Real-time aTmega microcontroller-based simulator enabled hardware-in-the-Loop for fuzzy control dual-sources HESS

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Abstract. In this paper, a real-time simulation of a hybrid energy storage system (HESS), using a hardware-in-the-loop (HIL) platform is proposed. The HESS is in a semi-active configuration including Supercapacitors (SC) controlled by a chopper and a Li-ion battery. The model organization was performed using Energetic Macroscopic Representation (EMR). The energy flow management is provided by an energy management strategy (EMS) based on fuzzy logic controller (FLC), developed in C language for ARDUINO and uploaded into the aTmega microcontroller. The main objective of this work, is to evaluate, on the one hand the performances of the proposed architecture, by reducing the factors that impact the battery performances. On the other hand, the program and the platform (HIL) developed, through the comparison of results with those of the simulation, performed on MATLAB/SIMULINK under ECE-15 cycle.

1 Introduction

Transportation requires a large proportion of the world's total energy. Most of this energy comes from oil. While the majority of other economic sectors, such as energy and industry, have reduced their emissions since 1990, the transport sector is responsible for more than a quarter of the EU's total greenhouse gas emissions [1]. This means that mobility is responsible for a significant part of greenhouse gas emissions and contributes significantly to climate change.

Actually, the reduction of the harmful effects related to transport, represents a strategic objective for the manufacturer. One of the most effective solutions is the inclusion of the cleanest means of transport, such as electric vehicles (EV). Nevertheless, this means of transport requires very important enhancements, in particular the performance of the on-board energy sources. In literature, battery lifespan is a major challenge for developers [2]. Indeed, a variety of solutions have been proposed, such as the integration of SCs [3] that support the power peaks, recovered during braking and required during fast acceleration, and the implementation of EMSs that ensure an efficient energy split in a dual-sources configuration. Thus, these solutions ensure a reduction of the battery state of charge (SoC) variations [4], fluctuations in the current supply and the reduction of battery stress. Hence, reducing stress and optimizing the main source lifespan. EMS is a key issue in improving the EV performance. Indeed, several approaches can be adopted [5]: rule-based EMSs such as fuzzy logic controllers (FLC) [6-7], deterministic rule-based EMS [8] applied to HESS control, and optimization-based EMSs such as dynamic programming (DP) [9] and genetic algorithms [10].

This work presents the evaluation results and a real-time simulation of a developed 1.5kW HESS model. This simulation uses a HIL solution based on an Arduino 2560 board aTmega microcontroller [11].

This paper is organized as follows: the modeling and control of the studied system is presented in section 2. Section 3 is dedicated to the description of the developed FLC-based control. The development and implementation process of the HIL simulation is described in Section 4. The results and discussions are presented in Section 5 and Section 6 concludes the paper.

2 Modeling and control of the studied HESS

2.1. System modeling

The proposed system is a 1.5kW semi-active [12] HESS, based on a dual source configuration (Li-Ion battery, SCs) (see Fig. 1). it includes a bidirectional DC-DC converter used to control SCs block. The 100Ah battery is in direct connection with DC bus. The power source characteristics are shown in Table 1 and Table 2.

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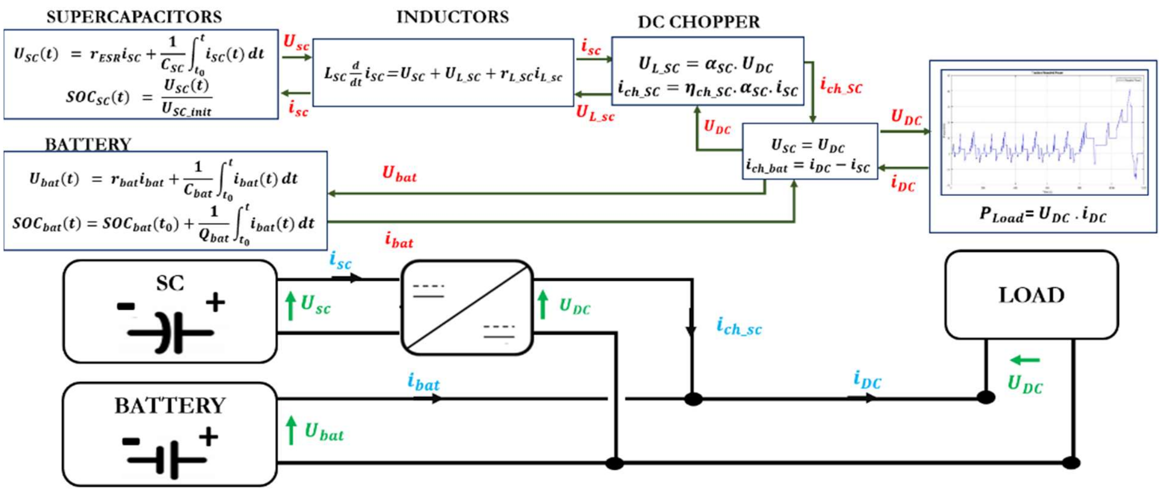

Fig. 1. Components models and scheme of the proposed HESS.

The battery represents the main source of the studied HESS. Thus, a simplified model is considered in this study, which consists in considering the battery as a capacitor with high capacity and internal resistance. A model for the SoC_{bat} calculation is implemented in order to follow its performances during the simulation. The SCs block uses a generic model represented by an internal capacitance and the equivalent series resistance (ESR) [13].

The SoC_{SC} is calculated based on the nominal voltage of the SCs. In addition, the DC-DC converter used in this model, is a bidirectional chopper, able to supply the DC bus, and to recharge the SCs by controlling the U_{DC} voltage. The DC-DC converter uses an average model [14] and a smoothing inductor L_{SC}.

Finally, in order to simplify the proposed model, the load model is represented by an equivalent source with a maximum power of 1.5kW. Thus, the load is modeled by a controllable current source.

2.2 System Control

In order to realize the control layer, the EMR approach [15] is adopted. This technique allows to organize the HESS model in subsystems according to their multi-physics nature. Indeed, referring to the inversion-based rules of the EMR approach [15], the construction of the control layer can be performed using the studied model's EMR. This allows to realize the maximum control structure (MCS) (see Fig. 2).

According to the proposed HESS's MCS model, i_{bat_ref} represents the control parameter. In addition, the current smoothing inductor (L) of the chopper, represents an accumulation element characterized by energy storage block, which requires a controller in the control layer. In this case, the controller type IP is implemented.

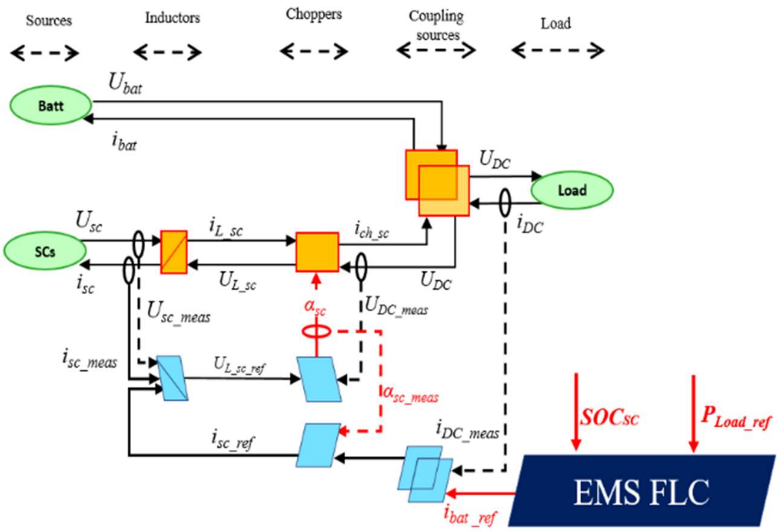

Fig. 2. MCS of HESS's EMR.

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3 Energy Management Strategy

Initially, the methodology adopted in this paper has two main objectives:

- The development of an EMS able to define an appropriate current reference, which guarantees the reduction of its fluctuations, and the optimization of battery lifespan,
- The validation of the FLC code developed, implemented and executed in microcontroller, via the HIL simulator.

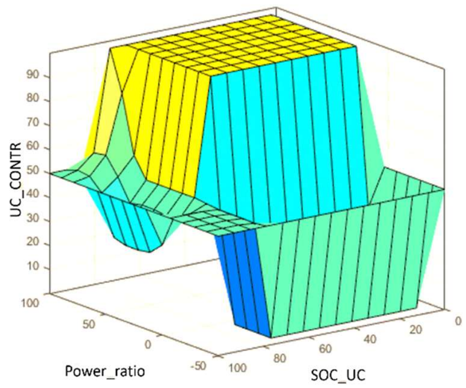

Fig. 3. Rules-base of the proposed FLC-EMS.

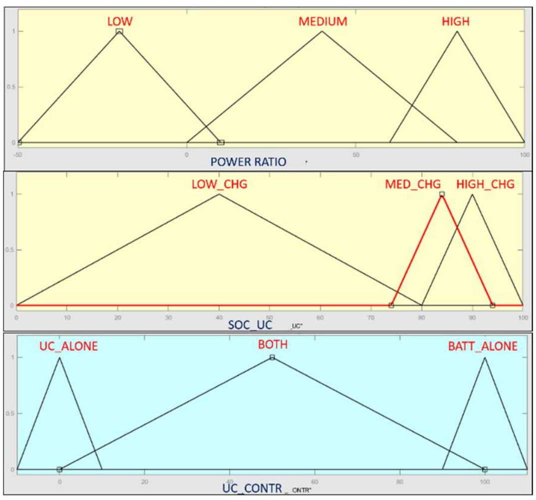

Fig. 4. Membership functions of the proposed FLC-EMS.

Therefore, the developed FLC should ensure an efficient distribution of power flow between HESS dual sources, i.e., the battery and the SCs. According to the MCS constructed from the system EMR (see Fig. 2), the FLC takes the SoC of the SCs and the battery power limit as inputs (see Fig. 3 and Fig. 4), to control the battery contribution k_{cont}. Thus, the proposed FLC supports three membership functions (MF) for the SoC_{SC} (LOW_CHG, MED_CHG, HIGH_CHG), and three MF for the requested power ratio $\eta_{Pload/Plim\_bat}$ considering the battery power limit (LOW, MEDIUM, HIGH). In order to define the coefficient k_{cont} which determines the progressive contribution of the dual energy sources according to three MF (UC_ALONE, BOTH, BATT_ALONE). Therefore, based on the inference rules, the developed EMS should ensure the following operations:

- Very high-power demand: EMS enables SCs to support power peaks,
- Very high-power recovery: the EMS activates SCs to recover power peaks and recharges them to be able to satisfy the next power demand,
- Constant or quasi-constant power: the battery takes over the supply of the load during less fluctuating power demands.

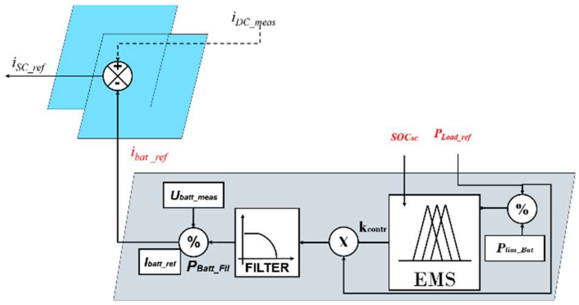

Fig. 5. Fuzzy logic strategy scheme.

The proposed EMS uses a low-pass filter at the output (see Fig. 5), which allows to decompose the current reference into a low frequency component designed for battery, and the high frequency component, used as a reference for SC, due to its ability to support high current fluctuations.

4 HIL development

The real-time HIL simulator is a software and hardware-based platform, which allows the diagnosis of an electronic system, the control and supervision of its parameters that describe its performances.

Fig. 6. Hardware-in-the-loop (HIL) architecture for proposed HESS.

The simulator enables to validate the performances of a developed system by taking into account the hardware-based constraints. (Fig. 6) shows the block diagram of the HIL, based on the MATLAB/SIMULINK software and two Arduino 2560 boards (ATmega32u4 microcontroller) that are used as the HIL interface and the EMS.

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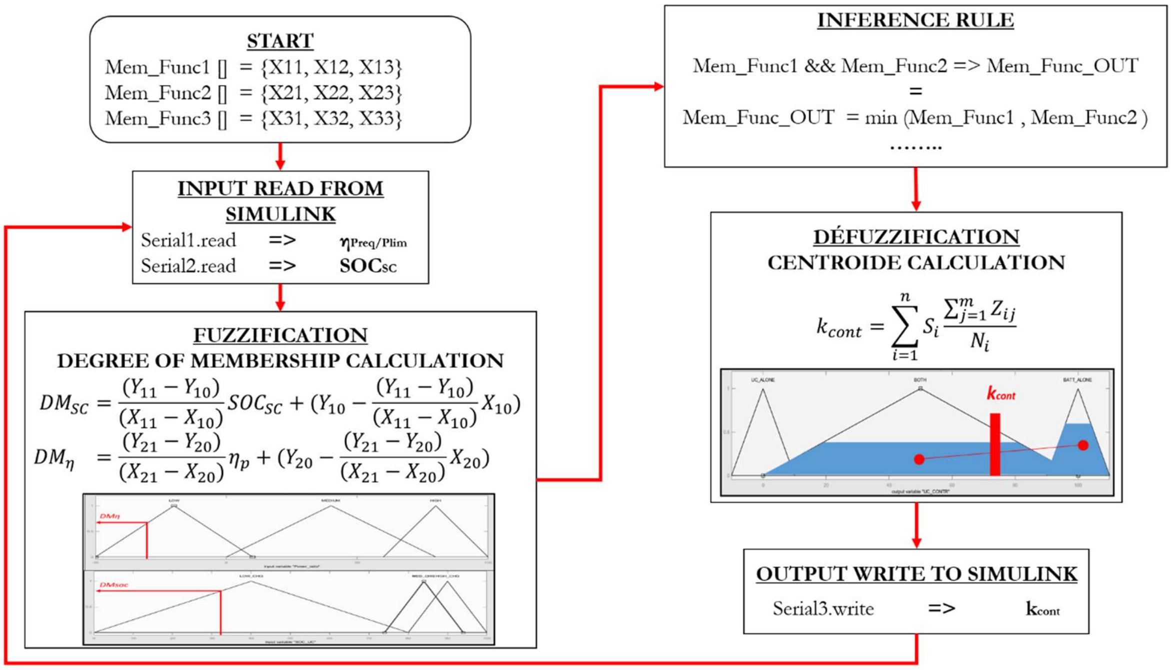

Fig. 7. Flowchart of the developed EMS algorithm.

The flowchart (see Fig. 7) describes the processing performed by the program developed and embedded in the aTmega32u4 microcontroller. During the first step, the microcontroller proceeds to the assignment of the variables loaded in the arrays, representing the membership functions. Then, it proceeds to the reading of the serial ports to load the variables of type "double" of the SoC_{SC} and the power ratio $\eta_{Pload/Plim\_bat}$. Once the variables are loaded, the processing calls the first function that starts the fuzzification operation, which is based on the mathematical models presented in the figure (see Fig. 7). Then another function determines the degrees of membership of the output parameters, according to the inference rules that define the minimum value of the two input values, related by a logical operator "and".

After determining the degrees of membership, a defuzzification function calculates the centroid of the obtained surfaces. This output value is transmitted to the MATLAB/SIMULINK software via the serial port, before starting a new loop.

5 Simulation and Experimental Results

In order to verify the theoretical analysis, the proposed real-time HIL simulation was performed in the MATLAB/Simulink software environment, and compared with the simulation results on the same software platform. The parameters shown in Table 1 and Table 2 were adopted, and the simulations were performed under ECE-15 driving cycle. The initial SoC_{SC} and SoC_{bat} are 83.5% and 95% respectively.

Table 1. Characteristics of the Battery pack.

Variables	Symbol	Value	Unit
SoC Limits	SoC_{bat}	[30, 100]	%
Cell Voltage	U_{cell}	3.7	V
Total Voltage	U_{bat}	24	V
Energy density	ρ_{bat}	160	Wh/kg
Battery Energy	E_{bat}	100	Ah

Table 2. Characteristics of the SCs pack.

Variables	Symbol	Value	Unit
SoC Limits	SoC_{sc}	[50, 100]	%
ESR	R_{ESR}	0.21	mΩ
Total Voltage	U_{sc}	35.1	V
Cell Voltage	U_{c_sc}	2.7	V
Capacitance	C_{sc}	500	F

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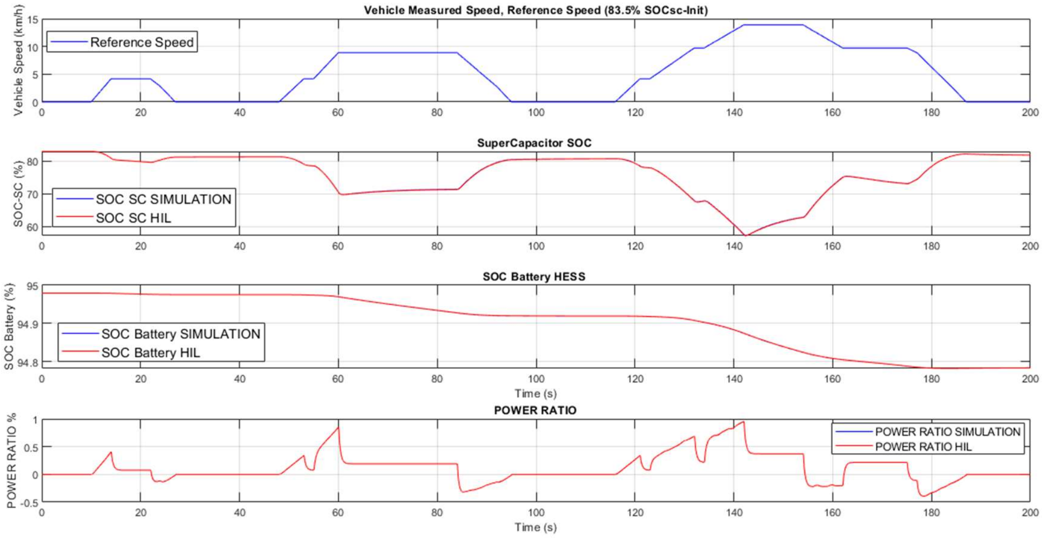

Fig. 8. Simulation results of the EV's HESS under ECE-15 (HIL and simulation results).

The simulation analysis (see Fig. 8) shows the results of the proposed HESS energy parameters, under the ECE-15 cycle speed function. The value of the U_{DC} voltage is constant U_{DC}=24V during the cycle, which proves the stability of the proposed system and the performance of the used controller. Indeed, according to the analysis of the SoC_{SC} and SoC_{batt} curves, a limited variation of SoC_{bat} is noticed, which allows a low stress on the battery and consequently an optimization of its lifespan.

Moreover, the SoC_{SC} is considered as a criterion for performances evaluation of the developed EMS. According to the SoC_{SC} variation curve: SoC_{SC} (t_0) at the beginning and $SoC_{SC}(t_f)$ at the end of each cycle are equal SoC_{SC} (t_0) = $SoC_{SC}(t_f)$ = 83.5%. Therefore, the SCs work as a perfect energy buffer.

In addition, the ratio of the battery power requirement limit remains less than $\eta_{Pload/Plim\_bat} < 1$, which shows the robustness of the developed EMS, taking into consideration the battery capacities.

Thus, according to the curves of the battery currents and SCs (see Fig. 9), the SCs supply energy during acceleration of the vehicle and recover it during braking. The battery supports the requirements of constant and quasi-constant current.

On the other hand, the system response results simulated using HIL allow to validate the EMS based on the fuzzy controller code, developed and embedded in the microcontroller. Hence, the curves of the energetic parameters of both simulators (see Fig. 9) are in perfect agreement. Moreover, the curves of the battery contribution coefficient for both types of simulation are also in perfect agreement, which demonstrates the robustness of the developed C code and the perfect application of the theoretical basis of FLC.

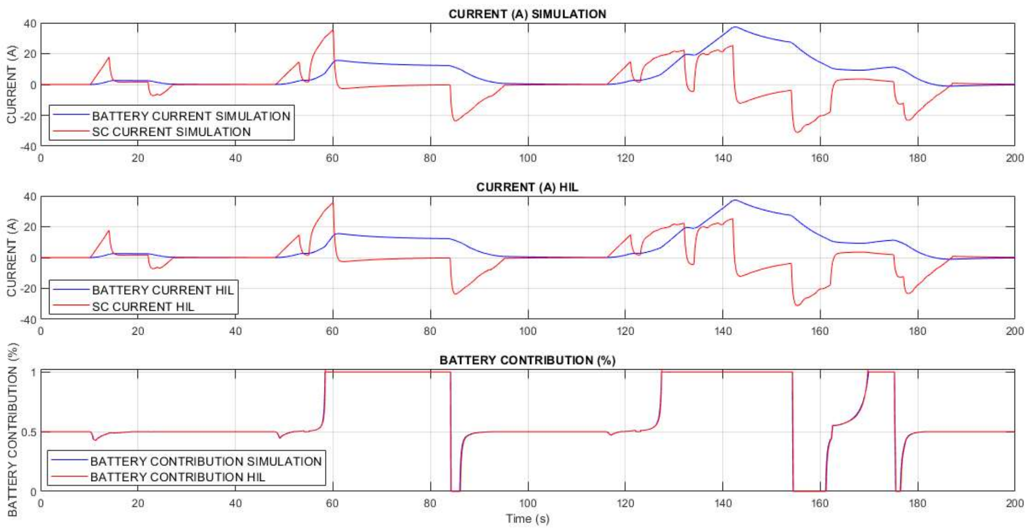

Fig. 9. Battery-SCs currents HESS and Battery contribution factor (HIL and simulation results).

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6 Conclusion

In this paper, an architecture of a 1.5kW HESS is proposed. The power flow management is provided by a developed rule-based EMS using a fuzzy controller. The proposed EMS was evaluated through a real-time simulation based on an aTmega microcontroller, using a HIL platform. Thus, the performance evaluation of the proposed HESS architecture and the developed HIL platform has been successfully performed and validated. The comparison of the results obtained from the HIL with the results of the simulation performed on MATLAB/SIMULINK, demonstrates the robustness and correctness of the developed C code.

Future work will focus on the development of a HESS prototype proposed in the simulation during this work, and its validation using a FPGA and dSPACE-based HIL simulator.

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