Overview on Energy Management Strategies for Electric Vehicles – Modelling, Trends and Research Perspectives

Pedro Melo(1), Rui Esteves Araújo(2), Ricardo de Castro(3)
(1) Instituto Superior de Engenharia do Porto, Porto, Portugal
(2) INESC Porto, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal
(3) Faculdade de Engenharia da Universidade do Porto, Porto, Portugal
pma@isep.ipp.pt, {raraujo, sirpdc}@fe.up.pt

***Abstract*--** **The economical and environment impacts of fossil energies increased the interest for hybrid, battery and fuel-cell electric vehicles. Energy management systems (EMS) have a fundamental role in achieving high efficiency levels in vehicle performances, without compromise its drivability features. This is a complex task, since one is dealing with the integration of different physical subsystems. In addition, several vehicle electric power-train architectures must be considered, requiring different energy management approaches. Considering EMS for real-time applications will bring a higher complexity level. This paper aims at putting these efforts into perspective deriving a more holistic view of the literature in this topic. We start the analysis on the general requirements for EMS to identify the more demanding ones for real-time applications. Based on this analysis, we suggest some open challenges and describe new research opportunities.**

***Index Terms*--** **Electric vehicles, energy management, optimization, modeling, simulation.**

I. INTRODUCTION

The several energy crises at the end of the 20th century, together with the environment impacts and the awareness of the limits of fossil fuel reservations are the main reasons why hybrid and electric vehicles have been known an increasing interest, as they represent, at the moment, a clear alternative to the classic vehicles based on internal combustion engine (ICE).

It is in the transportation sector that the fossil energy consumption achieves the higher levels, which are increasing every year [1]. Particularly on urban centers, electric vehicle´s spreading will be responsible for considerable reductions in the air pollution, as well in noise levels. The green house gases emissions of fuel electric plants related to the electric vehicles will be much lesser than the ones in ICE vehicles. The main reasons are the electric power train higher efficiency and regenerative braking mode.

Hybrid and electric vehicles are bringing new engineering challenges, since several different domains (electric motors, power electronics, energy storage devices, control theory, automobile technology) must be coherently integrated, in order to achieve, at least, similar drivability goals of conventional vehicles. The dynamic interactions between its several different components and its multidisciplinary nature make it difficult to analyze – a deep knowledge on this issues is mandatory for the development of an EMS, which turns to be determinant for the vehicle´s future.

EMS´s purpose in electric vehicles (EV) is to control, with the highest efficiency levels, the power flow between storage devices (batteries, supercapacitors (SC)), generation devices (fuel cells (FC)) and electric motors, including the power electronic converters, its control systems and auxiliary storage devices. These purposes must be achieved under instantaneous drive performance demands. Therefore, development of real-time EMS will be mandatory. In addition, different EV power-train architectures mean different system configurations (battery+SC, battery+FC, FC+SC, battery+SC+FC, etc.), so a single EMS design may not suite all the possible configurations.

Different EMS structures, together with efficient real-time performance, significantly increases the control task complexity. Modeling and simulation are crucial in order to reach these goals, since it allows concept evaluation and prototyping, in a non expensive and time consuming way. This is determinant for new power-train configurations and controllers development [2], [3].

This paper is structured as follows: Section II presents an overview on hybrid and electric vehicles main features. In Section III a general review of EMS models for EV is presented, including conventional mathematical approaches and more recent graphic ones. The purpose is to establish a preliminary starting basis for our goals: development of real-time EMS algorithms for EV. Section IV includes the conclusions and the next steps in our work.

II. BACKGROUND ON HYBRID AND ELECTRIC VEHICLES

This section provides a general sight in electrical vehicles topics that are required for the overview in EMS which are to follow.

Alternatives to ICE vehicles can be classified as Hybrid Electric Vehicles (HEVs) and pure electric vehicles (EVs), which include battery-powered electric vehicles (BEVs) and fuel cell vehicles (FCVs). By pure electric vehicle (EVs), one means drive-trains without ICE, only electric motors are present – fully electric vehicles.

A. *Hybrid Electric Vehicles*

HEVs use a combination of ICE power train and an electric motor power train to overcome the disadvantages of both ICE vehicles (demand for oil, green house gas emissions) and the pure battery-powered electric vehicle (high initial cost, short driving range and long charging time) [2], [3]. HEVs use the electric motor(s) to optimize the efficiency of the ICE, as well to recover the kinetic energy during the vehicle braking. Basically, there are three different configurations, depending on the ICE connection to the electric propulsion system [2], [4]:

1) Series HEV

The ICE mechanical output is converted into electricity using a generator, which either charges the battery or is used to propel the wheels via the same electric motor and mechanical transmission. So, there is no mechanical connection between the ICE and the traction load. The decoupling between the ICE and the driving wheels has the advantage of flexibility for fixing the engine operating states. Nevertheless, it has three propulsion devices (ICE, generator, electric motor). Therefore, the efficiency of series HEV is generally lower.

2) Parallel HEV

It allows both the ICE and electric motor to deliver power in parallel to drive the wheels. Both the ICE and electric motor are generally coupled to the drive shaft of the wheels via two clutches, so the propulsion power may be supplied by the ICE alone, by the electric motor, or by both.

The electric motor can be used as a generator to charge the battery in two ways:

- Regenerative braking;
- Absorbing power from the ICE when its output is greater than that required to drive the wheels.

The parallel hybrid needs only two propulsion devices – ICE and the electric motor. Another advantage over the series case is that a smaller ICE and a smaller electric motor can be used to get the same performances.

3) Series-Parallel HEV

This configuration incorporates the features of both the series and parallel HEVs, but involving an additional mechanical link and an additional electric machine compared with, respectively, the series hybrid and parallel hybrid. A planetary gear set must be included in the drive-train, in order to allow the mechanical coupling between the three machines and the transmission shaft.

It presents the good features of both the series and parallel HEVs. However, the planetary gear set and the three machines make the drive train more complicated, costly and increase the control complexity. In order to reduce the system weight and size, a combination of two concentric electric machines can be used as a power split device, instead of the planetary gear set [4]. In addition, special electromechanical converters were developed: the two electric machines are substituted by a single one, with double rotor – the electric variable transmission concept [5], [6].

B. Fully Electric Vehicles (FEVs)

For FEVs there are several electric motor topologies, including more than one motor [7]: a single electric motor, an electric motor in each of the steering wheels, a motor for each rear wheel and one motor per wheel.

As stated before, there are two different concepts for EV:

1) BEV

As the vehicle is powered only by batteries, zero emission can be achieved. The high initial cost of BEVs and its weight, its short driving range and long recharging time, together with low power densities, are the main drawbacks. Several batteries types have been developed in the last years [8].

Presently, the most common batteries for HEV and EV are Nickel Metal Hydride (NiMH), Lead Acid (Pb Acid), and Lithium Ion (Li Ion). These last ones have known a considerable improvement in its energy density values (at the moment they present the highest ones). Recently, new BEV architectures have been proposed that use several energy sources – hybrid storage systems. In fact, there is a clear trend for combining batteries with other storage devices, particularly, SCs (high power density) [2], [9], [10]. The inclusion of power electronic converters at the storage energy level not only allow to decouple the power (acceleration, braking mode) and energy (cruise speed) functions of storage, providing lower power levels in batteries, but also improves the energy management efficiency in the storage system [10], [11], [12], [13]. For instance, in [12] it is shown the improvement in the capability of storing the braking energy, together with the control of Joule losses, both in the battery and in the SC.

2) *Batteries for FEVs*

Traction batteries generally operate in very aggressive operating environments, submitted to wide temperature ranges. In addition, the hard loading cycles to which they are subjected, as well as shock and vibration may lead to fast aging (loss of capacity and internal resistance increase) [4]. These batteries have more demanding features than the ones for standby power units and portable electronic devices (lap-top computers, cellular phones, etc.).

There are several factors that affect battery performance, such as: [14]

- State of charge (SOC);
- Battery storage capacity;
- Rate of charge/discharge;
- Operation temperature;
- State of health (SOH);
- Age.

Every battery pack must include a management system, not only to monitor and protect the battery and its users, but also for keeping it ready to deliver (or charging) the power demanded by EMS. The battery management system (BMS) must pay a special attention to braking modes, since the large current and gradient values may destroy the battery pack.

Particularly, lithium battery cells must be operated under tight controlled conditions. These cells are affected by over voltage, over current and temperature, which may lead to irreversible cell damage.

An important challenge to BMS is also the ability to monitoring the battery SOH in real time. In fact, most of the present methods used for this purpose are time consuming, meaning they are not suitable for online applications [15].

To predict the performance of batteries, different mathematical models exist. Accurately modeling battery in HEV and EV is important and it is not easy. The reason is that the main variables that characterize battery operation (state of charge, voltage, current, and temperature), are dynamically related to each other [11].

3) FCV

Includes an electrochemical device (FC) that generates electrical energy as a result of an electrochemical reaction based on hydrogen (nonpolluting fuel, with a high energy content per unit of weight). In addition, the fuel cell reaction´s product is water steam. There is an important difference between a fuel cell and a battery: the first one generates (convert) energy, the last one stores it. Some of its advantages are efficient conversion of fuel (hydrogen) to electrical energy, quiet operation, zero or very low emissions and rapid refueling. [2], [3]

Fuel cell´s produced electricity can be used to provide power to the propulsion motor or stored in batteries or super-capacitors for future use. [2]

Development of mathematical models of Fuel-cells is also fundamental for EMS purposes.

4) HEV, BEV and FCV Impact Preview

HEV and BEV spreading, particularly in urban centers, will be responsible for considerable reductions in the air pollution, as well in noise levels. The green house gases emissions of fuel electric plants related to BEV will be much lesser than the ones in ICE vehicles. The main reasons are the electric power train higher efficiency and regenerative braking mode. EMS´s are a fundamental key for vehicle´s energy fluxes control with high efficiency levels.

FCV development is in a lower lever than the previous ones. A major issue is that the future of FCV is dependent on the development of a large scale hydrogen infrastructure – hydrogen economy paradigm [16]. According to this reference, there are several on-going European projects trying to coordinate fuel cell and hydrogen technologies development. However, this is a subject far from unanimous view [17]: many authors and experts have a reluctant perspective about a hydrogen based economy.

Plug-in electric vehicles (PV) are an important step toward zero emissions goal, particularly with renewable energy sources integration [18]. However, having in mind battery´s sate of the art, it is predictable, in the near future, that PV will be limited to urban drive scenario (relative short distances). Another relevant feature of PVs is that can be used as energy storage units to serve the grid when they are parked and plugged-in. So, PVs can be recharged during the night (low demand for electric energy) and supply energy to the grid during day time (high demand for electric energy). This could help to achieve a more uniform grid charge diagram [18], [19]. Table I presents the main characteristics of each kind of vehicle.

TABLE I
CHARACTERISTICS OF HEV, BEV AND FCV [4]

	HEV	**BEV**	**FCV**
Energy Storage Subsystem (ESS)	- Battery - Supercapacitor - Fossil or alternative fuels	- Battery -Supercap.	- H_2 tank -Battery & supercapacitor to enhance power density
Energy Source and Infrastructure	- Gasoline stations -Electrical grid charge facilities (Plug-in hybrid)	-Electric grid charge facilities	- H_2 -H_2 production and transport infrastructure
Characteristics	- Low local emissions - High fuel economy - Dependence on fossil fuel - Long driving range - Higher cost than ICE vehicles	- Zero local emissions - High energy efficiency - Independent of fossil fuel - Relatively short range - High initial cost	- Zero local emissions - High energy efficiency - Fossil fuel independent (if not using gasoline to produce H_2) - High cost

III. Overview On Energy Management Models For BEVs And FCVs

The power and energy control of multiple energy storage systems within FEV vehicle architectures have been addressed through several approaches, as will be presented in section C.

In the last years an intensive research work has been done in developing energy management models for HEVs. Nevertheless, they can easily be adapted to BEVs and FCVs: in fact, these two kinds of vehicles can be considered as specific cases of HEVs [4], since it is inevitable that the system includes multiple energy sources. This does not exclude the eventual necessity of developing specific models for BEVs and FCVs. Fig.1 presents a general structure of BEV and FCV.

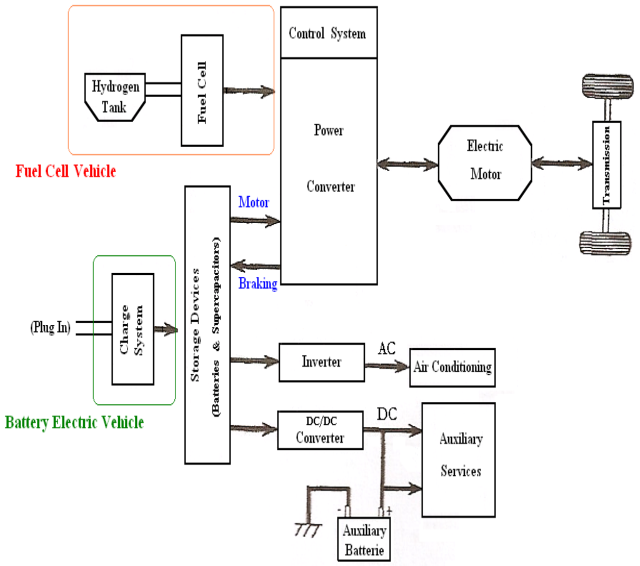

Fig. 1. BEV and FCV basic structure (based on [2]). Devices outside color rectangles are the common ones for both structures

The EMS is a fundamental component for HEV, BEV and FCV, since the energy flux in the drive-train must be always associated to high efficiency levels, without compromising vehicle performance constraints.

As stated before, the FEVs future will pass by multiple energy sources and converters, to benefit from the best characteristics of the energy sources available. The FEVs energy management issue is related to the necessity of multiple energy sources (hybridization) [20].

Modeling these systems is a fundamental step to achieve efficient EMS. However, it is complex due to the multiple interconnected physical subsystems and the multiple levels of the different dynamics [4]. For instance, considering FEV, basic drive train structure includes fuel cell and/or batteries, super-capacitors, power converters, electric motors and mechanical transmission [11]. In order to have a reference for driving behaviors, a set of standard driving cycles was created. This way, different EMS efficiency can also be implemented and compared, under same references. The most common standards in use are [21]:

- In USA, the urban driving dynamometer schedule (UDDS), for city driving; outside urban environment, the federal highway driving cycle (FHDS);
- In Europe was defined the urban driving cycle (ECE 15) and extra-urban driving cycle (EUDC), for highway driving. More recently a mixed driving cycle (urban/sub-urban) was created in Europe: the New European Driving Cycle (NEDC);
- In Japan, a mixed driving cycle (urban and extra urban features) was defined: the 10-15 mode.

Real world drive features, like speed and acceleration characterization, are much more complex than the ones in standard driving cycles [11]. EMS for real-time applications must deal with more complex drive scenarios, difficult to be modeled [22], [23].

A. EMS Strategic Levels

Due to the system complexity, energy management should be considered at two different levels [4]:

- Local energy management, for each subsystem, in real time;
- Global energy management, at system level to coordinate the power flow in each subsystem and supervising the whole system.

For local energy management, forward (engine-to-wheel) dynamic causal models are indicated for developing real-time algorithms for efficient management of the subsystems dynamics, since real-time control of the energy flow is more suitable. For global energy management, a backward (wheel-to-engine) quasi-static causal model can be used for coordinating the energy flow from each subsystem. As an advantage, the simulation time is smaller than in dynamic models.

Knowledge and comprehension of each subsystem function is essential. A functional model is more appropriated than a structural model, since it represents the system through mathematical functions, in which each function is associated to a physical device (subsystems), making easier the system analysis [4], [24]. However, the system physical structure is not present. In structural models, the system is represented with interconnected independent devices, according to its physical structure. For energy management, a causal model (based on the cause-effect principle) is more appropriate than a non-causal model. In fact, the last one will not adapt easily to a driving cycle different from the fixed one (it is not as robust as a causal model). As a consequence, an energy management system based on a non-causal model may not be able to improve system efficiency; at the same time, it can also increase the risk of damage. A relevant issue is that designing an EMS which is efficient across a variety of operating conditions determined by traffic conditions, topography, and driver characteristics, is a hard task, particularly for real-time applications. With the availability of traffic information from global positioning systems (GPS), mobile phones, and geographic information systems (GIS), predictions of the vehicle propulsion load can be made. This way, it should be possible to develop EMS using predictive control schemes [25]. In this reference, a very significant conclusion is presented: the possibility to predict the propulsion load can have a significant influence on the power-train design. As stated before, modeling and simulation are fundamental for analysis of different and complex vehicle topologies.

Table II summarizes some references of software for vehicle simulations, both for steady-state and dynamic analysis.

TABLE II

VEHICLE SIMULATION SOFTWARE [14]

	Steady-State Models	**Dynamic Models**
Software Designation	- ADVISOR - SIMPLEV - PSAT - MARVEL - JANUS	-Matlab/Simulink - Simplorer - Saber - Modelica/Dymola - V-Elph - PSCAD

B. Mathematical Models for EMS

Conventional models have been used for modeling relative simple systems; for applications involving multiple interconnected physical systems they have some limitations [4].

1) Conventional Mathematical Models:

a) *Steady-State models:*

All the transient phenomena are not considered. Due to system complexity, it is frequent to use experimental data, both in the form of lookup tables and efficiency maps [24], [26]; naturally, computation time for its implementation is smaller than for dynamic models.

b) *Quasi-Static models:*

In order to include some dynamics, a mix of steady-state model with a low order dynamic model is very frequent.

These two kinds of models are usually used in the design phase to make architectural decisions and to evaluate high-level operating strategies [4], [9],[14].

c) *Dynamic models:*

Applied on subsystem level (low-level operating strategies) in order to analyze its dynamic features and to support subsystem design [4], [9], [14]. The most common approaches are as follows [4]:

d) *State-space models:*

They provide a mathematical causal description of the system, since the state variables are expressed as a consequence of the inputs. They are usually obtained as a result of physical modeling. These models are very useful for showing system properties, such as controllability and observability. Since they are functional models, the system physical structure is not present. Also, state space representation allows both single-input-single-output and multivariable systems to be treated in the same way.

e) Block diagram models:

It allows a clear vision of system´s topology. Transfer functions are derived from differential equations, and subsystem inputs and outputs are organized to couple the different subsystems. An important limitation is that no rule is defined to verify the coherence of the model with the system being modeled. They are applied for linear continuous and time-independent systems; when modeling EV and HEV it is fundamental to consider the nonlinearities and other constraints that occur in such complex multi-element systems. This way, its application to these systems finds limitations.

2) Graphical Models [2], [3], [4]:

These modeling approaches were developed to overcome the limitations of block diagram models for complex systems. In the last decade, the number of applications base on Energetic macroscopic representation (EMR) has been growing. In this approach, all model´s elements are connected according to the action–reaction principle; since physical causality is always respected, control schemes can be deduced from this description. According to [4], it presents some features that may overcome the limitations of conventional models for dealing with highly complex systems, such EV. Some of those advantages are:

- Graphical models propose a unified description of multiphysical systems;
- Graphical models provide a global perspective of the system and the interactions between its subsystems;

These are interesting approaches to analyze in our future work, since it allows a global overview of the system, including its main physical properties.

C. Energy Management Approaches for HEV, BEV and FCV Currently in Use

Basically, are two main different approaches [4], [27], [28]:

- Rule-based control strategies, which depend on the mode of operation (Fig. 2);
- Optimization strategies (Fig. 3).

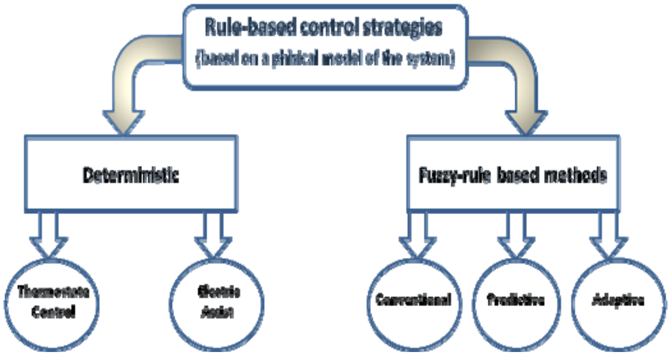

Fig. 2. Energy management rule-based strategies

Deterministic methods do not guarantee that drive-train efficiency optimization is achieved, since these are systems with a high complexity level. This is the main reason why fuzzy rule-based methods have known a considerable application: the model has to allow the correct analysis of power flows between the various subsystems to deduce control laws (rules). They can be easily implemented with real-time supervisory control, to manage power flow in a hybrid power train. The rules can be determined based on human intuition and/or intelligence (machine learning methods), heuristics, or mathematical models.

In Optimization Strategies the models are used to develop the simulation, which will be used to assess the energy-management performance. Basically there are two approaches (Fig. 3):

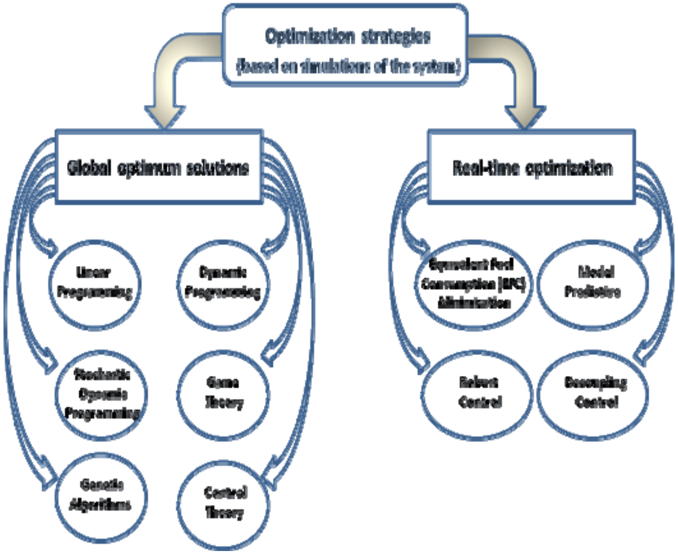

Fig. 3. Energy management optimization strategies

Global optimum solutions can be obtained by performing optimization over a fixed driving cycle (non-causal models), using knowledge of future and past power demands. Optimization problem formulation is usually employed. The main goal is the reduction of the energy to be used, under a set of different constraints, like drivability and drivetrain components requirements. [11]

In FEVs, this approach is particularly suitable for hybrid storage/generation systems (Fig. 4). $P_m(t)$ is the mechanical power in the wheels, $P_{el}(t)$ is the electrical power in the traction converter terminals. $P_{fc}(t,u)$ is the instantaneous power supplied by the FC´s hydrogen tank, $P_{bat}(t,u)$ and $P_{sc}(t,u)$ are the instantaneous power extracted/stored in the battery and SC systems, respectively, according to u(t) (which may be associated, for instance, to a set of rules or to an optimal control signal), that minimizes the EV total energy consumption. Naturally, individual device efficiency has also a deep influence on the energy reduction levels. About Fig. 4, it should be pointed that there are several possible configurations for the energy storage level, it is not mandatory a specific power converter for each storage device [12], [29].

The main constraints are imposed by the storage devices (batteries and SC) and generation ones (fuel cells) physical limits. SOC levels in storage devices are also fundamental constraints [11]. A general optimization problem formulation may have the following structure:

min $J(X_1, X_2, X_3, x_4, \ldots, x_n)$
subj. to:
<u>Constraint Bat</u> → [decision variables: X_1 (may include several battery state variables, like SOC, charge/discharge rates, internal resistance, voltage and power levels, etc)];
<u>Constraint SC</u> → [decision variables: X_2 (may include SOC, charge/discharge rates, voltage and power levels, etc)];
<u>Constraint FC</u> → [decision variables: X_3];
<u>Constaints related to other EV components</u> → [may include electric motors and power converters limits (temperature, power and voltage levels, switching frequencies, etc) and mechanical transmission specifications. Decision variables: $x_4, \ldots, x_n$].

Also, the following instantaneous relations must be observed (from Fig. 4):

<u>Motor mode</u>

$$P_{el}(t)=P_{bat}(t,u)\cdot\eta_{bat\text{-}sys(M)}+P_{sc}(t,u)\cdot\eta_{sc\text{-}sys(M)}+ +P_{fc}(t,u)\cdot\eta_{fc\text{-}sys} \tag{1}$$

$$P_m(t)=P_{el}(t)\cdot\eta_{Dtrain(M)} \tag{2}$$

<u>Regenerative braking mode</u>

$$P_{el}(t)=P_{bat}(t,u)/\eta_{bat\text{-}sys(R)}+P_{sc}(t,u)/\eta_{sc\text{-}sys(R)} \tag{3}$$

$$P_m(t)=P_{el}(t)/\eta_{Dtrain(R)} \tag{4}$$

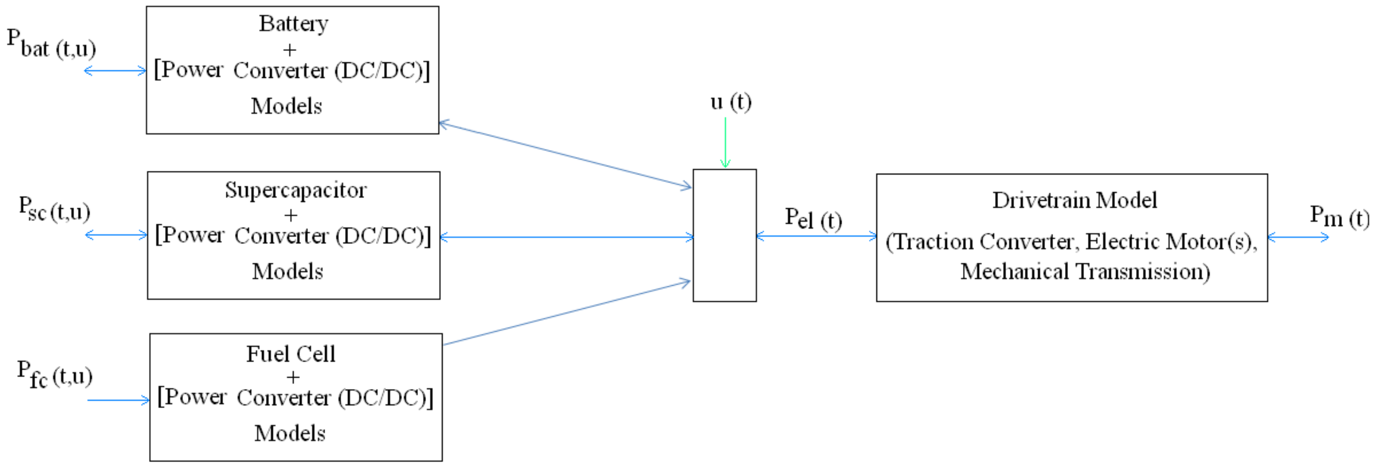

Fig. 4. FEV optimal power flow problem (based on [13])

$\eta_{bat\text{-}sys}$, $\eta_{sc\text{-}sys}$ and $\eta_{fc\text{-}sys}$ are the efficiencies of, respectively, the battery + power converter, the SC + power converter and the fuel cell + power converter. The efficiency of the drivetrain block is η_{Dtrain}. The index (M) is related to motor mode, while (R) refers to regenerative mode. All these efficiencies values are dependent on their system´s power level.

The cost function $J(X_1, X_2, X_3, x_4, \ldots, x_n)$ can be defined as the total vehicle energy losses. This way, optimization performance can be achieved, both for motor and regenerative braking modes. As stated before, for these energy optimization problems, knowing the drive cycle is mandatory (non-causal approach). Depending on the proposed goals, different models can be used and also some constraints may be relaxed.

With these non-causal control techniques, real-time energy management is not directly possible. However, the results of these strategies can be used to compare the features of other control strategies and/or as a base to define rules for online implementation [27], [28]. A real-time optimization control strategy is based only in the system variables at the present time (causal models). Although the solutions achieved are not globally optimal, they can be used for real-time implementation.

IV. CONCLUSIONS AND FUTURE WORK

There is a general perception that FEVs energy management systems must rely on multiple energy sources, since batteries, SC and fuel cells technologies have complementary features.

So far, the main industrial and academic research efforts in developing EMS for HEV and FEV have been centered in off-line non-causal algorithms. EMS methodologies for real-time applications remain a hard and challenging task – deeper efforts must be done in this field, in order to support FEV´s future. Nevertheless, there is a trend to develop EMS for real time applications. Predictive models and advanced control theory, together with modern information techniques, will have a significant contribution in achieving this goal.

Every component of the system has an impact on the global efficiency; on the other hand, the influence of a given subsystem in global energy efficiency is usually dependent on interactions with other subsystem. This way, analysis and development of different models of FEV drivetrain will be fundamental. Modeling and simulation is a fundamental key in achieving efficient real-time EMS algorithms. So far, graphical models have been applied in a much smaller degree than conventional mathematical models. As stated before, EMR seems to have interesting features that makes it worth to explore in FEV modeling.

The increase of power computing is allowing the development of more powerful computational methodologies, from which hardware-in-the-loop (HIL) models and simulations are a good example, since it is possible to study and test multiple systems to be designed in parallel, having different components and topology configurations.

The final aim of the present research is to study and optimize the energy flow between the electrical and mechanical sides of a FEV. In parallel to an overview of current EMS´s strategies, we also intend to make an analysis of the most current approaches in mathematical models for all EV subsystems – batteries, SC, its power converters architectures and control schemes; electric motors and specific power converters (also including its control); mechanical transmission.

In the context of hybrid energy storage devices, we are also working on the development of an EMS for a system with a battery and SC, each one with its own power converter (DC/DC, bi-directional), both connected to a common DC bus. The goal is to achieve the best battery and SC features, with high efficiency levels, without compromise the device´s physical limits. At the same time, both SC SOC and DC bus voltage level will be also controlled.

This paper aspired to help current research efforts in this field by surveying current approaches and putting them into perspective, deriving a more holistic view. The authors had mainly aimed to identify future research directions and open issues.

V. REFERENCES

[1] International Energy Agency: World Energy Outlook (2008).

[2] Gao, D. W., Mi, C., Emadi, A.: Modeling and Simulation of Electric and Hybrid Vehicles. Proc. of the IEEE, Vol. 95, 4, 729--745 (2007).

[3] Letrouvé, T., Bouscayrol, A., Lhomme, W., Dollinger, M., Calvairac, F.M.: Different Models of a Traction Drive for an Electric Vehicle Simulation. VPPC (2010).

[4] Chan, C.C., Bouscayrol, A., Chen, K.: Electric, Hybrid and Fuel- Cell Vehicles: Architectures and Modeling. IEEE Trans. Vehic. Tech. Vol.59, 2, 589--598 (2010).

[5] Hoeijmakers, Martin J., Ferreira, Jan A. "The Electric Variable Transmission", IEEE Transactions on Industry Applications, Vol.42, No4, pp. 1092-1100 (2006).

[6] K. T. Chau and C. C. Chan. "Emerging energy-efficient technologies for Hybrid Electric Vehicles," *Proc. IEEE*, vol. 95, no. 4, pp. 821–835 (2007).

[7] Valsera-Naranjo, Eduardo et . "Electric Vehicles: State of the Art and Issues for their Connection to the Network", 10th International Conference on Electrical Power, Quality and Utilization, September 15-17, Poland (2009).

[8] Affanni, Antonio et al. "Battery Choice and Management for New-Generation Electric Vehicles", IEEE Transactions on Industrial Electronics, Vol.52, No5, pp. 1343-1349 (2005).

[9] Chan, C.C.: The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles. Proc. of the IEEE, Vol. 95, 4, 704--718 (2007).

[10] Ferreira, A.A., Pomilio, G. Spiazzi, Silva. L de Araujo. "Energy Management Fuzzy Logic Supervisory for Electric Vehicle Power Supplies System", IEEE Transactions on Power Electronics, Vol.23, No1, pp. 107-115 (2008).

[11] Guzzella, Lino, Sciarretta, Antonio: Vehicle Propulsion Systems-Introduction to Modeling and Optimization. Springer, Heidelberg (2005).

[12] Miller, John M., Startorelli, Gianni. "Battery and Ultracapacitor Combinations – Where Should the Converter Go?", IEEE Vehicle Power and Propulsion Conference (VPPC), September 1-3, France (2010).

[13] Iannuzzi, Diego. "Improvement of the Energy Recovery of Traction Electrical Drives Using Supercapacitors". 13th International Power Electronics and Motion Control Conference (2008).

[14] Zoroofi, Siavash: Modeling and Simulation of Vehicular Power Systems. Master Thesis, Chalmers University of Technology, Sweden (2008).

[15] Banaei, Anahita, Fahimi, Babak. "Real Time Condition Monitoring in Li-Ion Batteries via Battery Impulse Response", IEEE Vehicle Power and Propulsion Conference (VPPC), September 1-3, France (2010).

[16] Neef, H.-J ."International overview of hydrogen and fuel cell research". J. Energy 34, 327--333 (2009).

[17] Bossel, Ulf. "Does a Hydrogen Economy Make Sense?", European Fuel Cell Forum (2005).

[18] Amjad, S., Neelakrishnan, S., Rudramoorthy, R.: Review of Design Considerations and Technological Challenges for Successful Development and Deployment of Plug-in Hybrid Electric Vehicles. Renewable and Sustainable Energy Reviews. 14, 1104-1110, Elsevier (2010).

[19] Somayajula, D., Meintz, A., Ferdowsi, M.: Designing Efficient Hybrid Electric Vehicles. IEEE Vehic. Tech. Magazine. Vol.4, 2, 65--72 (2009).

[20] Silva, M., Trovão, J.P., Pereirinha, P., Marques, L.: Multiple Energy Sources Monitoring System for Electric Vehicle. SPEEDAM (2008).

[21] Serrao, Lorenzo: A Comparative Analysis of Energy Management Strategies for Hybrid Electric Vehicles. Ph.D. Thesis, The Ohio State University, USA (2009).

[22] Adornato, B., Patil, R., Filipi, Z., Baraket, Z., Gordon, T.: Characterizing Natural Driving Patterns for Plug-in Hybrid Electric Vehicle Analysis. VPPC (2009).

[23] Crolla, D.A., Ren, Q., ElDemerdash, S., Yu, F.: Controller Design for Hybrid Vehicle – State of the Art Review. VPPC (2008).

[24] Williamson, S., Lukic, M., Emadi, A.: Comprehensive Drive Train Efficiency Analysis of Hybrid Electric and Fuel Cell Vehicles Based on Motor-Controller Efficiency Modeling. IEEE Trans. Power Electronics, Vol.21, 3, 730--740 (2006).

[25] Johannesson, L., Pettersson, S., Egardt, B.: Predictive Energy Management of a 4QT Series-Parallel Hybrid Electric Bus. Control Eng. Practice, Elsevier (2009).

[26] Feroldi, D., Serra, M., Riera, J.: Energy Management Strategies Based on Efficiency Map for Fuel Cell Hybrid Vehicles. J. Power Sources. 190, 387--401, Elsevier (2009).

[27] Salmasi, F. R.: Control Strategies for Hybrid Electric Vehicles: Evolution, Classification, Comparison and Future Trends", IEEE Tran. Vehic. Tech. Vol.56, 5, 2393--2404 (2007).

[28] Desai, C., Williamson, S.: Comparative Study of Hybrid Electric Vehicle Control Strategies for Improved Drivetrain Efficiency Analysis. IEEE Electrical Power & Energy Conf. (2009).

[29] Vinot, Emmanuel, Trigui, Rochdi, Jeanneret, Bruno Gianni. "Optimal Management of Electric Vehicles with a Hybrid Storage System", IEEE Vehicle Power and Propulsion Conference (VPPC), September 1-3, France (2010).

Pedro Melo (S'10) received the M.Sc. degree from the Faculty of Engineering of Porto University, in 2005, where he is currently a Ph.D. student.

In 2001 he joined the Departement of Electrical Engineering of the Scholl of Engineering of the Polytechnic of Porto as an assistant teacher. His main research areas include electrical machines modelation and control and energy management systems for electric vehicles.

Rui E. Araújo was born in Viana do Castelo, Portugal in 1964. He received the electrical engineering graduation, M. Sc. and Ph. D. degrees from the Faculty of Engineering of the University of Porto, Portugal in 1987, 1992 and 2001, respectively. From 1987 to 1998, he was an Electrotechnical Engineer in Project Department, Adira Company, Porto, Portugal, and from 1988 to 1989, he was researcher with INESC, Porto, Portugal. Since 1989, he has been with the University of Porto, where he is an Assistant Professor with the Department of Electrotechnical and Computer Engineering at Faculty of Engineering. He is a Researcher in the Power Systems Unit of INESC PORTO. His research interests are focused on motion control and electric vehicles.

Ricardo de Castro was born in Porto, Portugal in 1983. He received the E.E.C Diploma from Universidade do Porto in 2006 and he is currently a Ph.D. Student in the same university. His main research interests include Reconfigurable Embedded Systems, friction estimation and Control of Multi-Motor Electric Vehicles.