EVS27
Barcelona, Spain, November 17 - 20, 2013

Hybrid Topologies Comparison for Electric Vehicles with Multiple Energy Storage Systems

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Abstract

Global warming and fuel depletion issues demand for more sustainable means of transportation, where the electric vehicles are gaining prominence on the transportation market perspectives. Fast development of power electronics and electric vehicles suitable energy storage systems allows the production of high efficiency electric vehicles. In this paper are discussed the advantages and drawbacks of three different arrangements for two considered energy sources, batteries and supercapacitors, using a bidirectional DC-DC converter. Two different control solutions based on proportional-integral controllers and a low-pass filter are also discussed. The global system performance from the energy storage system perspective is presented. The presented results were preformed using a 410 seconds sample of the Artemis drive cycle and Matlab/Simulink environment for the simulations.

Keywords: EV (electric vehicle), power management, regenerative braking, specific energy, specific power

1 Introduction

The electric vehicle (EV) has been receiving growing attention in the last few years especially due to the greenhouse gases effects and the global energy crises. These issues led to a new consciousness towards the transportation sector, one of the top global pollution contributors due the massive utilization of internal combustion engine vehicles. The EV utilization has several advantages but also some important challenges, being the most important the energy storage and the related vehicle autonomy. One interesting possibility, to improve this aspect, is to have more than one energy source type which combines and improves both the energy and power system responses [1, 2, 3]. In this case, one crucial aspect is to try to maximize the efficiency of the multiple energy storage systems (ESS) utilization. The hybridization concept of several ESS relies on the optimized management of the transferred power between the sources and the EV powertrain, including between the sources itself [4, 5, 6]. This is possible by energy management decisions applied to the controllers designed for the power electronic converters of each considered topology. Therefore, a hybrid energy storage system (HESS) is a combination of multiple ESS merging their energy through a common stable voltage DC-Link, for optimized load supply under controlled decisions. These decisions imply energy management and power flow control algorithms, which can be more or less complex accordingly to the used HESS and the power converter topology. Many HESS topologies are presented in the literature being the passive and active topologies the most referred which can be subdivided in other types as discussed in [7, 8, 9]. For EV applications a bidirectional DC-DC converter is commonly used as a two-way power flow interface device between each ESS and the DC-Link [10]. In this paper three cases are studied. The first is designated as battery topology which uses a power electronics converter, to stabilize the DC-Link voltage, and a battery pack. The second one uses a direct parallel between batteries and supercapacitors (SCs) and only one bidirectional DC-DC converter to the same purpose. This is designated as passive hybrid topology. Finally, the third is designated in the literature as parallel active hybrid topology, and is formed by two bidirectional DC-DC converters parallel linked, each devoted to the considered ESS (i.e. batteries and SCs), enhancing the performance facing the passive topology, but increasing the control complexity.

2 Case Study

2.1 Considered Hybrid Energy Storage System Topologies

In this topic the studied topologies are presented, where the usage of, at least, one DC-DC converter is crucial. This remains by the necessity of a constant DC-Link voltage regulation, avoiding voltage sources fluctuations. The topology presented in Fig.1, designated as battery topology, is formed by only one battery pack as ESS, which is linked to the bidirectional DC-DC converter. This topology is the most simple. Nevertheless, major drawbacks for the batteries appear since the energy requested or provided by the DC-Link is only supported by the battery pack. This fact leads to high levels of stress during batteries operation.

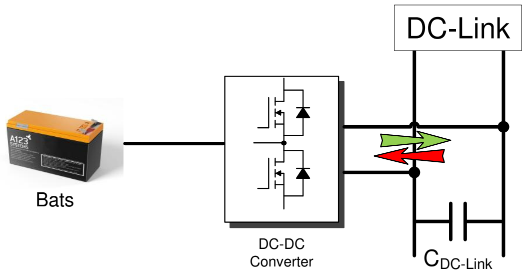

Figure 1: Battery topology

Relatively to the considered HESS topologies, this paper mainly focuses on the topologies presented in Fig.2 and Fig.3. Fig.2 presents an HESS with passive hybrid topology. This uses battery and SCs packs as ESS, linked directly in parallel to one bidirectional DC-DC converter. This topology forces the battery and SCs packs to have the same voltage level. This configuration allows a smoother current variation at the batteries for charge and discharge situations. Nevertheless, as its SoC depends on the voltage which cannot vary significantly due to the batteries, as there is no active power management involved, the energy contribution of each energy source for the load demand is defined by the internal resistance of the ESS involved. Consequently, this topology leads to a limited utilization of SCs.

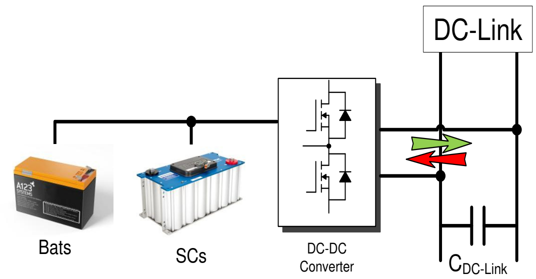

Figure 2: Passive hybrid topology

The third studied HESS topology, presented in Fig.3, is a parallel active hybrid topology. This has one bidirectional DC-DC converter devoted to each source, which means that the battery and the SCs packs are managed independently, allowing this way to decouple the power supply paths. This configuration allows more flexibility, stability, overall efficiency and performance. The ESS voltage variation issue is solved and allows a smoothed current flow, being attained the best performance and a good cost-simplicity trade-off. Some of the disadvantages are related to the use of a more complex control scheme and an increment on the semiconductors number for added source.

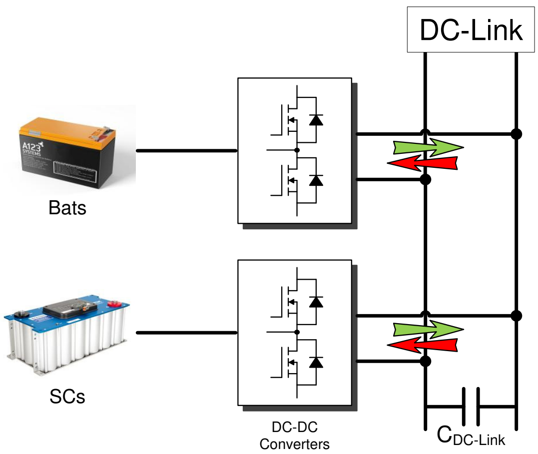

Figure 3: Active hybrid topology

2.2 Control Implementation

The bidirectional DC-DC converter controller for each considered topology was designed to ensure a constant voltage on the DC-Link. The control block diagram presented in Fig.4 performs the requirements to control the two topologies presented in Fig.1 and Fig.2. Two cascade proportional-integral (PI) controllers were used, one to control the DC-Link voltage and another to control the ESS current.

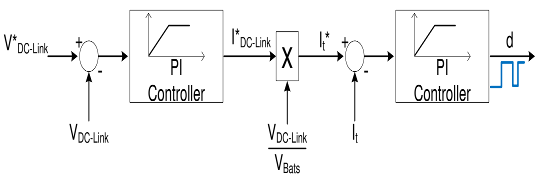

Figure 4: Battery and passive hybrid topologies control diagram

The applied control was already studied and tested in previous works [11, 12].
For the topology presented in Fig.3, there will be one bidirectional DC-DC converter for each source, being the current I_t^* divided in other two references. Fig.5 shows the control block diagram used in the topology presented in Fig. 3. One part of that current will be the contribution from the batteries and the other part will be the contribution from the SCs. The sum of the two current contributions must be equal to the required I_t^* in order to maintain a stable DC-Link voltage.

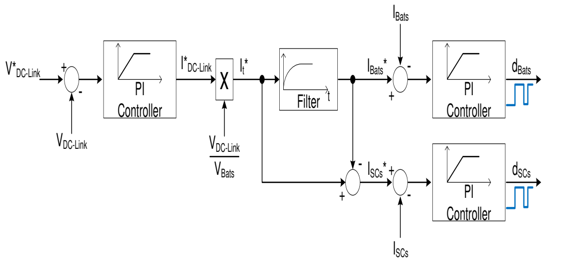

Figure 5: Parallel active hybrid topology control diagram

It is always possible to perform some adjustments in terms of cut-off frequency of the low-pass filter, in order to attribute a more or less active role for the batteries mainly in the transient response for the applied $P_{DC-Link}$. As next presented in section 3, it is possible to notice that the considered controllers were properly designed, being this verified by the correct matching of the reference and measured currents. Therefore, the overall system performance is the expected.

2.3 Applied Energy Management Strategies

The energy management is a very important topic to be considered when HESS topologies are discussed. In the simplest considered case, presented in Fig.1, it is only used one ESS (batteries), being all the energy that flows to and from the DC-Link in the battery pack referential. In the other two HESS topologies, the energy management plays a very important role. For the Fig.2 case, the energy management is done by the inner-resistance of each source, meaning that, the energy management depends on the type of sources used for the hybridization and on its dynamic response. This response is defined at the design stage. For the Fig.3 topology and for the proposed study, in order to achieve better comparison facing the passive topology, a frequency-based power allocation strategy is used [11]. Observing Fig.5, there are two different current setpoints ruled by the time constant of a low-pass filter. For this topology, slightly changes can be made to go beyond the filtering process and reach a more complex energy management, including intelligent energy management strategies.

3 Simulation Results and Discussion

In order to compare future laboratory tests, the simulation model was set with the real characteristics of the ESS, which are presented in Table 1. To match future workbench tests, lead-acid was the batteries technology chosen and 100F/2,7V for the supercapacitors (see Table1).

Table 1: Considered batteries and SCs specifications

	Batteries	Super-Capacitors
Nominal voltage [V]	12	48,6
Capacity/Capacitance	7Ah	5,5 F
# Packs	3 (in series)	2 (in parallel)
Internal resistance [mΩ]	120	45
Storage energy [Wh]	84	0.101
Specific Power [Wh/kg]	0,181	6,23

All the further presented results were obtained using a period from 220 sec to 630 sec of the Artemis drive cycle. It was also established a trade-off between the considered energy sources and the maximum power for each topology. The achieved results present increments of approximately 250 W for the $P_{DC-Link}$, among the considered topologies. The maximum power levels were defined taking into account the source characteristics presented in table 1 and the empiric/theoretical knowledge about the three approached topologies. As it was expected the battery topology (Fig.1) presents a more stressful behaviour for the batteries, when compared to the remained considered topologies. Through Fig.6 and Fig.7 analysis it is possible to verify that the $P_{DC-Link}$ is completely sustained by the battery pack. Therefore the transient response entails significant current peaks that are supported only by the batteries. Negative current values regard regenerative braking situations.

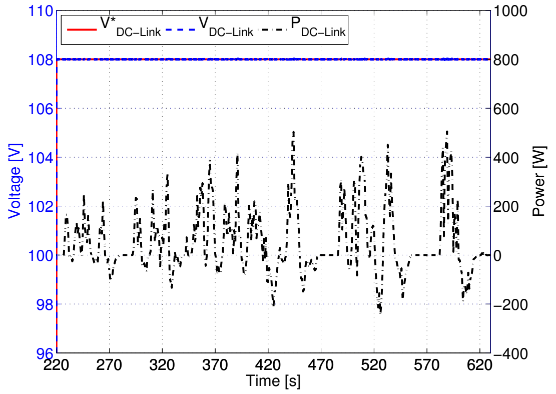

Figure 6: DC-Link voltage and power in battery topology

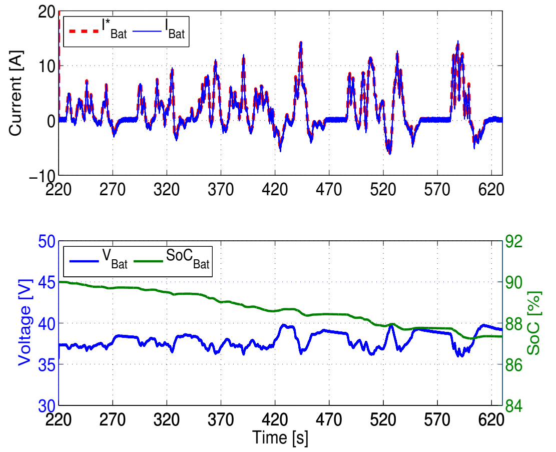

Figure 7: Battery's current, voltage and SoC in battery topology

However, the main goal is achieved, as powertrain energy demands are fulfilled with a stabilized DC-Link voltage. The maximum required power is 500 W.

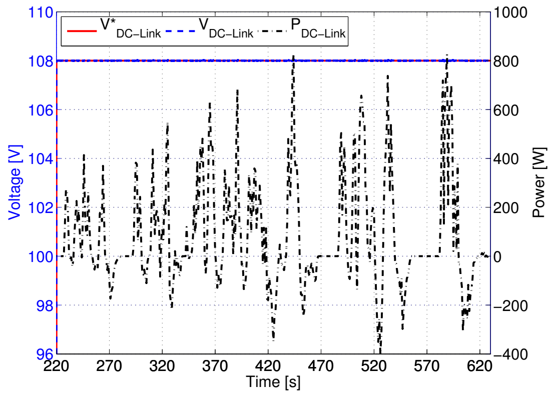

Figure 8: DC-Link voltage and power in passive topology

The passive hybrid results, $V_{DC-Link}$ and $P_{DC-Link}$, presented in Fig.8 demonstrates the desired voltage stability in the DC-link, even for the high power peak demand of 800 W. Moreover, through Fig.10 and 9 analysis is verified that the batteries have a less stressful behavior, which is a positive aspect for their life time.

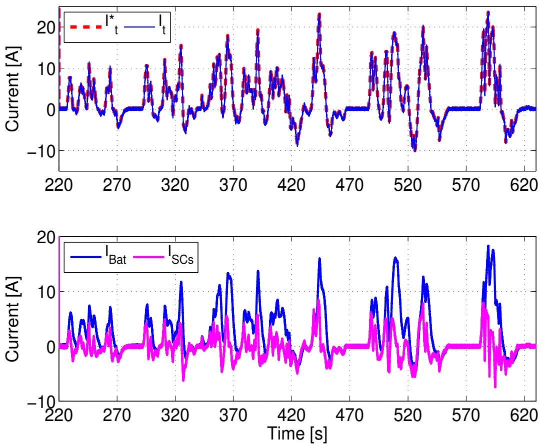

Figure 9: Total current required and sources current distribution

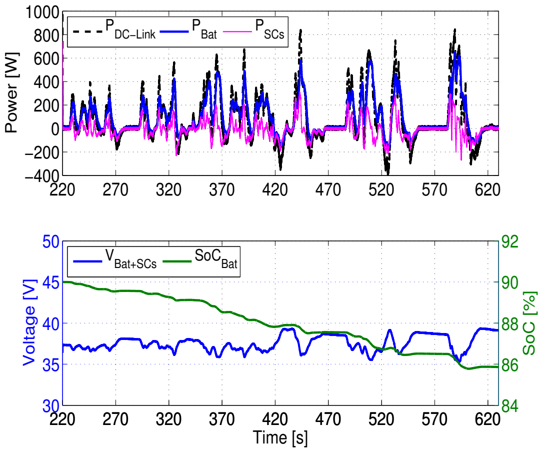

Figure 10: DC-Link power profile, sources power distribution, voltage and SoC in passive topology

This is possible due to the SCs faster response, being these responsible for sustain high frequency energy demands as can be seen through P_{SCs} and I_{SCs} behaviour in Fig.10 and 9 respectively. As a result, the power and consequently current profile for the batteries is smoother, because this source has a higher internal resistance when compared to the SCs and, therefore, a slower response time. Notice that, for the current reference of this topology, only I_t is presented because this topology uses just one DC-DC converter for both sources, meaning that, the I_t is the sum of I_{Bats} and I_{SCs}. The same happens with the sources voltage curve, V_{Bats} and V_{SCss} due to their direct parallel configuration. The SCs SoC curve is proportional to the square of voltage, thus, only the voltage is presented.

For the parallel active hybrid topology, it was once more attained the desired behaviour with the DC-link power demand fulfilled being the DC-link voltage maintained stable (see Fig.11).

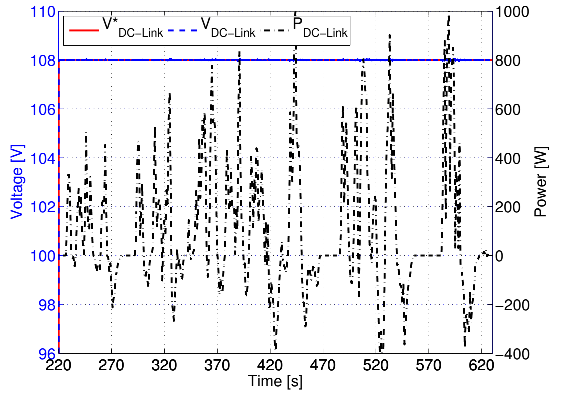

Figure 11: DC-Link voltage and power in active topology

In this topology there are two different current references, one for the batteries and one for the SCs respectively, which have a good match with the measured ones, meaning that the PI controllers were well designed. The total current, I_t, is also displayed in order to easily compare the total needed current and its distribution between the sources. From the analysis of the controller scheme of this topology and for the presented behaviour of each source, it is quite easy to understand that the current references are being ruled by the low-pass filter. Fig.12 shows that the SCs are responsible for satisfying the high frequency current demands. As a consequence the batteries have a smooth behaviour similar to the one obtained in the passive hybrid topology, as presented in Fig.13, but in this case this behaviour can be adjusted by changing the cut-off frequency of the low-pass filter. Therefore, this aspect represents an increment on the degrees of freedom of the energy management with this topology.

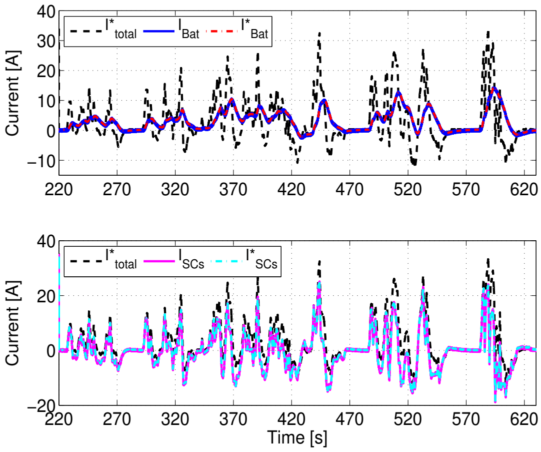

Figure 12: Total current required and sources current distribution in active topology

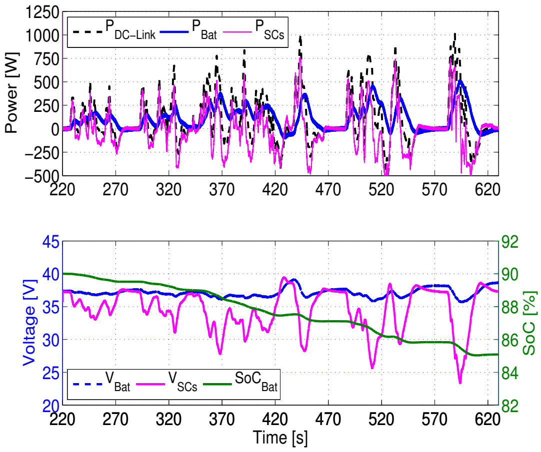

Figure 13: DC-Link power profile, sources power distribution, voltage and SoC in active topology

In all previous presented situations it is possible to notice that the $P_{DC-Link}$ demands are correctly fulfilled. This is verified by the sources current evolution, where it is noticed a perfect match between the measured and the reference currents, being always achieved a stable DC-Link voltage. Through Fig.13 analysis, the measured P_{Bats} and P_{SCs} values sum matches the $P_{DC-Link}$ demand, where once more, the desired effect of batteries smoothest behaviour is achieved being the SCs responsible for satisfying the transient power demands. Thus Fig.13 also shows an higher V_{SCs} oscillation, mainly caused by low-pass filter tuning and high $P_{DC-Link}$ power when compared to the previous presented cases. It is also interesting to remark that the final SoC_{Bats} value in these three topologies will be lower in a decreasing presentation sequence. However, this difference on the SoC_{Bats} value for each case is small when compared to the increment of power done for each test. Moreover, it is important to notice that in the topologies using SCs, the amount of regenerative energy received by the batteries is small, as is desired.

4 Conclusion

This paper presents a detailed analysis for three different hybrid topologies for EV powertrain purpose, namely battery, passive hybrid and parallel active hybrid topology. The required power electronics, applied controllers and energy management philosophy for each one of them are also mentioned in this paper. In order to understand what is the most suitable topology, simulations were preformed using a 410 seconds sample of the Artemis drive cycle and Matlab/Simulink environment. Therefore, from the achieved results the parallel active hybrid topology is the one who provides the best performance and cost-simplicity trade-off, exploiting the energy in a more effective way the battery pack (main ESS), avoiding them to operate in a less advisable region, which leads to an increase of their life time. This topology offers major degrees of freedom, and it is the one that allows the integration of intelligent energy management strategies.

Acknowledgments

This work has been framed under the Energy for Sustainability Initiative of the University of Coimbra and supported by the R&D Project EMSURE - Energy and Mobility for Sustainable Regions (CENTRO-07-0224-FEDER-002004) and by FCT through the grants UI0308-PTDC/EEA-EEL-1/2012, UI0308-PTDC/EEA-EEL-1/2013 and project grants PTDC/EEA-EEL/121284/2010, FCOMP-01-0124-FEDER-020391, MIT/SET/0018/2009, MIT/MCA/0066/2009 and PEst-C/EEI/UI0308/2011.

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