached, the reference subsystem decreases the reference voltage to the photography mode.



C1 BwL DC1M 1.00 V/div -3.000 V ofst
C2 BwL DC1M 200 mV/div -400.0 mV
C3 BwL DC 200 mA/div -400.0 mA
C4 DC 200 mA/div -400.0 mA
Timebase -7.96 s Roll 2.00 s/div 1.00 MS 50 kS/s
Trigger C2 Stop 380 mV Edge Positive
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Fig. 6 .The inductor current (in green), the load current (in violet), the fuel cell current (in blue) and the output voltage (in yellow) under turning on in photography mode.

IV. CONCLUSIONS

In this paper, a fuel cell–supercapacitor hybrid power supply for a Digital Camera is proposed, although the control algorithm can be efficiently applied to other portable devices. The power management system also provides the load levelling function, optimizing the hydrogen consumption. The stack current is directly controlled and a multiple-steady-state control technique is implemented, optimizing the hybrid source performances. The hybrid power supply is neither affected by the fuel cell transient response nor by the supercapacitor bank runtime. Experimental results on a laboratory prototype, powering a Fujifilm S5500 digital camera, are shown. The fuel cell current is kept constant at the minimum allowable value considering turning-off risk and the DSC stand-by mode.

The robustness and the efficiency of the power supply system have been tested. As experimental results show, an accidental DSC turn-off is always avoided. The device run time depends on hydrogen availability only, so optimizing the hybrid source energy density. The transient response of the hybrid power supply depends on the transient response of the power density basic source, the supercapacitor, and it is independent of the transient response of the fuel cell, the low power density basic source. The designed control loop optimizes the hybrid source performances in terms of both power and energy density.

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