Analysis of Operation Modes for a Neighborhood Electric Vehicle with Power Sources Hybridization

João P. Trovão [1,3], *Student Member, IEEE*, Paulo G. Pereirinha [1,3,4], *Member, IEEE*, and Humberto M. Jorge [2,3], *Member, IEEE*

[1] IPC-ISEC, Polytechnic Institute of Coimbra, R. Pedro Nunes, P-3030-199 Coimbra, Portugal
[2] DEEC – FCTUC, University of Coimbra - Pólo II, P-3030-290 Coimbra, Portugal
[3] Institute for Systems and Computers Engineering at Coimbra (INESC-Coimbra), Portugal
[4] APVE, Portuguese Electric Vehicle Association.
E-mails: {jtrovao, ppereiri}@isec.pt; hjorge@deec.uc.pt

***Abstract*-Electric vehicles will have a fundamental place in sustainable mobility due to its very high efficiency and local/global emissions levels. To accomplish this role, both high power and high energy sources are desirable. In spite of recent advances in battery technology, this was not yet achieved and power sources hybridization can be a way to accomplish it. This is particularly true in the case of urban electric vehicles with very frequent speed variations and where regenerative braking can play an important role. In this paper the operation modes for a neighborhood electric vehicle with power sources hybridization are analyzed to define the convenient control strategy for its DC-DC converters. A system simulation is performed and an energetic analysis of different energy sources mix is done considering different acceleration requests. This is used to obtain a maximum energetic efficiency equation that can be used to optimize the control of the DC-DC converters.**

***Keywords*-Neighborhood Electric Vehicle, Power Sources Hybridization, Operation Modes, DC-DC converters, Energetic Efficiency.**

I. Introduction

Societies' development is closely connected to people and goods mobility. However, economic, ecologic and geopolitical aspects related with energy availability and unsustainable mobility threaten that humanity fair aspiration. Due to its very high efficiency and much smaller local/global emissions levels comparatively to internal combustion engines vehicles, electric traction has a fundamental place in sustainable mobility, especially road electric vehicles (EVs) [1]. Nevertheless, the EVs still have a major drawback: the energy storage. Typically, an EV stores energy in batteries that are bulky, heavy and expensive. Due to this problem, with current battery technology, it is very difficult to make a general purpose EV that effectively competes with ICE cars. For massive deployment of EVs its driving range problem must be solved.

At present and in the foreseeable future, the viable EVs energy sources are batteries, fuel cells, supercapacitors (SCs) and ultrahigh-speed flywheels. Batteries are the most mature source for EV application but currently they offer either high specific energy (HSE) or high specific power (HSP). Fuel cells are relatively less mature and expensive for EV application. They can offer exceptionally HSE, but with very low specific power. Such low specific power almost rules out their standalone application to EVs that require a high acceleration rate or high hill climbing capability and they are incapable of accepting the regenerative energy during EV braking or downhill driving. Also, in spite of EEStor company so far non verified claims, available SCs do not have the energy capacity needed for standalone application. However, these can offer exceptionally HSP. Flywheels are technologically immature for EV application. [2-4]

A primary objective, pursued by some researchers, is to improve both the vehicle driving range and battery/power sources cycle life, using a global energy storage system with multiple energy sources, taking full advantage of the best characteristics of each source type [5-7]. This can be particularly important in the case of urban electric vehicles, with very frequent speed variation and where regenerative braking can play an important role [7].

Those goals can be achieved by the use of efficient multiple input DC-DC converters in order to manage the power and energy correctly among the different sources, and the full utilization of the installed energy capacity [8, 9], taking into account each source characteristics and the current needed or available at each moment [5]. One of the most important issues is then to decide and control at each moment the power flow between all the components.

In this paper the operation modes for a neighborhood electric vehicle with power sources hybridization are analyzed to define the convenient control strategy for the power sources DC-DC converters. To do so, some results of the modeling and implementation on Matlab/Simulink of a double DC-DC converter (Fig. 1), to control independently two power sources for a particular small urban EV, whose authors' team has been working on [10], are shown and a maximum energetic efficiency equation is extracted from the results.

978-1-4244-8218-4/10/$26.00 ©2010 IEEE

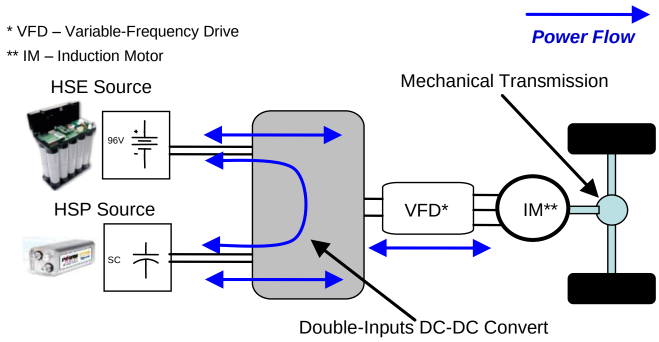


Fig. 1 Studied drive topology

II. MULTIPLE SOURCES AND DC-DC CONVERTERS

To use multiple energy sources that generally must have the possibility to exchange energy with the traction system but also between them, bidirectional DC-DC converters are needed, together with a careful study of the intended and authorized operation modes. This will allow defining the convenient control strategy for the power sources DC-DC converters as well as the components sizing.

A. Multiple Sources for EVs

A proper design of a powertrain for EVs has to select the components, in particular, energy sources, with the objective of optimize variables such as cost, weight and autonomy vehicle range [6]. The concept of using and coordinate multiple energy sources, to power the EV, is typically denominated hybridization. This allows the specific advantages of the various EV energy sources to be fully utilized, leading to optimized energy economy while satisfying the expected driving range and maintaining other EV performances. [6][11, 12]. For example, the objective of coupling batteries and supercapacitors, is to reduce the current stress in the batteries in order to decrease its size and cost and to improve its lifetime [13].

To obtain the hybridization of energy sources in autonomous systems, it is necessary to adapt its characteristics and particularly the voltage levels. For this and as the energy storage in autonomous systems is done in DC, there is the need to use the DC-DC converters to meet the intended requirements.

Among the viable EVs energy sources, it was chosen batteries and supercapacitors coupled to a double-input DC-DC converter in parallel configuration.

B. Multiple DC-DC Converters Topology

In the literature, several multiple input DC-DC converter topologies have been presented in the last years. These are based mainly in pulse width modulation (PWM), in the concept of flux additivity or in converters for energy storage devices with advanced batteries and supercapacitor banks. [8]

For the proposed study, the VFD DC link has a 600 V voltage and the first power source is a battery bank with 96 V voltage (2 parallels of 8x12V NiMH modules) and the second power source is a supercapacitor bank, 80 V (5x16V modules). The used power scheme is presented in Fig. 2.

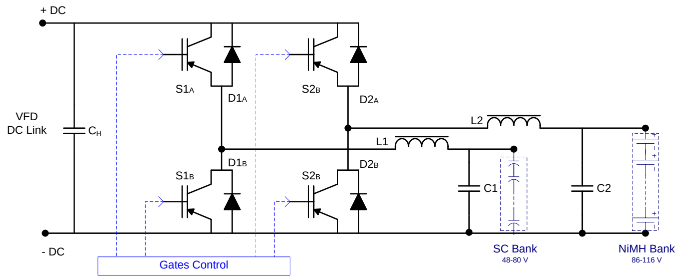


Fig. 2 Double-input DC-DC converter used power sheme

As the EVs sources have dynamic performance, according to the applied load, and its voltage varies over time, the duty-cycle will be dynamically adjusted through the constant monitoring of input and output voltages. The converters operate in boost or buck modes depending on the level of the voltage in the DC link, e. g., when there is energy regeneration and the voltage level of the DC link increases needing to be conducted to a source, then one of the choppers start to operate in buck mode.

DC-DC converters are used as switching-mode regulators to convert a DC voltage to a regulated DC output voltage. The regulation is achieved by Pulse-Width Modulation (PWM) at a fixed frequency and with an IGBT as the switching device.

III. EV OPERATION MODES

Depending on the vehicle's operation modes the electric machine can work as a motor or a generator and also there can be several energy flow needs.

For example, considering the simplest displacement of a vehicle, shown in Fig. 3, there is an acceleration phase (red one), a phase of constant speed operation (blue one) and a deceleration phase (green one). From this diagram, the energy trading needed to respond to driver requests can be defined, using the energy sources previously choose. Since the vehicle has two energy sources, two additional phases where considered, one to prepare the start and another to prepare the shutdown.

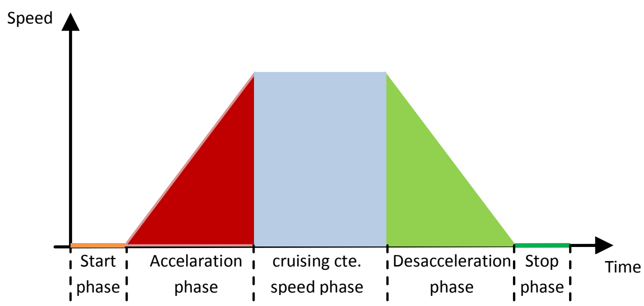


Fig. 3 Typical driving phases

The "Start" and "Stop" phases are used to prepare the energy storage system to a state that best suits the next phase. Prior to an acceleration phase, it is needed to full charge the unit with more HSP (supercapacitors) from the other unit that has more HSE (batteries). On the other hand for security reasons, it is convenient to discharge the SCs when the key is turned off. In this case, the regenerated energy stored in the SCs during the deceleration can be returned at a slower and convenient charge rate to the batteries. So in the "Start" and "Stop" phases the two DC-DC converters are operating simultaneously, but in the first case the batteries' converter works as a boost and the SCs converter like a buck, and in the other one, they reverse working modes. Therefore during these phases the currents of the sources are equal but with opposite signs, when one is positive, the other is negative.

A full study must be done concerning all the EV other operation modes, considering the sources capacities, its convenient and maximal charge and discharge rates, in order to define the DC-DC converters control strategy, to respond to the road and driver's demands and maximizing the regenerative energy use, without compromising the sources lifetime.

IV. MATLAB/SIMULINK MODELLING

The EVs and its components were modeled by Matlab/Simulink, using the SimPowerSystems library [14, 15]. The main models used in this study are the sources and the double-input DC-DC converter. These used models are presented bellow.

A. Batteries bank model

The batteries bank is modeled by SimPowerSystems library, through a block allowing the modeling and computational implementation of batteries (Fig. 4). The Battery block implements a generic dynamic model parameterized to represent most popular types of rechargeable batteries. The parameters of the equivalent circuit can be modified to represent a particular battery type, based on its discharge characteristics. For the purpose project, the main power sources are two NiMH battery banks with 96 V nominal voltages and 13,5 Ah rated capacity (2 parallels of 8x12V SAFT VH modules).

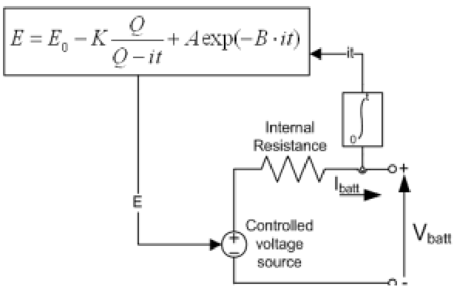


Fig. 4 The equivalent circuit of the NiMH battery

B. Supercapacitors bank model

At present, there are several propositions of supercapacitor model representation [16]. The simplest of all is the classical equivalent circuit and it consists of a capacitance (C), an equivalent series resistance (ESR) representing the charging and discharging resistance, and an equivalent parallel resistance (EPR) representing the self-discharging losses with the lumped capacitance. Fig. 5 shows the classical equivalent circuit with the three parameters. The EPR represents the current leakage and influences the long-term energy storage. In multiple series connections of supercapacitor, the EPR influences the cell voltage distribution due to the resistor divider effect, and since the EPR models leakage effects and influences long-term energy storage performance of the supercapacitor [16], only the ESR will be taken into account. The supercapacitor bank (5x16 V MAXWELL BMOD0330 modules) model has been implemented in Matlab/Simulink for this study.

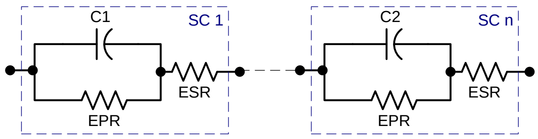


Fig. 5 Classical equivalent circuit of n Supercapacitors

C. DC-DC converter model

The global electrical system contains also a DC-DC converter. The role of the DC-DC converter is to adapt the low voltage of the battery (96 V) to the DC bus, which feeds the AC drive at about 600V voltage. It models a two-quadrant chopper (buck-boost converter). The VFD DC link voltage is provided by an IGBT buck-boost converter controlled by a PI regulator [14]. The inductor size depends on voltage boost, average DC current, and AC ripple current. Considering a 25 kHz constant switching frequency, and a peak-to-peak ripple current of chopper's inductors close to 2 A, the inductors values are 1.4 mH. In this DC-DC converter modeling it was used a saturated inductor model in order to approximate the simulations to the prototype test-bed. For the capacitor filter, it was chosen a 100 μF with a very low ESR.

V. SIMULATION RESULTS

Using the considered energy storage models presented before and the VEIL dynamical model [14], the system behavior was computed using Matlab/Simulink®, with the SimPowerSystems library. For all the simulations, the power system has been discretised with a 20 μs time step. The speed controller uses a 100 μs sampling time and the space vector modulator also uses a 20 μs sampling time in order to simulate a microcontroller control device. The implemented models took into account the characteristics of the project EV. Its specifications, used for this computer modeling and simulation study, are presented in Table I.

TABLE I

EV PROJECT VEHICLE SPECIFICATIONS

Parameter	Value
Vehicle mass (kg)	500
Rolling Resistance Coefficient	0.015
Aerodynamic Drag Coefficient	0.51
Front Area (m^2)	2.4
Wheels radius (m)	0.26
Gearbox transmission ratio	10

The results of the VEIL simulations are presented in Fig. 6. In the simulation shown, the vehicle was submitted to a maximum speed of 50 km/h with a 6.25 m/s^2 acceleration which corresponds to a passage from standstill to 50 km/h in 8 s. The speed set point is presented in Fig 6a) (red curve). It starts with a first 10 s period where the requested speed is null. Then there is an 8 s acceleration phase (as described above), followed by cruising at constant speed (50 km/h). After that, the vehicle decelerates from 50 km/h to standstill in 8 s. Finally, in the last 4 s, the vehicle is in stationary mode, waiting for another possible move.

The vehicle's speed evolution is a good approximation in time domain to the request, as can be seen in Fig. 6a) from the dashed blue curve. The vehicle follows almost perfectly the speed set point, with minor fluctuations in speed, especially at the end of the quick acceleration. The Currents and Voltages of the Energy Sources and DC link are presented in Fig. 6b).

In the first 10 s, when the vehicle is stopped, since it is wanted a sharp acceleration, the batteries charge the SCs. Care has been taken to use a current controller that can control the battery discharge current with a current that does not damage them. Referring to the datasheet of the manufacturer, the constant discharge current allowed is 50 A (25 A per bank). It was considered that the battery SOC is 85% and the SCs have a previous charge corresponding to a 45 V voltage.

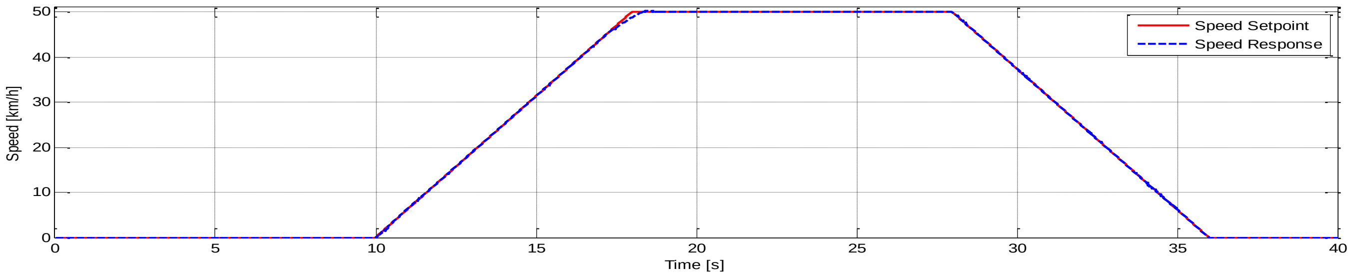
As can be seen in Fig. 6b), in the early 10 s the batteries provide a 50 A average current, which induces the presented battery voltage evolution, corresponding to a discharge. At the same time, the SCs charge with a starting current close to – 100 A, value that decreases as the voltage increases, synonymous of energy storage.

The next phase is the acceleration one. At the beginning of this phase, the power train does not need all of the maximum battery current, and the SCs continue to charge. When the power train current request is greater than the battery limit, the second source (SCs) passes from receiver to supplier, and helps the main source (battery) to feed the vehicle in order to achieve the acceleration request.

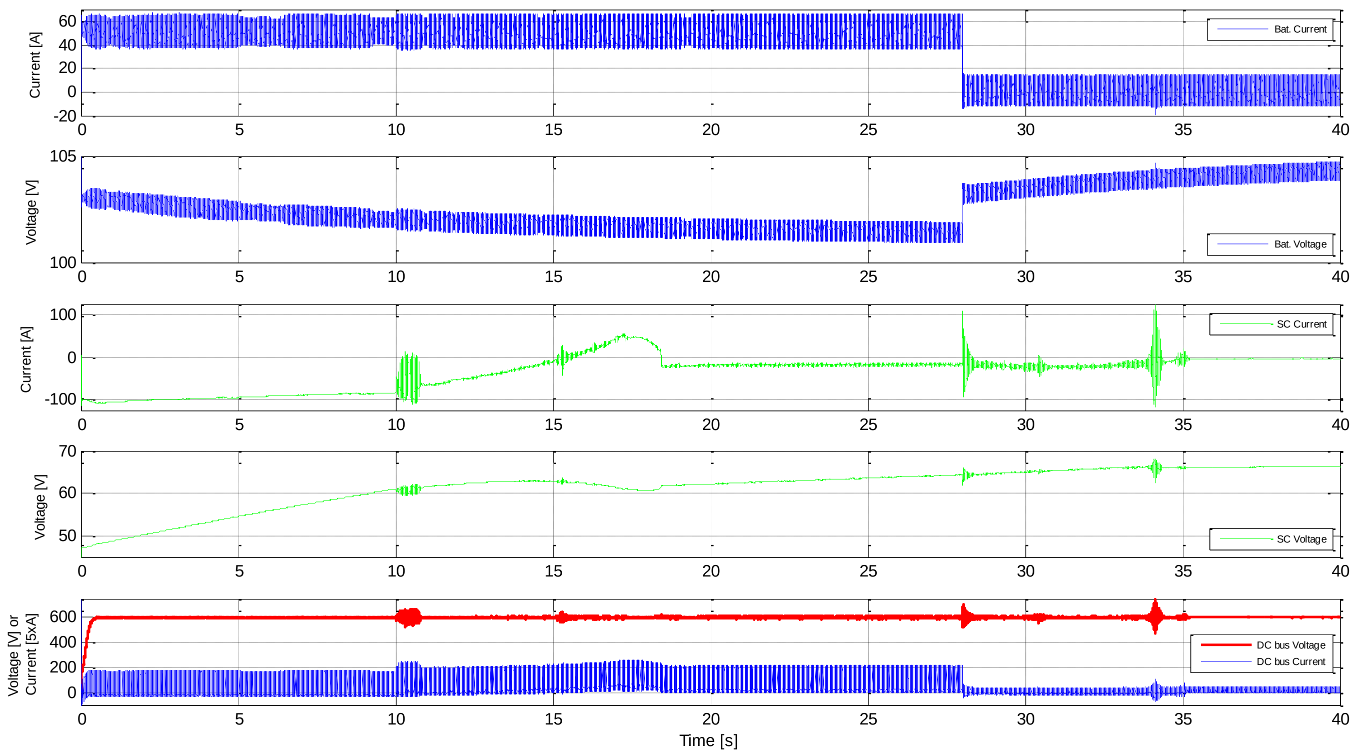
For the next 10 s, the vehicle cruises at 50 km/h, and it is verified that the battery limit of the 50 A is more than the power train needs, and so, the SCs are charged with the difference and as can be seen a much slower charge than in the initial phase.

In the deceleration phase, it was implemented a control that allows most of the regenerative energy to be absorbed by the SCs, as shown in the evolution of the curves associated with SCs. Finally, when the EV is stopped no energy exchange takes place.

The 600 V DC link presented a voltage evolution close to 600 V with particular fluctuation in the phase transitions.



a)



b)

Fig. 6 a) Driving speed setpoint and vehicle speed response; b) Currents and Voltages of the Energy Sources and DC link

VI. ENERGETIC ANALYSIS

After the hybridization EV model implementation and simulation, it was studied the best exchange of energy between the power source and the power train, in order to search the correct mix response to the power demand of some possible acceleration. To accomplish that, two phases were considered. The first one corresponds to an energy exchange between batteries and SCs where the batteries charge the SCs at the battery limit current. The second phase is the acceleration phase, considering different accelerations. The considered accelerations are presented in Fig. 7. All the accelerations are made in 8 s with different end speed set point (10, 20, 30, 32, 34.67, 37.34, 40 and 50 km/h).

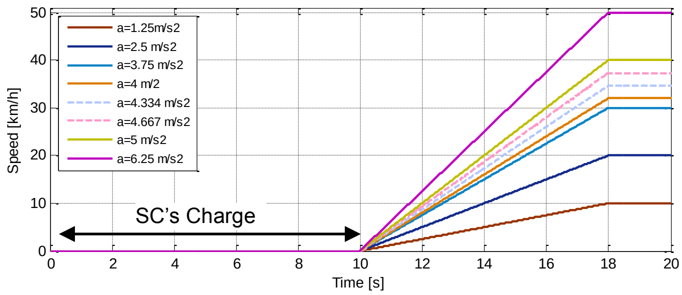


Fig. 7 Considered accelerations for energy analysis

To evaluate the hybridization response of the two considered energy sources, in the acceleration phase different mixes for each acceleration were compared. In Fig. 8 is presented the seven mixes combination used in the efficiency comparison. The extreme situations represent the use of a single source, Case 1-SCs only and Case 7-Battery only. Case 3 use 50% of each power source. Case 2 and 6 are symmetric, divide the powered energy into 25% and 75% of the two sources. Case 4 and 5 powered 62% and 68% of the total energy by the batteries and SCs provide the remaining.

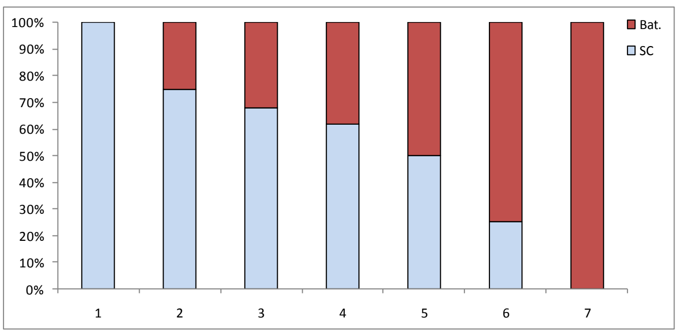


Fig. 8 Different mix of energy use considered for each acceleration

Since the second power source (SCs) cannot be used if it has not been previously charged, then the first phase is crucial and should be considered in the energy efficiency computation. Therefore, the used equation to evaluate the performance is presented in (1), where p_{Total} is the total instantaneous power demand by the EV power train, p_{F_1} is the power supplied by the main source (batteries) and p_{F_2} is the power supplied by the second source (SCs).

$$\eta_{W_{Total}} = \frac{\int_0^t p_{Total}(t).dt}{\int_0^t p_{F_1}(t) + p_{F_2}(t).dt} \quad (1)$$

The considered period, for the computation of the energetic efficiency of the power sources hybridization, is 18 s. Equation (1) can be developed taking into account the two phases, the first when the SCs charge directly from the batteries and the second when the EV requests to the power sources in order to acceleration responds. Thus, equation (1) can be manipulated to obtain equation (2), which integrates the instantaneous power in the two phases, as well as the powers provided by energy sources. The first integration is done between 0 and 10 s and the second is between 10 and 18s.

$$\eta_{W_{Total}} = \frac{\int_0^{t_1} p_{Total}(t).dt + \int_{t_1}^{t_2} p_{Total}(t).dt}{\int_0^{t_1} p_{F_1}(t) + p_{F_2}(t).dt + \int_{t_1}^{t_2} p_{F_1}(t) + p_{F_2}(t).dt} \quad (2)$$

For the proposed study, when it is needed to operate the first phase, energy does not flow to the power train and the integration of p_{Total} is null and all the energy supplied by the batteries flows to the SCs (except the choppers, electrical interconnections and cables losses). In the specific case in which only feeds from the EV batteries, the first integration in the period t_1 to t_2 is not required and it is only used the integration over the second period (second phase).

Computing equation (2) for all the accelerations presented in Fig. 7 with the power source mixes presented in Fig. 8, it was obtained the energetic efficiency as a function of the used ratio of the main energy source (batteries) in the sources mix, for each EV accelerations (and corresponding currents), as presented in Fig. 9.

Equation (3) presents the relation between the acceleration, a, and the nominal current demand, I_{load}. This equation was obtained by polynomial approximation using simulation made for the several accelerations.

$$I_{load} = 3.898 \cdot a^2 - 6.789 \cdot a + 7.905 \quad (3)$$

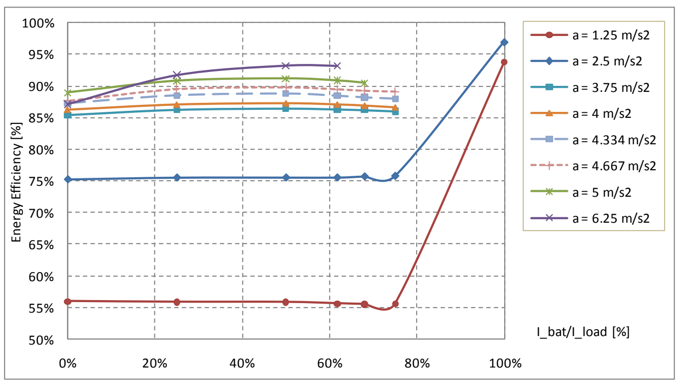


Fig. 9 Energetic efficiency as a function of the batteries usage in the sources mix for different accelerations, a

Analyzing the results presented in Fig 9, it is clear that for accelerations where the load current does not exceed the maximum current set to discharge the battery (50 A), and for the power requested by the vehicle, should only be used the power supply through the batteries. Therefore, at this stage there is no need to charge the SCs and to bear their and associated electronics losses in the global operation. This is consistent with common sense and to the specific purpose of using a second source, since this is mainly required to reduce the stress caused by requests for high currents to the batteries, thus extending its life. Hence, from the energetic efficiency point of view, for the specific case of VEIL, it appears that until an acceleration of around 4 m/s^2 power directly from the main source is the most efficient. On the other hand, more demanding accelerations than 4 m/s^2, can only be achieved with the help of the second source. Zooming the accelerations' results, between 3.75 m/s^2 and 6.25 m/s^2, it evidences an evolution that can be approximated by second order polynomials, as shown in Fig. 10.

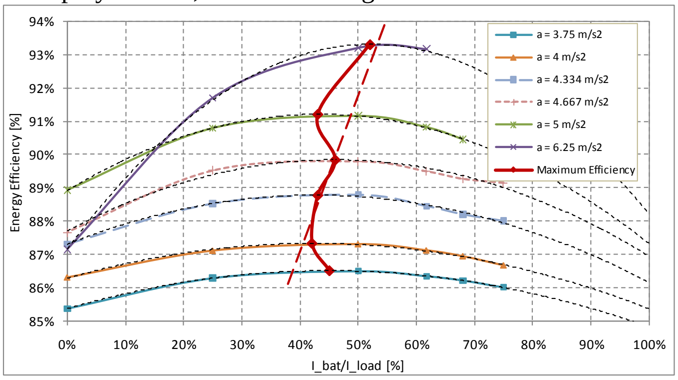


Fig. 10 Energetic efficiency evolution for higher accelerations

With this approach, the maximum efficiency for each acceleration can be found and thus to obtain the mix of the two sources that lead to this maximum efficiency. Representing in Fig. 10 these maximum values and linking them, it was obtained a curve that suggest a possible linearization in order to obtain the optimal power flow distribution's ratios requested from two sources. This proposed linearization presents the following expression (4).

$$\eta_{W_{max}} = 0.473 \cdot \frac{I_{bat}}{I_{load}} + 0.681 \quad (4)$$

Expressions (3) and (4) can be combined at any time, through the acceleration required (or desired speed for EV), to calculate the energetically most efficient mix of the two considered sources. This can be used with more advanced algorithms to optimize the energy management for full EV with hybridization concept.

VII. CONCLUSIONS

In this paper the operation modes for a neighborhood electric vehicle with power sources hybridization were presented and analyzed. A system simulation was performed and a methodology to obtain a maximum energetic efficiency equation, considering different energy sources mix ratios and different acceleration requests, was developed. This can be used to optimize the control of the DC-DC converters and power flows.

REFERENCES

[1] P.G. Pereirinha, J.C. Quadrado, J. Esteves, "Sustainable Mobility: Part I – MAIN PROBLEMS and "Sustainable Mobility: Part II – Some Possible Solutions Using Electric and Hybrid Vehicles", CEE´05 - International Conference on Electrical Engineering, in CD-ROM, October 10-12, 2005, Coimbra – Portugal;

[2] K.T. Chau, Y.S. Wong; "Hybridization of energy sources in electric vehicles", Energy Convers Mgmt 42 - 9 (2001), pp. 1059–1069;

[3] Burke, A.F., "Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles", Proceedings of the IEEE, Volume 95, Issue 4, April 2007 Page(s):806 – 820;

[4] Lukic, S.M., Jian Cao, Bansal, R.C., Rodriguez, F., Emadi, A., "Energy Storage Systems for Automotive Applications", IEEE Transactions on Industrial Electronics, Volume 55, Issue 6, June 2008 Page(s):2258 – 2267;

[5] Schupbach, R.M.; Balda, J.C.; Zolot, M.; Kramer, B.; "Design methodology of a combined battery-ultracapacitor energy storage unit for vehicle power management"; Power Electronics Specialist Conference, 2003. PESC ´03. 2003 IEEE 34th Annual; Volume 1, 15-19 June 2003;

[6] Trovão, J. P., P. G. Pereirinha, H. M. Jorge. "Design Methodology of Energy Storage Systems for a Small Electric Vehicle", World Electric Vehicle Journal Vol. 3 - ISSN 2032-6653, 2009;

[7] Paulo G. Pereirinha, João P. Trovão, "Comparative study of multiple energy sources utilization in a small electric vehicle", 3rd European Ele-Drive Transportation Conference EET-2008 - Geneva, March 11-13, 2008;

[8] K. P. Yalamanchili, M. Ferdowsi, "Review of multiple input dc-dc converters for electric and hybrid vehicles," IEEE Vehicle Power and Propulsion Conference, 7-9 Sept. 2005, pp. 160-163;

[9] S. H. Choung, A. Kwasinski, "Multiple-Input DC-DC Converter Topologies Comparison", in 34th Annual Conference of IEEE Industrial Electronics, 2008. IECON 2008, 10-13 Nov. 2008, pp. 2278-2283;

[10] P. Pereirinha, J. Trovão, L. Marques, M. Silva, J. Silvestre, F. Santos, "Advances in the Electric Vehicle Project-VEIL Used as a Modular Platform for Research and Education", EVS-24, The 24th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition, Stavanger, Norway, May 13-16, 2009, in CD-ROM;

[11] Y.M. Chen, Y.C. Liu, F.Y. Wu, and T.F. Wu, "Multi-Input DC-DC Converter based on the Flux Additivity," in 36th Annual Industry Applications Conference, vol. 3, 30 Sept.-4 Oct. 2001, pp. 1866 – 1873;

[12] A. Di Napoli, F. Crescimbini, S. Rodo, and L. Solero, "Multiple input DC-DC power converter for fuel-cell powered hybrid vehicles," in 33rd Annual IEEE Power Electronics Specialists Conference, vol. 4, 23-27 Jun 2002, pp. 1685–1690;

[13] Allegre, A.L. Bouscayrol, A. Trigui, R.; Influence of control strategies on battery/supercapacitor hybrid Energy Storage Systems for traction applications , IEEE Vehicle Power and Propulsion Conference VPPC '09, Sept. 7-10,2009;

[14] João P. Trovão, Paulo G. Pereirinha, Humberto M. Jorge, Simulation and Road Tests Comparative Results of a Small Urban Electric Vehicle, IEEE IECON 2009, The 35th Annual Conference of the IEEE Industrial Electronics Society, November, 3-5, 2009, Porto, Portugal;

[15] João P. Trovão, Paulo G. Pereirinha, Fernando J. T. E. Ferreira, "Comparative Study of Different Electric Machines in the Powertrain of a Small Electric Vehicle", 18th International Conference on Electrical Machines, ICEM'08, Vilamoura, Portugal, 6-9 September 2008 in CD-ROM;

[16] E. Surewaard, M. Tiller, D. Lizen, and D. Linzen, "A comparison of Different Methods for Battery and Supercapacitor Modeling," presented at SAE Future Transportation Technology Conference - SAE Technical Paper Series 2003-01-2290, 2003.