An Integrated Fuzzy Logic Energy Management for a Dual-Source Electric Vehicle

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***Abstract*—Electric vehicles (EVs) have been gaining prominence in the future of sustainable transportation. Advances in energy management systems have shown that EVs with hybrid electric storage systems might be important in situations with frequent speed variations as in urban traffic, attaining more efficient powertrain energy application. Therefore, EVs energy management is an important issue with significant influence in EVs performance. EVs management systems provide important benefits such as reducing energy consumption, decreasing pollution and improving driving performance in the EVs perspective. In this paper, a promising EV dual source architecture, with supercapacitors and batteries is proposed in order to satisfy the EVs energy requirements. Considering several EVs power scenarios, an energy management system based on fuzzy logic control strategy was developed. Thus, for a future reduced scale implementation on laboratory workbench, a good energy trade contribution from the two involved sources is required, improving the EVs efficiency and the performance of the overall system.**

Keywords*—Electric Vehicles, Batteries, Supercapacitors, Hybrid Storage Systems, Energy Management, Fuzzy Logic Controller.

I. Introduction

The growing concerns about oil depletion and the impact of internal combustion engine massive utilization, have led to new global consciousness. Scientific R&D teams and the automotive industry have forced to search for novel, more efficient and environmental friendly transportation vehicles. Thus, the EVs have emerged as an alternative, which still have some drawbacks. The EVs main disadvantages are the autonomy and the cost, being this related to EVs energy source storage capability. Considering the usable energy sources state of the art, this problem cannot be solved in a short-term. The hybridization of several sources can be the best choice for EVs autonomy improvement in situations with frequent speed variations, as in urban traffic [1]–[3]. In fact, there are several energy sources that can be combined in order to satisfy all the energetic requests of EV powertrains. Nowadays the most suitable energy sources for EV applications, considered in the literature, are batteries (of different chemistry), supercapacitors (SCs) and fuel cells. However, in order to decrease the complexity of the hybrid energy storage system and the respective controller, batteries and SCs were considered for EVs as they complement each other [4]. Thus, it is possible to satisfy several energetic demands of the EV improving the vehicle autonomy and performance, avoiding excessive power sources degradation and increasing the safety levels. As the chemical to electrical energy conversion depends on a slow electrochemical process, a SCs bank utilization is a solution to improve the time response of the supply system under high and rapid load disturbances. Moreover, energy storage devices like SCs allow more efficient energy recover during regenerative braking [5]. However, the sources hybridization concept requires an advanced energy management system (EMS) in order to achieve the best EV energy sharing, introducing the energy management issue as one of the key points in EV research. The EMS and the applied controllers are intrinsically related, being the designed controllers at a hierarchy layer lower than fuzzy logic controller (FLC) [2].

The idea of an EMS ruled by a FLC has already been tested in previous works. Through [2], [6], [7] analysis, FLC is used as control strategy at the same level that the PI controllers in order to provide the signal references. Nowadays FLC technology is one of the most profitable method for intelligent energy management in HEV and EV which can be used by it self or assisting other control techniques. [7]–[9].

This paper tackles a FLC EMS for an EV dual source energy consumption optimization. The proposed FLC adjusts the references to the controllers based on EV power demand signal accordingly to the rules specified further in this paper. In section I a paper overview is presented and the section II presents the energy management approach. The third section explains the implemented FLC strategy, the section IV tackles the considered case study, being the final section reserved to simulation results presentation and respective discussion.

II. EV Energy Management

An efficient EMS can highly improve EV autonomy as well as the life cycle of the electric storage system components [10]. Nevertheless, one of the main objectives, the DC-Link voltage stabilization, can not be neglected in order to properly feed the powertrain demands. Thus, the EMS controls both energy sources accordingly to the load power demand. Under energy peaks from the DC-Link or regenerative braking, where the power on the DC-Link ($P_{DC-Link}$) is respectively positive and negative, the SCs bank is always used to provide or absorb respectively this energy, instead of the batteries pack. This allows to significantly increase the batteries life time as well as the EV performance.

In this paper, the battery pack is the main energy source of the EV feeding system and the SCs bank is an integrated assisting module in order to improve the overall system response.

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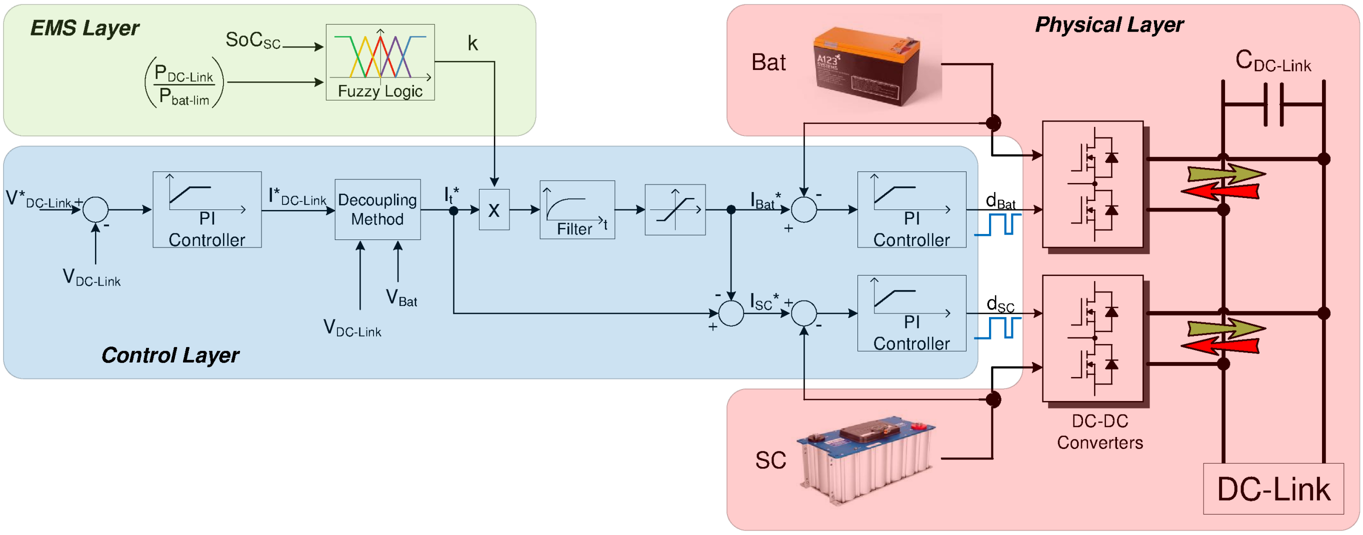

Fig. 1. Diagram of the implemented system

A FLC was studied and designed to provide a high-efficiency energy management between the two sources. [10]–[12]. The EMS control strategies are dependent on the considered FLC rules and control parameters feedback. The FLC rules are determined and controlled based on the best operating points of the EV power sources. This allows to make a proper use of energy storage in each source, maintaining the best possible performance of EV. Therefore the EMS main objectives are the improvement of the power sources individual performance and ensure the lack of current and voltage fluctuations. This is a fundamental aspect for EV to achieve good performance. In terms of the overall control structure, as presented in Fig. 1, the layer below the EMS, which are the PI controllers, are used to regulate the duty ratios that govern the DC-DC converters and consequently the energy sources.

III. Fuzzy Logic Controller

There are several computing based techniques which are useful tools for solving engineering problems that are not possible or convenient to handle by traditional methods. These computing based techniques allow efficient modelling analysis, and decision making. Some of these techniques are the Artificial Neural Networks (ANNs), Fuzzy Logic Controllers (FLCs), evolutionary computation, metaheuristics [10], [12] and dynamic programming, having all of them some advantages and disadvantages [1], [13].

The advantages and disadvantages trade-off, simplicity, robustness of the FLC for on-line EV energy management and its strong validation on previous literature works, as explained below, were the reasons to choose this technological approach to the presented EMS. The FLC operation principle is based on "if ... then" statements, which are known as rules, relating two or more membership functions that come from input variables through a process of fuzzification. When one or more rules are verified as matching a certain situation, an output membership function suffers defuzzification process, resulting on an output signal from the FLC to the system.

This approach is commonly used for many engineering control problems, providing a useful simplification of a control/strategy methodology description, where the human language can be used to describe the problem and its solutions. In many control applications, the model of the system is unknown or the input parameters are variable and unstable. In such cases, FLC is suitable to be applied. Moreover, the FLC is more robust than conventional linear controllers, being also easier to understand and modify FLC rules, which are expressed in natural linguistic terms [13].

One of the main aspects involved in fuzzy-rule based energy management approaches is their effectiveness in real-time supervisory control of powertrain energy demand [2]. The rules are designed based on heuristics, intuition, human expertise and even mathematical models, generally without a prior knowledge of a predefined driving cycle. Looking into EVs powertrain energy demand as a multi domain, nonlinear and time varying plant, FLC is one of the most logical approaches to the multi-source management problem.

The main advantages of fuzzy rule based methods are: the robustness and flexibility, tolerance to imprecise measurements and component variations, is wide adaptive method being easily tuned. A FLC is also very useful to control nonlinear systems and does not necessitate a system mathematical model for control purpose, allowing to be implemented together with conventional control techniques without any kind of incompatibility.

All this advantages enhance the controllers degree of freedom, allowing better EV global performance thought the SCs assistance during the batteries hard transient states, increasing their life time. The energetic efficiency is also improved using the SCs for regenerative braking, which is another example of fuzzy method adaptability.

However, one disadvantage of the fuzzy approach is the lack of guarantee that the fuzzy system developed will have sufficiently good performance, especially for a complex system problem with large number of uncertain variables. Thus, this issue demands for optimization methods like genetic algorithms or dynamic programming [1], [8], [13]. Another disadvantage is related to the computational resources needed to the fuzzification and defuzzification processes. This problem is minimized with the current Digital Signals Processors (DSPs) and Field Programmable Gate Arrays (FPGAs). On the other hand the mentioned advantages provide a high abstraction level and a robust controlling capacity applied at the EMS.

IV. Implemented Fuzzy Strategy

The overall system can be divided in three layers, as shown in Fig. 1. The FLC belongs to the EMS layer, in green, which is the highest level layer on the proposed architecture. A middle layer was considered to be a control layer, in blue and aims to maintain the $V_{DC-Link}$ on a constant value. Finally, there is the physical layer, in red, composed by the sources, converters and sensors.

The FLC is directly linked to the batteries and SCs behaviour through the following equations:

$$I^*_{Bat}(t) = k \cdot I^*_t(t) \cdot (1 - e^{\frac{-t}{\tau}}), \quad I^-_{Sat} \leq I^*_{Bat} \leq I^+_{Sat} \tag{1}$$

$$I^*_{SCs}(t) = I^*_t(t) - I^*_{Bat}(t) \tag{2}$$

where the constant τ is the cutting frequency of the low-pass filter and (I^-_{Sat}, I^+_{Sat}) are the input and output maximum current values on the batteries.

The FLC has to accomplish three main objectives:
1) Let the SCs to supply a certain amount of energy when the requested power from the DC-Link is near/equal/greater than the nominal capacity of the main source, (batteries);
2) Make the SCs to absorb all the energy from a regenerative braking, which is normally a high amount of power in a short time period;
3) Set a certain SoC reference to the SCs in order to let them ready to respond to the two situations explained before;

To successfully achieve the proposed objectives three membership function groups were considered, two groups of inputs and one output group. The first input group is the *Power Ratio*, δ. This ratio defines the relation between the DC-Link power, $P_{DC-Link}$, and the battery power, $P_{Bat-lim}$, ($\delta = {}^{P_{DC-Link}}/_{P_{Bat-lim}}$). The second input group is the *SoC*. It refers the state-of-charge of the SCs, it is designated on text as *SoC*. The last group of membership functions is the output group. It was named *SCs-Contribute* and it determines the distribution of the requested current from the DC-Link between the two available sources. The *SCs-Contribute* is regulated by the k variable.
The membership functions are presented in Fig. 2. Where the range of each input and output values can be seen.

For the input *Power Ratio*, seven membership functions are identified: when the δ values are below zero, $\delta \leq 0$, the chosen membership function is the *UnderZero*; for low δ values, $\delta \in [-5\%, 5\%]$, the membership function is *NearZero*; the *VeryLow* membership function was chosen to $\delta \in [0\%, 50\%]$; for values of $\delta \in [30\%, 70\%]$ the membership function is *Low*; the *Normal* occurs when $\delta \in [60\%, 80\%]$; in cases of $\delta \in [70\%, 100\%]$ the considered membership function is *High*; finally, for $\delta \geq 90\%$ the membership is *VeryHigh*.

There are six membership functions for the *SoC* input: for low levels of *SoC*, namely $SoC \in [0\%, 65\%]$, the membership function is *V-Low*; in cases of $SoC \in [55\%, 75\%]$ the membership function is *Low*; an *Optimal* membership function is considered when $SoC \in [70\%, 80\%]$; the *High* membership function occurs when $SoC \in [75\%, 95\%]$; when

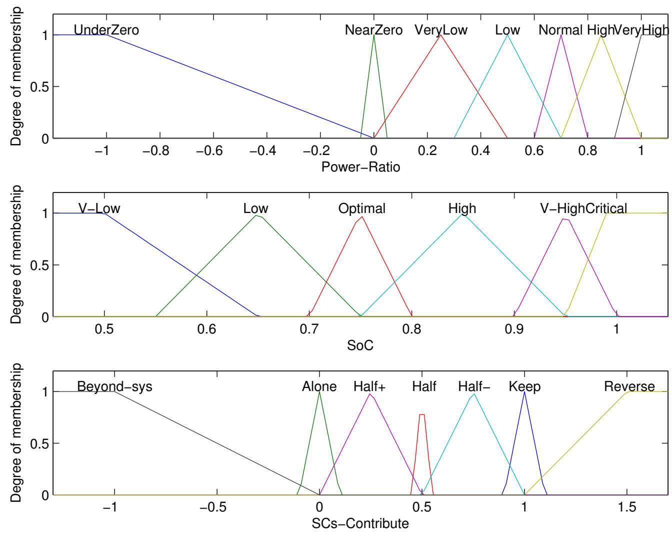

Fig. 2. Proposed membership functions

$SoC \in [90\%, 100\%]$ a *V-High* membership function is considered ; the last membership function of this group, *Critical*, occurs for $SoC \geq 95\%$.

Finally, the *SCs-Contribute* output, k, memberships functions are: *Beyond-sys* when the $k \leq 0$; the *Alone* output membership regards the values $k \in [-10\%, 10\%]$; for $k \in [0\%, 50\%]$ the membership function is *Half+*; output values of $k \in [45\%, 55\%]$ are in the *Half* membership function; the *Half-* membership function occurs for $k \in [50\%, 100\%]$; there is a *Keep* membership function for values of $k \in [90\%, 110\%]$; and the last output membership is *Reverse*, considering values of $k \geq 100\%$.

The percentage of k output values is applied to I^*_t (see Fig. 1). Taking the example of an output *Half+*, the SCs will give more than half of that requested current and the batteries will feed what is left.
Table I shows some of the fuzzy rule-base used in the fuzzy inference process.

TABLE I. Rule-base of Fuzzy Logic Controller

	Power Ratio (δ)		**SoC**		**SCs-Contribute**
if	UnderZero	**and**	Optimal	**then**	Alone
	UnderZero		High		Half+
	...		...		...
	NearZero		Optimal		Keep
	...		...		...
	VeryLow		Low		Reverse
	...		...		...
	Normal		Low		Reverse
	Normal		Critical		Alone
	...		...		...
	High		Optimal		Half
	...		...		...
	VeryHigh		V-Low		Half-
	VeryHigh		V-High		Alone

From Fig. 2 and Table I analysis it can be verified that the rules are in line with the proposed objectives.

Assuming that the limit of the battery power, $P_{Bat-lim}$, is a constant positive value chosen by the system designer in accordance with battery maximum power available, it can be said that when the δ is a negative value the system is under a regenerative breaking. In this situation, the FLC will decide what to do with that energy. If the *SoC* is lower than an optimal state, the FLC output k will tend to zero, meaning that all the energy coming from the regenerative braking will be absorbed by the SCs. If the regenerative braking persists for a long period, the *SoC* will, perhaps, reach a level higher than the optimal state, and on that situation the output k will start to be raised to positive values by the FLC in order to decrease the quantity of energy going to the SCs to prevent an over voltage.

When the δ is *VeryLow*, *Low* or *Normal* and the *SoC* is lower than *Optimal*, the behaviour of the system will tend to charge the SCs. If the *SoC* is higher than *Optimal*, the FLC trend will be discharging the SCs. The charging and discharging rates will depend on the δ and the *SoC*, for instance, a lower δ will originate higher charge rates and a higher *SoC* levels will originate higher discharge rates.

Given high positive values of δ, the SCs should assist the batteries on the $V_{DC-Link}$ stabilization, always regarding the *SoC* state. Considering δ to be *VeryHigh* after a regenerative breaking, where the *SoC* have reached a Critical level, the FLC decision on that situation will be *Alone*, meaning that the SCs will support the DC-Link power alone, performing a high rate discharge in order to get the voltage decreased on the SCs.

V. Case Study

In this paper, the simulations were performed under a reduced scale. This scale reduction was done to enable a future implementation of the system in a laboratory workbench [10], where the maximum power available is 1kW. The sources used on the simulation were:

1) A battery pack composed by three modules of Pb (Lead–acid) batteries in series, each module with a nominal voltage of $12V$ and a rated capacity of $7Ah$. The pack nominal voltage was $V_{Bat} = 36V$;
2) Two branches of SCs, manufactured by Nesscap, in parallel with a nominal voltage of $V_{SCs} = 48.6V$ and a capacitance of $11.11F$. Each branch has 18 cells with a nominal voltage of $2.7V$ and a capacitance of $100F$;

The voltage of the DC-Link is $V_{DC-Link} = 108V$, meaning that the DC-DC converters voltage gain, referred to the main source, is ${}^{V_{DC-Link}}/_{V_{Bat}} \approx 3$. The used model sources on the simulations were obtained based on previous works [10], [12].

The main idea is to verify the functionality of the overall system in order to make it applicable to an already existing project named VEIL ("Veículo Eléctrico Isento de Licença de condução", meaning license free electric vehicle) [14], [15].

The case study of this paper is in line with previous works at the Electrical Engineering Department of the Engineering Institute of Coimbra (DEE-ISEC). A project, named VEIL, was started at this department with the objective of converting an Internal Combustion Engine into an EVs [14], [15]. VEIL is a project focused on an EV prototype for urban purposes with an hybrid electric storage system (HESS), where the energy management is crucial.

A. Control Loop Approach

In this paper, the control is at a lower hierarchy level compared to the FLC EMS. The main objective of the used control is to maintain the voltage on the DC-Link constant in order to properly feed the traction system. The control functionality, to maintain a stable $V_{DC-Link}$, was already proved in previous literature works [10], [16], [17]. The control structure is constituted by a two cascaded Proportional+Integral (PI) controllers, as showed in Fig. 1. The first controller calculates the error between the measured voltage at the DC-Link and a certain reference, and its output will be a current referred to the sources side through a method called Decoupling Method [16]. This current reference will feed a current PI controller, which calculates the error between the measured current on the source and the reference current given by the first PI controller. Its output is a square wave controlling the DC-DC converter through Pulse Width Modulation (PWM) method. In this specific case, the output current reference of the first PI controller is splitted in two, to feed the current PI controllers of each source.

B. Driving Cycle

An urban driving cycle was chosen to validate the simulations and to put the system under conditions as close as possible to reality. It was chosen the Artemis drive cycle due to its realistic urban profile, as in previous works [12], [18]. The Artemis drive cycle is divided as showed in Fig. 3. In this paper a time slot of 200s, with $t \in [280, 480]s$, was chosen within the free-flow urban segment.

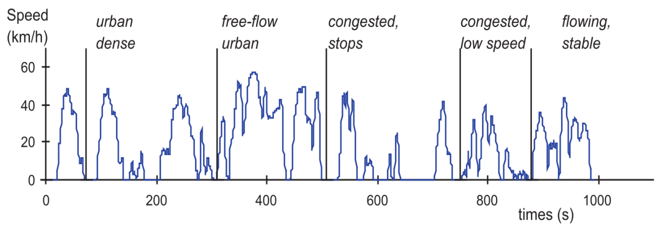

Fig. 3. ARTEMIS urban driving cycle [18]

VI. Simulation Results and Discussion

The simulations were performed to validate the controller of the multiple input DC-DC converter and the FLC EMS using MATLAB/Simulink®. The Simulink model was inspired on Fig. 1 block diagram.

Several simulations were done with different SCs starting SoC values. In this paper two simulations are discussed, the first one starts with a SoC value of 50% and a second one with 100%. These two starting SoC values are the *VeryLow* and the *Critical*, chosen in order to put the system under proof. The first situation represents a very low SoC of the SCs, leading to a non meaningful SCs contribution. The second situation regard a high SCs SoC value, meaning that they wont be able to absorb any energy coming from the DC-Link. The results are discussed through the analysis of the SCs SoC, of the V_{SCs} as well as the power distribution through the sources, P_{Bat} and P_{SCs}. The power sum of each source, P_{Bat} and P_{SCs}, is equal to the requested power from the DC-Link, $P_{DC-Link} = P_{Bat} + P_{SCs}$.

Fig. 4 shows the DC-Link measured voltage ($V_{DC-Link}$), its reference ($V^*_{DC-Link}$) and the power requested on the

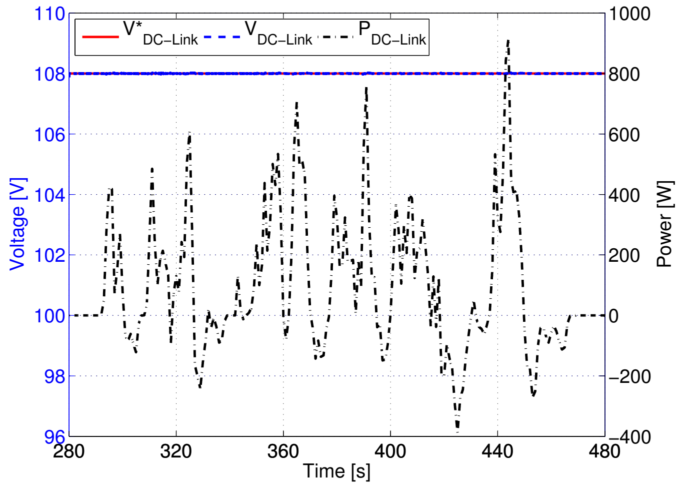

Fig. 4. DC-Link Voltage and Power demand (Artemis [280-480]s)

DC-link, $P_{DC-Link}$, according to the driving cycle and the dynamics of the EV.

It can be seen that even with the high amplitude variations on the $P_{DC-Link}$, $V_{DC-Link}$ is maintained on the same value, showing that the controller is keeping the $V_{DC-Link}$ stabilized.

Fig. 5 and 6 are the simulations with the SoC on the SCs starting at 50%.

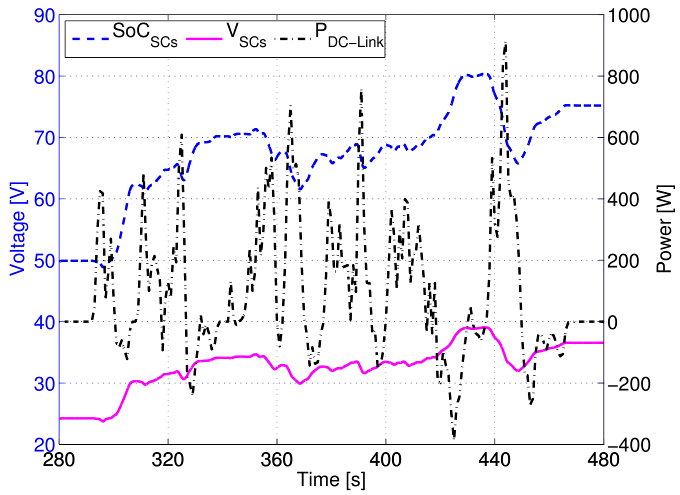

Fig. 5. Simulation with SoC starting at 50%

Fig. 5 shows that the SoC and voltage of the SCs are very low at the beginning, nevertheless, they are brought to values up to 70% within 50s, without compromising the DC-Link stabilization.

In Fig. 6, the black waveform represents $P_{DC-Link}$, which is directly linked to the requested power of the drive cycle Artemis at $t \in [280, 480]s$. The red waveform is the battery's power, P_{Bat}, the power on SCs, P_{SCs}, is represented by the green waveform. This simulation, Fig.6, was done with a starting 50% SoC on the SCs, which is a quite low value for practical use purposes. The overall system behaviour should be capable to bring the SoC of the SCs to higher levels without compromising the realization of the considered cycle and also without asking too much energy from batteries. In fact, at near

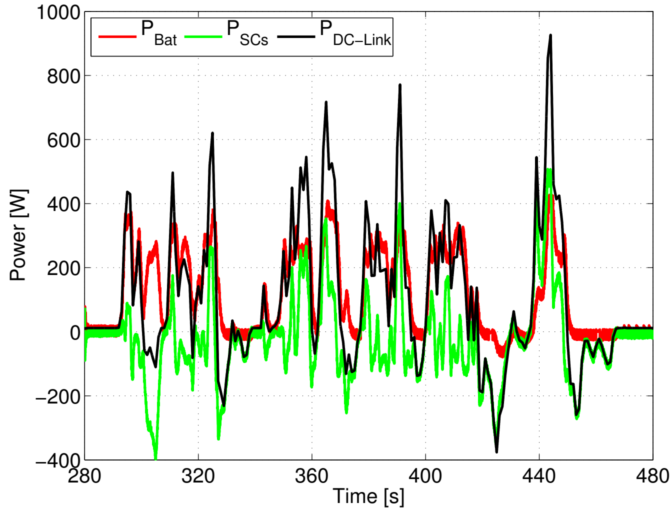

Fig. 6. Power on Bateries, SCs and DC-Link (50% starting SoC simulation)

300s, the FLC took the decision of charging the SCs based on the $P_{DC-Link}$ power request, that was going from *VeryLow* to *UnderZero*, and also based on the SCs SoC, that was *V-Low*. The mentioned behaviour shows a very good decision from the FLC, as the SCs absorbed the power from the DC-Link, moreover, the batteries were asked to contribute to the SCs charging with almost 300 W at the same time. In Fig. 6 was proved the possibility of energy exchange between sources.

The analysis of the simulations with a starting SoC of the SCs at 100% is done based on Fig. 7 and 8.

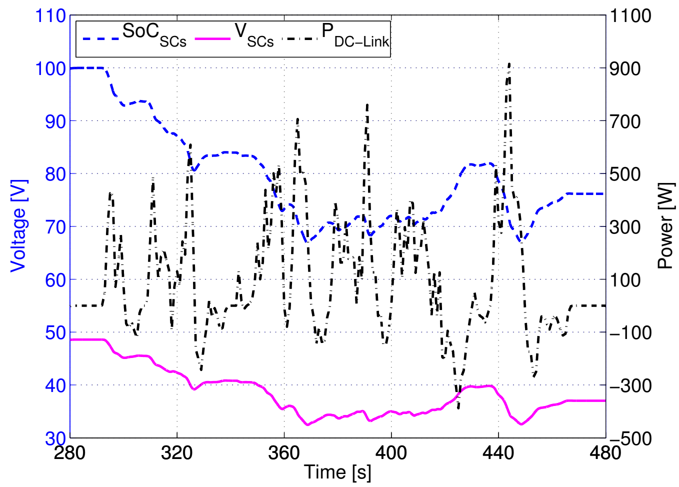

Fig. 7. Simulation with SoC starting at 100%

From Fig. 7 we can see that the simulation has started with a critical SoC value of 100%. The SoC was brought to values below 90% in less than 40s, which is a very good behaviour, thanks to the FLC EMS.

Fig. 8 shows that, in order to discharge the SCs, the P_{Bat} was less than 100W during the initial 40s, meaning that, the source supporting the the $P_{DC-Link}$ were the SCs. This decision was taken by the FLC EMS.

A detailed analysis between Fig. 5 and 7 shows that the

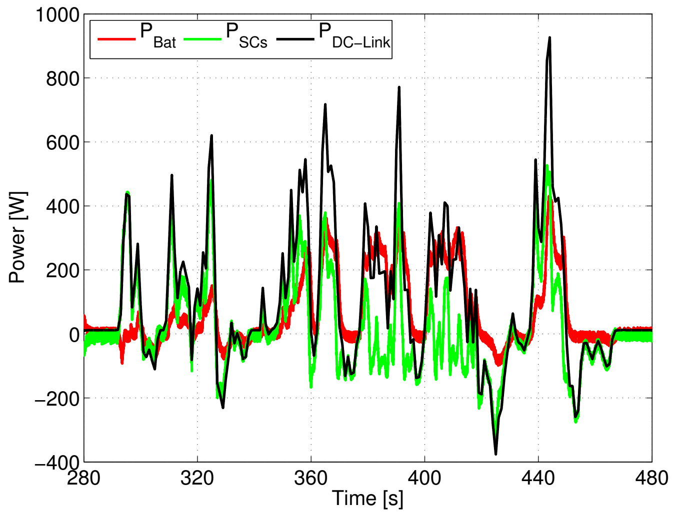

Fig. 8. Power on Bateries, SCs and DC-Link (100% starting SoC simulation)

system has a recovering period, in which the SoC goes from an abnormal value to an acceptable state. Beyond that recovering time it is seen that the SoC's path is very close on the two simulations. For instance, near 380s the SoC was in between 65% and 70% on the two simulations, around the 430s the SoC on the two simulations was passing above 80%, finally, the two simulations ended at 480s with a SoC near 75%.

CONCLUSIONS

In this paper a FLC EMS for EVs with HESS's was proposed. The FLC EMS was studied to be integrated within a control loop based on a Decoupling Method with an Online Filtering Technique. The FLC output influence is focused on the current of each source, meaning that adjusting the current will also adjust the power distribution of each source. Through the voltage PI controller, the $V_{DC-Link}$ was maintained constant. Through the FLC EMS, the requested power was distributed intelligently through the two sources and the SoC of the SCs was kept on an optimal state in order to support the batteries. Finally, through the Online Filtering Technique, the batteries were saved from high frequency current request, that were supported by the SCs, reducing the current peaks at the batteries. The tests were performed using a time slot of a known driving cycle and the results were in line with what was expected from a good EMS. It was proved that energy exchanges between the two sources exists, and those exchanges were done at the right time, without compromising the overall system behaviour. The three main objectives were accomplished with the proposed FLC EMS. Moreover, the FLC can be adjusted to set the *Optimal* SCs SoC to operate in a more efficient area. Therefore, given this paper results and its good perspectives, future works will be made in order to implement the proposed FLC EMS in a laboratory workbench.

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