

Energy Management Strategies for Fuel Cell Hybrid Vehicles; an Overview

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Abstract

For proper operation, fuel cell hybrid propulsion systems need an Energy Management Strategy (EMS). A variety of such EMSs have been presented in literature. This paper provides an overview of EMSs recently proposed in literature. It categorizes the EMSs to their theoretical background, their applicability to different electric topologies, the storage technology used and the considered vehicle type. From this inventory is concluded that for a broad range of topologies for PEM-based fuel cell hybrid propulsion systems, EMSs are available in literature. Issues left for further scientific research are the further exploration how to integrate a-priori information as trip data in the EMS and how to expand the lifetime of the fuel cell stack and/or the storage by including models and measures against degradation in an optimizing EMS. Issues left for practical implementation are an extension of the area of operation to harsh environments and cold startups and a real-time validation of proposed EMSs on actual fuel cell hybrid vehicles.

Fuel Cell Hybrid Vehicle, Energy Management Strategy, Control Theory

1 Introduction

1.1 Background

Hybrid propulsion systems by definition comprise a primary power source and an energy storage. For Fuel Cell Hybrid Electric Vehicles (FCHEV), the fuel cell system acts as the primary source and a battery and/or supercapacitor enables the storage of electrical energy. As both the primary source and the storage can provide electric power for propulsion, a control strategy is needed to define the distribution of this power demand over fuel cell stack and storage. In literature, this supervisory control strategy is referred to as the power split strategy, power split control, power management strategy or energy management strategy. In this paper it will be referred to as the Energy Management Strategy (EMS).

The EMS has to ensure that constraints on the operation of the fuel cell system and storage are not violated, without compromising on the drivability of the vehicle. Main constraints to be consid-

ered are the power ratings of fuel cell stack and storage and the prevention of depletion or overcharging the storage. As not violating these constraints does not result in one unique solution, it leaves the EMS room for optimization. This freedom in the control problem is reflected in the variety of EMSs presented in literature.

1.2 Objective

This paper intends to provide an overview of EMSs for fuel cell hybrid propulsion systems discussed in literature. Objective of this overview is to enable the reader to decide which literature to examine in support of own EMS development and implementation.

1.3 Approach

Based on a literature survey over journals of publishers as Elsevier, IEEE and Springer, and conferences regarding fuel cell hybrid propulsion,

recent developments in EMSs for FCHEVs have been evaluated. These results are merged with the observations made in a PhD project on energy management for hybrid propulsion systems [86].

2 Publications

Clearly, energy management for fuel cell hybrid propulsion is a recent area of scientific research. Although both fuel cell technology and control and optimization theory exists for over at least five decades, the vast majority of publications on the subject are presented only in the last ten years (figure 1). This is in line with the recent awareness for sustainable transportation.

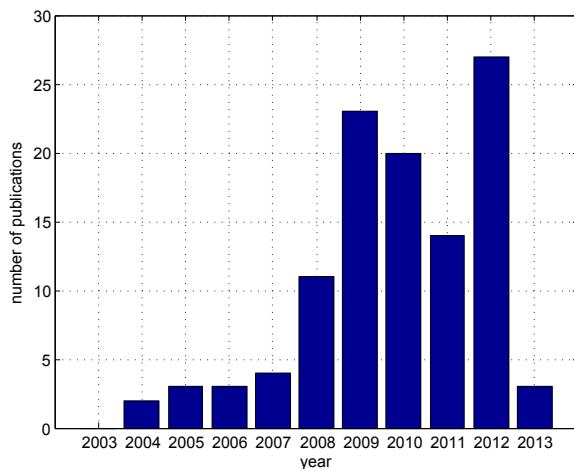


Figure 1: Publications per year.

With respect to publications, it is remarkable that first authors countries, contributing most to EMS solutions for fuel cell hybrid propulsion, are not necessarily countries with a traditional large automotive industry (see figure 2). Countries with a modest automotive industry, as Canada and Spain, do significantly contribute to this subject. For Canada, this can be partly understood from their leading fuel cell industry. More remarkable is that countries like Germany and Japan, with a strong automotive industry, appear to have no significant contribution on the subject.

3 Vehicles

Most publications on EMSs for FCHEVs do not state to which vehicle type the presented EMS applies. Therefore, most EMSs can be considered sufficiently generic to be relevant to a broad variety of vehicle types.

Nevertheless, a few papers consider a specific type of vehicle, such as a three-wheel auto rickshaw [62], a scooter [48, 83], an unmanned ground combat vehicle [1], a low speed cargo vehicle [26, 67], a city bus [33, 57, 95, 102, 103,

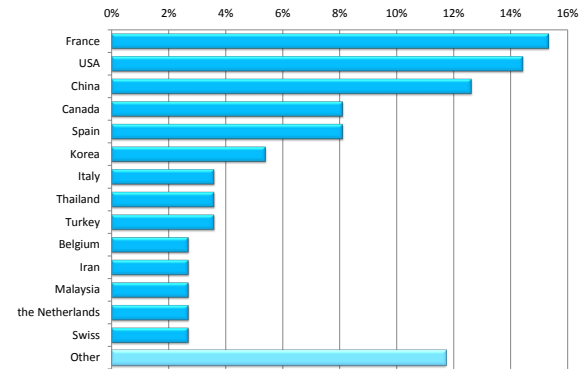


Figure 2: Publications found, categorized per first authors country.

104], a tramway [29, 34, 93, 95] and a specialized test vehicle [63]. Although specific in vehicle type, most of these papers can be considered a demonstration of a generic EMS on a specific vehicle. This further supports the statement that most presented EMSs are sufficiently generic to be applicable to different vehicle types.

In addition, some papers also consider stationary back-up systems [95] and grid connected systems including a reformer [37], extending the application of the EMS to more than vehicles.

4 Topologies

As primary power source, generally Polymer Electrolyte Membrane (PEM) fuel cells are considered. For propulsion, PEM technology is that common, that the majority of publications just refer to fuel cells, even when considering only PEM fuel cells. A few publications explicitly consider different fuel cell technologies, as High Temperature PEM ([46]) and a fuel cell system including a reformer [37]. Although the characterization of these fuel cell technologies for EMS differs slightly from PEM, the EMSs presented for specific fuel cell technologies should not be considered very different from those considering low temperature, direct hydrogen PEM.

With respect to the storage of electrical energy, two main groups can be distinguished: EMSs that consider a battery and EMSs that consider a supercapacitor or ultra-capacitor as storage, as indicated in figure 3. A minority considers the combination of both a battery and a supercapacitor, or more than one storage configuration, including no storage at all.

When defined, the battery technology considered is dominantly lithium-ion.

All EMSs consider the amount of stored energy. From the perspective of the EMS, a supercapacitor has the advantage over a battery that the amount of stored energy is directly indicated by the voltage on its terminals, whereas for batteries, most EMSs assume a State Of Charge (SOC) or State Of Energy (SOE) estimator to identify the

amount of stored energy, without further specification.

The electric motor(s) of the vehicle are connected by an inverter to the DC-bus of the propulsion system. The fuel cell stack and the battery and/or supercapacitor as storage can be electrically connected to this DC-bus in several topologies. Figure 4 indicates some of these configurations.

- Topology (1) combines fuel cell stack and storage without any DC/DC converter. In this configuration, the power delivered by the fuel cell stack and the battery or supercapacitor are directly coupled. A reference to this configuration is rare [7].
- Topology (2) is a common configuration. It enables the control of the power split over the fuel cell stack and the battery. This configuration is referred to in [1, 6, 14, 17, 21, 22, 27, 28, 32, 36, 40, 45, 47, 49, 50, 51, 54, 56, 57, 58, 59, 61, 62, 65, 69, 75, 77, 78, 80, 81, 82, 83, 84, 85, 86, 93, 99, 100, 101, 102, 103, 104, 108].
- As the DC/DC converter in topology (3) is more complex (bidirectional) as in topology (2) and as energy from the storage will always pass the converter twice (charging/discharging), this topology is not favorable with respect to power electronics and losses. It is referred to in [16, 74, 96] and to some extent in [73].
- Topology (4) is commonly supported. This configuration enables the control of both fuel cell stack power and the power from the storage. As these powers should match the demanded power, a tight control of both converters is needed. An additional capacitor on the DC-bus to decouple fuel cell stack and storage power from the power demand relaxes this problem, but essentially, this results in topology (5). Configuration (4) enables the control of the DC-bus voltage, prohibiting large voltage swings on the

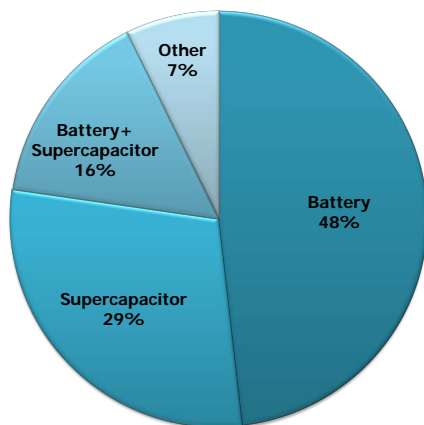


Figure 3: Energy storage.

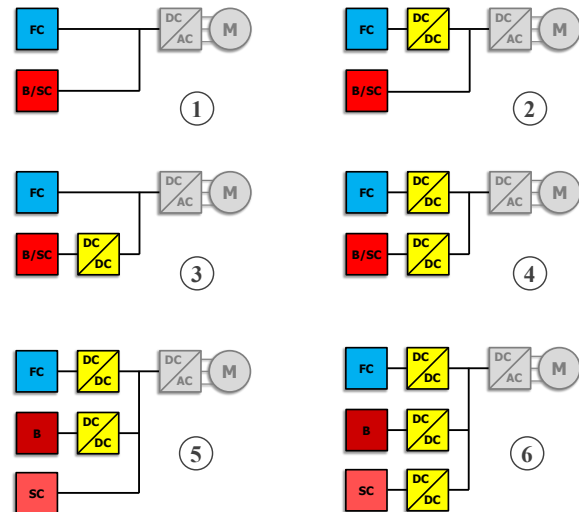


Figure 4: Topologies.

DC-bus. As a result, the inverter requirements on its DC-voltage can be less stringent. A few publications, as [38], discuss the topology on voltage level. Most publications only consider power flows, and do not further elucidate the subject. It is referred to in [2, 3, 5, 10, 12, 23, 30, 31, 34, 35, 37, 44, 41, 52, 53, 55, 60, 63, 64, 72, 79, 87, 88, 91, 92, 94, 97, 110, 112].

- Topology (5) includes both a battery and a supercapacitor as storage. Advantage of this configuration is the combination of the power handling capabilities of the supercapacitor with the energy storage capabilities of the battery. Disadvantage is its complexity. Disadvantage is its complexity. It is referred to in [33, 64]. This configuration, but with the battery and supercapacitor interchanged, is mentioned in [58].
- For topology (6), comprising a fuel cell stack, battery and supercapacitor, DC/DC converters are included between all components and the DC-bus [25, 66, 68, 89, 98, 105, 107]. As topology (5), it combines the advantage of the power handling capabilities of the supercapacitor with the energy storage capabilities of the battery. Comparable to topology (4) over (3), it enables voltage control of the DC-bus, but all against an increase in complexity.

A number of less frequent mentioned alternative topologies are reported. Some examples of variations mentioned:

- In [48] an integrated power electronics solution is presented for a relative low power application, combining the power flow of the fuel cell stack and supercapacitor in one converter structure.

- As alternative topology, [9] proposes to charge the battery from the fuel cell stack using a separate DC/DC converter, with a diode connection to the supercapacitor defining the DC-bus voltage. Although both DC/DC converters can be optimized for their specific task, a disadvantage seems that the battery can not be used to store significant amounts of regenerated energy (downhill driving). This is partly covered by a switch in parallel with the diode, but closing this switch disables the ability to control the battery and the supercapacitor independently.
- In [38, 39], a switched multi-power source approach is considered, which has some similarity with the interleaved multiple-input power converter of [42, 43] and the three-port for battery and supercapacitor in [96].
- As brake, [93] proposes a controlled electric resistor between the nodes of the DC-bus.
- In [106], the supercapacitor is connected via its own DC/DC converter to the input of the DC/DC converter of the fuel cell stack instead of to the DC-bus.
- A further generalization of topologies is found in [19], where DC/DC converters are considered between all elements in the propulsion system, including auxiliaries.

Discussions on different topologies are found in [70, 109]. A discussion on the differences between topology (1) and (2) for a supercapacitor as storage is raised in [83]. In [90], topology (4) with a supercapacitor as storage is compared with topology (2) with a battery as storage. In [70] it is concluded that for a battery as energy storage, topology (2) prevails with respect to a minimum fuel consumption.

Some publications do not state a topology of the propulsion system [20, 111] and discuss their EMS entirely on power level [11, 15, 71], including the properties of possible converters in their characterization of the fuel cell system or storage.

5 Energy Management Strategies

This section intends to provide an overview of presented EMSs for FCHEV, categorized per applied control theory. As presented EMSs occasionally combine different control theories and as control theories themselves are sometimes hard to categorize, these categories should be considered an indication only.

5.1 Classic control

With classic control we refer to linear feedback/feedforward control as PID-controllers. Within this category, there is a group of publications discussing a power converter on the level

of its electric components (as MOSFETs and IGBTs). As their focus is the discussion of the presentation power converter, a linear controller is included as EMS just to enable a proper operation of the considered converter [40, 96]. Generally, these publications do not consider control goals as a minimum fuel consumption.

The three-port power converter for battery and supercapacitor in [96, 97], includes an EMS implemented as (adaptive) PI-controllers, controlling the duty cycle of the semiconductor power switches. [7] provides a setpoint for a supercapacitor current, based on voltages in the system and a master PI controller. Setpoints are realized using slave PI-controllers. The approach to use the voltage of the supercapacitor as indicator of the amount of stored energy, is also applied in [87, 88], sometimes explicitly referred to as voltage control [75]. A comparable approach, extended to a battery, is presented in [68, 72]. A voltage control approach with a combined converter for fuel cell stack and supercapacitor is demonstrated in [48].

Also on power converter level, an H_∞ -controller balancing performance and robustness of the converter is discussed in [44]. Distinguishing between three modes of operation, [4] combines PI-control with sliding mode control to distribute transients over the different power sources.

When representing demanded torque and currents in the system as states, linear transfer functions can represent the system components, enabling a linear controller design. Such approach based on states also enables methods as state estimators and state feedback controllers [36].

Where classic control is dedicated to linear relations, flatness-based control can partly deal with nonlinearities in the system, still enabling linear control [73, 74, 92, 91].

5.2 Filtering

Two approaches focussing on wavelet decomposition are presented in [94] for a fuel cell/supercapacitor hybrid and in [107] for a fuel cell/battery/supercapacitor hybrid. These strategies focus on the distribution of the transients in the power demand. [3] combines wavelet decomposition with a small neural network, relating power demand and SOC to the power requested from the fuel cell stack.

Also [61] focusses on frequency content, but implements this on the level of the DC/DC converter using linear transfer functions. [6, 8] discuss an approach that also results in a power split over a frequency range, including the boundaries of the fuel cell stack and the supercapacitor. This approach results in a direct duty cycle control of the DC/DC converter between the supercapacitor and the DC-bus.

5.3 Heuristic strategies

Heuristic strategies do not derive an EMS from a general control theory, but rely on one or a set of heuristic rules to operate the system.

An example of such rule is presented in [1], where the reference for the fuel cell power equals the power demand plus a constant times the deviations in the SOC of the battery. A slightly more complex rule is presented in [108, 109], where a power split ratio between fuel cell stack power and battery power is defined based on the voltage of the fuel cell stack and the SOC of the battery. Such relations can be implemented using lookup tables [98]. [81] directly relates the SOC of the battery to an operating mode of the fuel cell stack, and extends this by shifting the point of operation of the fuel cell stack based on the observed efficiency of the system. As the SOC of the battery is not directly available as measurement, [50] proposes a rule using the open-clamp voltage of the battery to define the reference for the fuel cell stack current.

Under the assumption the battery can deliver power faster than the fuel cell stack, [89] focusses on controlling the battery, deriving the fuel cell stack current from the determined battery current, including a rate limiter on the fuel cell stack current in order to avoid fast changes in the fuel cell current. The reference for the battery current is derived from the DC-bus voltage. This approach is extended to fuel cell/battery/supercapacitor hybrids in [90].

A group of heuristic EMSs consider a set of operating modes. For a fuel cell/supercapacitor hybrid, such a rule based approach differentiating to modes of operation (as braking or delivering peak power), is presented in [29, 34, 71]. Such rules provide setpoints for operation, controlled by local PI controllers [29, 34]. In addition to these rules, the operating setpoint per mode can be optimized with respect to a minimum fuel consumption. The number of modes, sometimes referred to as states, may vary. By example, for a fuel cell/battery hybrid, [46] differentiates between six modes of operation, where [45] uses four modes. For a fuel cell/battery/supercapacitor hybrid, [39] uses seven modes to switch on and off the different power sources.

Advantage of most heuristic EMSs is their simplicity and focus on real-time implementation. Disadvantage is that, due to their nature, no guarantees can be provided on properties as stability or the ability to minimize the fuel consumption.

5.4 Fuzzy Control

Popular in the nineties of the last century, fuzzy control provides a linguistic way to create control systems. Compared to other control applications, fuzzy control is relatively frequently presented as approach to obtain an EMS for FCHEVs. This might be caused by the freedom in the system. As example: the amount of stored energy should be kept within the boundaries of the storage, whereas the absolute amount of stored energy is less relevant. This relaxes the accuracy of the control goals, which makes the control problem particularly suited for fuzzy control.

Essentially, fuzzy control defines static, nonlinear relations between inputs and outputs. Still,

dynamics can be included by referring to variables as an amount of stored energy or a rate of change. Proposed fuzzy control schemes indeed include the SOC of the battery as input variable, as for example in [15, 59, 66, 69, 100]. Where most papers use power and SOC for fuzzyfication, [55] details this to voltages, currents and changes in voltages, considering a supercapacitor as storage. The nonlinear nature of fuzzy controller is explicitly used in [13] to reduce voltage ripple on power converter level.

The rules in the inference of the fuzzy controller have to be defined by an expert, who also chooses the size of the fuzzy sets. Sets of seven or more membership functions are presented [33, 63, 80, 100], whereas sets of three or four membership functions [47, 56] also provide experimentally validated solutions [57, 62]. Generally, there is a balance between the number of membership functions and the care needed to define each single membership function. Still, a large number of membership functions increases the complexity of the inference, reducing its maintainability. To adapt to the driving pattern, [80] proposes to relate the position of the membership functions to the current operating conditions. In [56], the position of the membership functions is treated as an optimization problem, maximizing the efficiency of the propulsion system. An adaptive neuro-fuzzy inference system to improve the fuel economy of the vehicle is presented in [59].

Where [59] combines a small neural network with a fuzzy inference, [23, 24, 25] combine fuzzy control with wavelet filtering to split the power demand over fuel cell stack, battery and supercapacitor. A combination of fuzzy control and flatness control is presented in [106], where a flatness control algorithm decides on the power split between the fuel cell stack and a battery/supercapacitor combination, and within this combination, the fuzzy controller distributes the power over the battery and the supercapacitor.

Common to all fuzzy control schemes is that a real-time implementation is easily obtained. This is an advantage for more complex topologies comprising a fuel cell stack, battery and supercapacitors [33, 58, 66].

5.5 Optimizing strategies

As discussed in section 5.4, when there is freedom left in a controlled system, there is room for optimization. Optimizing strategies mathematically define control goals in a cost function, including constraints as power and energy ratings and a constraint on the average stored energy over a driving cycle. The cost function itself generally refers to a minimum in fuel consumption [77, 84, 86], a minimum in costs [104], a minimum in losses [85], or a combination of objectives [41, 42, 43].

Although comparable in their definition of the cost function, various approaches to obtain an optimal control are presented.

A number of papers propose numerical solutions, as Dynamic Programming (DP), nonlinear programming and variations as Stochastic Dynamic Programming (SDP) [51, 53, 54, 78, 82].

One SDP related optimization method including probability is referred to as ant colony optimization [76]. A second SDP related method, intended to approach the global optimum solution efficiently, is referred to as particle swarm optimization [41, 42, 43].

Disadvantage of DP-based solutions is the computational effort needed, possibly hindering real-time implementation. As solution [101, 104] simplifies its DP strategy by considering solutions per driving mode. By representing the cost function as a quadratic function [21, 22, 18, 105], a Linear Quadratic Control (LQC) approach is enabled. In [52], such approach is combined with a-priori road trip information.

A method originating from Internal Combustion Engine (ICE) based hybrid propulsion systems, is the Equivalent Cost Minimization Strategy (ECMS). A number of publications discuss the application of ECMS to FCHEVs [79, 93, 103]. ECMS characterizes engine and storage with first or second order polynomials to enable a global minimum. Some variations are presented combining ECMS with a prediction [35] or estimation of the power demand and transient load of the fuel cell stack [102].

The approximation of first principle models with polynomials is not necessary for fuel cell hybrids with a battery as storage, as the first principle characterization of the fuel cell stack and the battery have mathematically congruent representations. As a result, an EMS providing a global minimum can be derived based on the first principle models directly [84, 86]. Such analytical solutions based on Pontryagin's Maximum/Minimum Principle or Bellman's principle of optimality, provide real-time implementable solutions, still approaching optimality [86, 111]. Such optimal solution is even reduced further in complexity to a rule based EMS in [110, 112].

Still, to provide a solution, information is needed on the future behavior of the vehicle, typically to define the value of the Lagrange multiplier(s) in the optimization. In [11, 85] this Lagrange multiplier is related to the energy content of the battery. The need for this information is reduced to an estimate of the future average power demand, based on the past power demand, represented by the SOE of the battery in [85, 86]. In [84, 86], this is reduced to the current demand, represented by the SOC of the battery. An adapting algorithm estimating such future system behavior is proposed in [60], a heuristic prediction is presented in [14] and a-priori trip information is included in [52].

Model Predictive Controllers (MPC) predict the future, based on a model of the system. Such approach, including a quadratic cost function and system identification based on multiple models, is presented in [16]. Also [2] proposes to distribute the operating area of the propulsion system over a set of linear models and combines this with an MPC approach.

5.6 Maximizing efficiency

To obtain a minimum fuel consumption, a number of papers focus on the efficiency of the fuel

cell system [17, 19, 26, 95]. Based on a map of the fuel cell system efficiency, zones are defined with a mode of operation per zone as EMS [30, 31]. Also [12] defines modes by thresholds, and operates the fuel cell stack on its maximum efficiency in one of these modes. Essentially, these approaches are based on static considerations on the efficiency. In [20] such approach is combined with an adaptive controller to cover transients in the operation of the fuel cell system, attempting to maximize the efficiency of the fuel cell system dynamically.

When designing an EMS on efficiency maps, it should be noted that the maximum efficiency of the fuel cell stack does not necessarily match the maximum efficiency of the propulsion system.

6 Discussion

A few studies compare different EMSs. In [27] a PID-based EMS is compared with a fuzzy control based EMS. This is extended with an optimization method in [28], from which it was concluded that the optimization method prevailed with respect to a minimum fuel consumption. For heuristic approaches, [49] examined on/off strategies based on the maximum fuel cell power, on the maximum fuel cell stack efficiency and on a combination of both, for which the combination provided an acceptable balance between efficiency and power. Within optimizing methods, [85] compared a ECMS-based approach with an analytical solution to the optimization problem, where the analytical solution performed best on fuel efficiency, although differences are small.

Classic control theory uses linear models providing appealing properties as guaranteed stability and robustness. As the actual propulsion system is far from linear with respect to fuel consumption and voltage/current relations, a guaranteed minimum fuel consumption can not be expected when linear control theory is applied.

Heuristic strategies and fuzzy control can easily handle nonlinearities, providing, possibly combined with filtering techniques, an appropriate way to control also fuel cell hybrids with both a battery and a supercapacitor as storage. Heuristic rules defining different operating modes do have a risk. For each combination of modes or rules, it should be evaluated if the operation of the system is stable and oscillation when switching between states should be avoided.

When focus is on a minimum fuel consumption, optimizing strategies are preferred. With respect to fuel consumption, real-time implementation and plug-in functionality, an EMS based on an analytical solution to the optimization problem seems to be favorable for systems with only a battery as storage.

From the discussion which EMS optimizes the operation of a FCHEVs, naturally follows the discussion which component sizes for fuel cell stack and storage are optimal. A few publications make an observation on this subject [1, 9, 10, 86].

7 Conclusions

For a broad variety of vehicle types and propulsion system topologies, energy management strategies have been presented in literature. Also with respect to optimization goals as a minimum fuel consumption, solutions are presented. Therefore, we can conclude that for most fuel cell hybrid vehicle designs, literature provides an applicable EMS. Thus, compared with a decade ago, the design of an appropriate EMS is no hurdle anymore, hindering the introduction of fuel cell hybrid propulsion systems.

With respect to the validation of EMSs and considered topologies, only a minority of the presented work is reported to be validated on a fuel cell hybrid vehicle. Experiments and applied research can further elucidate the value of the proposed EMSs.

From a scientific standpoint, some subjects are interesting for further research. Especially with respect to optimizing strategies, possible information on the future driving cycle might further reduce the fuel consumption. Here, we can consider a prediction of the future driving cycle based on navigation data, dynamic route information or on statistical trip information. With respect to the propulsion system, using advanced models, issues as battery and fuel cell stack aging can be included in the optimization problem, extending the lifetime of the propulsion system. In addition, an extension of the area of operation to harsh environments and cold startups is interesting to increase the robustness of the fuel cell hybrid propulsion system.

References

- [1] An S.J., Lee K.I., Kim T.J., Performance analysis according the combination of energy storage system for fuel cell hybrid vehicle, *Int. J. of Automotive Technology*, vol. 9, pp. 111-118, 2008
- [2] Arce A., del Real A.J., Bordons C., MPC for battery/fuel cell hybrid vehicles including fuel cell dynamics and battery performance improvement, *J. of Process Control*, vol. 19, pp. 1289-1304, 2009
- [3] Ates Y., Erdinc O., Uzunoglu M., Vural B., Energy management of an FC/UC hybrid vehicular power system using a combined neural network-wavelet transform based strategy, *Int. J. of Hydrogen Energy*, vol. 35, pp. 774-783, 2010
- [4] Ayad M.Y., Becherif M., Henni A., Vehicle hybridization with fuel cell, supercapacitors and batteries by sliding mode control, *Renewable Energy*, vol. 36, pp. 2627-2634, 2011
- [5] Ayad M.Y., Becherif M., Henni A., Aboubou A., Wack M., Laghrouche S., Passivity-based control applied to DC hybrid power source using fuel cell and supercapacitors, *Energy Conversion and Management*, vol. 51, pp. 1468-1475, 2010
- [6] Azib T., Talj R., Bethoux O., Marchand C., Sliding mode control and simulation of a hybrid fuel-cell ultracapacitor power system, *proc. Int. Symp. on Industrial Electronics* Bari, Italy, 2010
- [7] Azib T., Bethoux O., Remy G., Marchand C., Berthelot E., An innovative control strategy of a single converter for hybrid fuel cell/supercapacitor power source, *IEEE Trans. on Industrial Electronics*, vol. 57, pp. 4024-4031, 2010
- [8] Azib T., Bethoux O., Remy G., Marchand C., Saturation Management of a Controlled Fuel-Cell/Ultracapacitor Hybrid Vehicle, *IEEE Trans. on Vehicular Technology*, vol. 60, pp. 4127-4138, 2011
- [9] Bauman J., Kazerani M., An analytical optimization method for improved fuel cell-battery-ultracapacitor powertrain, *IEEE Trans. on Vehicular Technology*, vol. 58, pp. 3186-3197, 2009
- [10] Bernard J., Delprat S., Guerra T.M., Fuel-Cell hybrid powertrain: Toward minimization of hydrogen consumption, *IEEE Trans. on Vehicular Technology*, vol. 58, pp. 3168-3176, 2009
- [11] Bernard J., Delprat S., Guerra T.M., Büchi F.M., Fuel efficient power management strategy for fuel cell hybrid powertrains, *Control Engineering Practice*, vol. 18(4), pp. 408-417, 2010
- [12] Bethoux O., Remy G., Riera J., Serra M., Azib T., Analyses of energy management strategies for a PEMFC/UC electric vehicle, *proc. IEEE Vehicle Power and Propulsion Conf.*, Seoul, Korea, 2012
- [13] Bizon N., Nonlinear control of fuel cell hybrid power sources: Part I - Voltage control, *Applied Energy*, vol. 88, pp. 2559-2573, 2011
- [14] Bubna P., Brunner D., Advani S.G., Prasad A.K., Prediction-based optimal power management in a fuel cell/battery plug-in hybrid vehicle, *J. of Power Sources*, vol. 195, pp. 6699-6708, 2010
- [15] Caux S., Hankache W., Fadel M., Hissel D., On-line fuzzy energy management for hybrid fuel cell systems, *Int. J. of Hydrogen Energy*, vol. 35, pp. 2134-2143, 2010
- [16] Chen Q., Gao L., Dougal R.A., Quan S., Multiple model predictive control for a hybrid proton exchange membrane fuel cell system, *J. of Power Sources*, vol. 191, pp. 473-482, 2009

- [17] Corbo P., Corcione F.E., Migliardini F., Veneri O., Energy management in fuel cell power train, *Energy Conversion and Management*, vol. 47, pp. 3255-3271, 2006
- [18] Da Fonseca R., Bideaux E., Jeanneret B., Gerard M., Desbois-Renaudin M., Sari A., Energy management strategy for hybrid fuel cell vehicle, *proc. Int. Conf. on Control, Automation and Systems*, Jeju Island, Korea, 2012
- [19] Dalvi A., Guay M., Control and real-time optimization of an automotive hybrid fuel cell power system, *Control Engineering Practice*, vol. 17, pp 924-938, 2009
- [20] Degliuomini L.N., Zumoffen D., Basualdo M., Feroldi D., Riera J., Adaptive predictive robust control for fuel cells hybrid vehicles, *proc. IEEE Vehicle Power and Propulsion conf.*, Lille, France, 2010
- [21] Di Domenico D., Fiengo G., A decoupled controller for fuel cell hybrid electric power split, *proc. Am. Control Conf.*, Seattle, USA 2008
- [22] Di Domenico A., Speltino C., Fiengo G., Power split strategy for fuel cell hybrid electric system, *Oil & Gas Science and Technology*, vol. 65(1), pp. 145-154, 2010
- [23] Eren Y., Erdinc O., Gorgun H., Uzunoglu M., Vural B., A fuzzy logic based supervisory controller for an FC/UC hybrid vehicular power system, *Int. J. of Hydrogen Energy*, vol. 34, pp. 8681-8694, 2009
- [24] Erdinc O., Vural B., Uzunoglu M., Ates Y., Modeling and analysis of an FC/UC hybrid vehicular power system using a wavelet-fuzzy logic based load sharing and control algorithm, *Int. J. of Hydrogen Energy*, vol. 34(12), pp. 5223-5233, 2009
- [25] Erdinc O., Vural B., Uzunoglu M., A wavelet-fuzzy logic based energy management strategy for a fuel cell/battery/ultra-capacitor hybrid vehicular power system, *J. of Power Sources*, vol. 194, pp. 369-380, 2009
- [26] Ettahir K., Boulon L., Agbossou K., Kelouwani S., Hammoudi M., Design of an energy management strategy for PEM Fuel Cell Vehicles, *proc. IEEE Int. Symp. on Industrial Electronics*, Hangzhou, China, 2012
- [27] Fadel A., Zhou B., Power management methodologies for fuel cell-battery hybrid vehicles, *SAE Technical Paper*, 2010
- [28] Fadel A., Zhou B., An experimental and analytical comparison study of power management methodologies of fuel cell-battery hybrid vehicles, *J. of Power Sources*, vol. 196, pp. 3271-3279, 2011
- [29] Fernandez L.M., Garcia P., Garcia C.A., Jurado F., Hybrid electric system based on fuel cell and battery and integrating a single dc/dc converter for a tramway, *Energy Conversion and Management*, vol. 52, pp. 2183-2192, 2011
- [30] Feroldi D., Serra M., Riera J., Energy management strategies based on efficiency map for fuel cell hybrid vehicles, *J. of Power Sources*, vol. 190(2), pp. 387-401, 2009
- [31] Feroldi D., Serra M., Riera J., Design and analysis of fuel-cell hybrid systems oriented to automotive applications, *IEEE Trans. on Vehicular Technology*, vol. 58, pp. 4720-4729, 2009
- [32] Gao L., Jiang Z., Dougal R.A., An actively controlled fuel cell/battery hybrid to meet pulsed power demands, *J. of Power Sources*, vol. 130, pp. 202-207, 2004
- [33] Gao D., Jin Z., Lu Q., Energy management strategy based on fuzzy logic for a fuel cell hybrid bus, *J. of Power Sources*, vol. 185(1), pp. 311-317, 2008
- [34] Garcia P., Fernandez L.M., Garcia C.A., Jurado F., Energy management system of fuel-cell-battery hybrid tramway, *IEEE Trans. on Industrial Electronics*, vol. 57, pp. 4013-4023, 2010
- [35] Geng B., Mills J.K., Sun D., Two-stage energy management control of fuel cell plug-in hybrid electric vehicles considering fuel cell longevity, *IEEE Trans. on Vehicular Technology*, vol. 61, pp. 498-508, 2012
- [36] Haitao Y., Yulan Z., Zechang S, Gang W., Model-based power control strategy development of a fuel cell hybrid vehicle, *J. of Power Sources*, vol. 180, pp. 821-829, 2008
- [37] Hajizadeh A., Golkar M.A., Feliachi A., Voltage control and active power management of hybrid fuel-cell/energy-storage power conversion system under unbalanced voltage sag conditions, *IEEE Trans. on Energy Conversion*, vol. 25, pp. 1195-1208, 2010
- [38] Hannan M.A., Azidin F.A., Mohammed A., Analysis of multi-power sources energy management system for electric hybrid vehicle, *proc. IEEE Power Electronics and Drive Systems*, Singapore, 2011
- [39] Hannan M.A., Azidin F.A., Mohammed A., Multi-sources model and control algorithm of an energy management system for light electric vehicles, *Energy Conversion and Management*, vol. 62, pp. 123-130, 2012
- [40] Harfman Todorovic M., Palma L., Enjeti P.N., Design of a wide input range DC-DC converter with a robust power control scheme suitable for fuel cell power conversion, *IEEE Trans. on Industrial Electronics*, vol. 55, pp. 1247-1255, 2008

- [41] Hegazy O., van Mierlo J., Lataire P., Design optimization and optimal power control of fuel cell hybrid electric vehicles based on swarm intelligence, *Int. Review of Electrical Engineering* vol. 6, pp. 1727-1738, 2011
- [42] Hegazy O., van Mierlo J., Optimal power management and powertrain components sizing of fuel cell/battery hybrid electric vehicles based on particle swarm optimisation, *Int. J. Vehicle Design*, vol. 58, pp. 200-222, 2012
- [43] Hegazy O., van Mierlo J., Barrero R., Omar N., Lataire P., PSO algorithm-based optimal power flow control of fuel cell/supercapacitor and fuel cell/battery hybrid electric vehicles, *Int. J. for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 32, pp. 86-107, 2013
- [44] Hernández-Torres D., Riu D., Sename O., Druart F., Robust optimal control strategies for a hybrid fuel cell power management system, *proc. IEEE Conf. Industrial Electronics Society*, Glendale, USA, 2010
- [45] Hwang J., Chen Y., Kuo J., The study on the power management system in a fuel cell hybrid vehicle, *Int. J. of Hydrogen Energy*, vol. 37, pp. 4476-4489, 2012
- [46] Jensen H.C.W., Schaltz E., Koustrup P.S., Andreasen S.J., Kær S.K., Evaluation of fuel-cell range extender impact on hybrid electrical vehicle performance, *IEEE Trans. on Vehicular Technology*, vol. 62, pp. 50-60, 2013
- [47] Jeong K., Lee W., Kim C., Energy management strategies of a fuel cell/battery hybrid system using fuzzy logics, *J. of Power Sources*, vol. 145, pp. 319-326, 2005
- [48] Jia J., Wang G., Cham Y.T., Wang Y., Han M., Electrical characteristic study of a hybrid PEMFC and ultracapacitor system, *IEEE Trans. on Industrial Electronics*, vol. 57, pp. 1945-1953, 2010
- [49] Jiang Z., Gao L., Blackwelder M.J., Dougal R.A., Design and experimental tests of control strategies for active hybrid fuel cell/battery power sources, *J. of Power Sources*, vol. 130, pp. 163-171, 2004
- [50] Jiang Z., Gao L., Dougal R.A., Adaptive control strategy for active power sharing in hybrid fuel cell/battery power sources, *IEEE trans. on Energy Conversion*, vol. 22, pp. 507-515, 2007
- [51] Kelouwani S., Agbossou K., Dubé Y., Boulon L., Anticipatory control of a PEM fuel cell for a serial hybrid electric vehicle, *proc. IEEE Vehicle Power and Propulsion Conf.*, Seoul, Korea, 2012
- [52] Kelouwani S., Henao N., Agbossou K., Dubé Y., Boulon L., Two-layer energy-management architecture for a fuel cell HEV using road trip information, *IEEE Trans. on Vehicular Technology*, vol. 61, pp. 3851-3864, 2012
- [53] Kelouwani S., Agbossou K., Dubé Y., Boulon L., Fuel cell plug-in hybrid electric vehicle anticipatory and real-time blended-mode energy management for battery life preservation, *J. of Power Sources*, vol. 221, pp. 406-418, 2013
- [54] Kim M., Peng H., Power management and design optimization of fuel cell/battery hybrid vehicles, *J. of Power Sources*, vol. 165(2), pp. 819-832, 2007
- [55] Kisacikoglu M.C., Uzunoglu M., Alam M.S., Load sharing using fuzzy logic control in a fuel cell/ultracapacitor hybrid vehicle, *Int. J. of Hydrogen Energy*, vol. 34, pp. 1497-1507, 2009
- [56] Li C., Liu G., Optimal fuzzy power control and management of fuel cell/battery hybrid vehicles, *J. of Power Sources*, vol. 192, pp. 525-533, 2009
- [57] Li X., Xu L., Hua J., Lin X., Li J., Ouyang M., Power management strategy for vehicular-applied hybrid fuel cell/battery power system, *J. of Power Sources*, vol. 191, pp. 542-549, 2009
- [58] Li Q., Chen W., Li Y., Liu S., Huang J., Energy management strategy for fuel cell/battery/ultracapacitor hybrid vehicle based on fuzzy logic, *Int. J. of Electrical Power & Energy Systems*, vol. 43, pp. 514-525, 2012
- [59] Li Q., Chen W., Liu S., You Z., Tao S., Li Y., Power management strategy based on adaptive neuro-fuzzy inference system for fuel cell-battery hybrid vehicle, *J. of Renewable and Sustainable Energy*, vol. 4, pp. 013106-1-12, 2012
- [60] Lin W., Zheng C., Energy management of a fuel cell/ultracapacitor hybrid power system using an adaptive optimal-control method, *J. of Power Sources*, vol. 196, pp. 3280-3289, 2011
- [61] Liu G., Zhang J., Sun Y., High frequency decoupling strategy for the PEM fuel cell hybrid system, *Int. J. of Hydrogen Energy*, vol. 33, pp. 6253-6261, 2008
- [62] Mallouh M.A., Surgenor B., Dash P., McInnes L., Performance evaluation and tuning of a fuzzy control strategy for a fuel cell hybrid electric auto rickshaw, *proc. American Control Conf.*, Fairmont, Canada, 2012

- [63] Martínez J.S., Hissel D., Péra M.C., Amiet M., Practical control structure and energy management of a testbed hybrid electric vehicle, *IEEE Trans. on Vehicular Technology*, vol. 60, pp. 4139-4151, 2011
- [64] Marco J., Vaughan N.D., Design of a reference control architecture for the energy management of electric vehicles, *Int. J. Vehicle Design*, vol. 58, pp. 240-264, 2012
- [65] Marx M., Özbek M., Söffker D., Power management investigations on a fuel cell-based hybrid HIL powertrain, *SAE Technical Paper*, 2010
- [66] Melero-Pérez A., Gao W., Fernández-Lozano J.J., Fuzzy logic energy management strategy for fuel cell/ultracapacitor/battery hybrid vehicle with multiple-input DC/DC converter, *proc. IEEE Vehicle Power and Propulsion Conf.*, Dearborn, USA, 2009
- [67] Montero C., Oliva A., Marcos D., González E., Bordons C., Ridao M.A., Camacho E.F., López E., Fuel cell and power control for a hybrid vehicle. Experimental results., *proc. IEEE Industrial Electronics Society*, Montreal, Canada, 2012
- [68] Na W., Park T., Kim T., Kwak S., Light fuel-cell hybrid electric vehicles based on predictive controllers, *IEEE Trans. on Vehicular Technology*, vol. 60, pp. 89-97, 2011
- [69] Naderi P., Samimi A., Fuel-cell/battery hybrid vehicle modeling and fuzzy controller design for power management, *Int. Review on Modelling and Simulations*, vol. 5, pp. 982-990, 2012
- [70] Ouyang M., Xu L., Li J., Lu L., Performance comparison of two fuel cell hybrid buses with different powertrain and energy management strategies, *J. of Power Sources*, vol. 163, pp. 467-479, 2006
- [71] Paladini V., Donato T., de Risi A., Laforgia D., Super-capacitors fuel-cell hybrid electric vehicle optimization and control strategy development, *Energy Conversion and Management*, vol. 48, pp. 3001-3008, 2007
- [72] Pany P., Singh R.K., Tripathi R.K., Power management of fuel cell and battery fed DC motor drive for electric vehicle application, *proc. IEEE Int. Conf. on Advances in Engineering, Science and Management*, Nagapattinam, India, 2012
- [73] Payman A., Pierfederici S., Meibody-Tabar F., Energy control of supercapacitor/fuel cell hybrid power source, *Energy Conversion and Management*, vol. 49, pp. 1637-1644, 2008
- [74] Payman A., Pierfederici S., Meibody-Tabar F., Energy management in a fuel cell/supercapacitor multisource/multiload electrical hybrid system, *IEEE Trans. on Power Electronics*, vol. 24, pp. 2681-2691, 2009
- [75] Perez-Pinal F.J., Nuñez C., Alvarez R., Cervantes I., Power management strategies for a fuel cell/supercapacitor electric vehicle, *proc. IEEE Vehicle Power and Propulsion Conf.*, Arlington, USA, 2007
- [76] Pourhashemi A.P., Medhi Ansarey S.M., Ant colony optimization applied to optimal energy management of fuel cell hybrid electric vehicle, *proc. Int. Congress on Ultra Modern Telecommunications and Control Systems*, St. Petersburg, Russia, 2012
- [77] Ravey A., Roche R., Blunier B., Miraoui A., Combined optimal sizing and energy management for hybrid electric vehicles, *proc. IEEE Transportation Electrification Conf.*, Dearborn, USA, 2012
- [78] Ravey A., Blunier B., Miraoui A., Control strategies for fuel-cell-based hybrid electric vehicles: From offline to online and experimental results, *IEEE Trans. on Vehicular Technology*, vol. 61, pp. 2452-2457, 2012
- [79] Rodatz P., Paganelli G., Sciarretta A., Guzzella L., Optimal power management of an experimental fuel cell/supercapacitor-powered hybrid vehicle, *Control Engineering Practice*, vol. 13(1), pp. 41-53, 2005
- [80] Ryu J., Park Y., Sunwoo M., Electric powertrain modeling of a fuel cell hybrid electric vehicle and development of a power distribution algorithm based on driving mode recognition, *J. of Power Sources*, vol. 195, pp. 5735-5748, 2010
- [81] Sarioğlu I.L., Klein O.P., Schröder H., Küçükay F., Energy management for fuel-cell hybrid vehicles based on specific fuel consumption due to load shifting, *IEEE Trans. on Intelligent Transportation Systems*, vol. 13, pp. 1772-1781, 2012
- [82] Schell A., Peng H., Tran D., Stamos E., Lin C., Kim M.J., Modelling and control strategy development for fuel cell electric vehicles, *Annual Reviews in Control*, vol. 29, pp. 159-168, 2005
- [83] Sripakagorn A., Limwuthhigraijirat N., Experimental assessment of fuel cell/supercapacitor hybrid system for scooters, *Int. J. of Hydrogen Energy*, vol. 34, pp. 6036-6044, 2009
- [84] Tazelaar E., Veenhuizen P.A., van den Bosch P.P.J., Grimminck M., Analytical solution and experimental validation of the energy management problem for fuel cell hybrid vehicles, *proc. EEVC*, Brussels, Belgium, 2011

- [85] Tazelaar E., Veenhuizen P.A., van den Bosch P.P.J., Grimminck M., Analytical solution of the energy management for fuel cell hybrid propulsion systems, *IEEE trans. on Vehicular Technology*, vol. 61(5), pp. 1986-1998, 2012
- [86] Tazelaar E., Energy management and sizing of fuel cell hybrid propulsion systems, *PhD thesis, Eindhoven University of Technology*, 2013
- [87] Thounthong P., Rafaël S., Davat B., Control strategy of fuel cell/supercapacitors hybrid power sources for electric vehicle, *J. of Power Sources*, vol. 158, pp. 806-814, 2006
- [88] Thounthong P., Rafaël S., Davat B., DC bus voltage regulation supplied by fuel cell/supercapacitor hybrid source, *ECTI trans. on Electrical Eng., Electronics, and Communications*, vol. 4(2), pp. 90-95, 2006
- [89] Thounthong P., Chunkag V., Sethakul P., Davat B., Hinaje M., Comparative study of fuel-cell vehicle hybridization with battery of supercapacitor storage device, *IEEE trans. on Vehicular Technology*, vol. 58 3892-3904, 2009
- [90] Thounthong P., Rafaël S., Davat B., Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications, *J. of Power Sources*, vol. 193, pp. 376-385, 2009
- [91] Thounthong P., Pierfederici S., Davat B., Analysis of differential flatness-based control for fuel cell hybrid power source, *IEEE trans. on Energy Conversion*, vol. 25, pp. 909-920, 2010
- [92] Thounthong P., Pierfederici S., Martin J., Hinaje M., Davat B., Modeling and control of fuel cell/supercapacitor hybrid source based on differential flatness control, *IEEE trans. on Vehicular Technology*, vol. 59, pp. 2700-2710, 2010
- [93] Torreglosa J.P., Jurado F., García P., Fernández L.M., Hybrid fuel cell and battery tramway control based on an equivalent consumption minimization strategy, *Control Engineering Practice*, vol. 19, pp. 1182-1194, 2011
- [94] Uzunoglu M., Alam M.S., Modeling and analysis of an FC/UC hybrid vehicular power system using a novel-wavelet-based load sharing algorithm, *IEEE trans. on Energy Conversion*, vol. 23(1), pp. 263-272, 2008
- [95] Valero I., Bacha S., Rulliere E., Comparison of energy management controls for fuel cell applications, *J. of Power Sources*, vol. 156, pp. 50-56, 2006
- [96] Wang L., Wang Z., Li H., Optimized energy storage system design for a fuel cell vehicle using a novel phase shift and duty cycle control, *proc. IEEE Energy Conversion Congress and Exposition*, San Jose, USA, 2009
- [97] Wang L., Hui L., Maximum fuel economy-oriented power management design for a fuel cell vehicle using battery and ultracapacitor, *IEEE trans. on Industry Applications*, vol. 46(3), pp. 1011-1020, 2010
- [98] Wong J.H., Sutikno T., Idris N.R.N., Anwari M., A parallel energy-sharing control strategy for fuel cell hybrid vehicle, *Telkomnika*, vol. 9, pp. 357-364, 2011
- [99] Wu D., Fuel cell-hybrid electric vehicle power train system design and control, *MSc thesis, Concordia University, Montreal, Canada*, 2008
- [100] Xiao D., Wang Q., The research of energy management strategy for fuel cell hybrid vehicle, *proc. IEEE Int. Conf. on Industrial Control and Electronics Engineering*, Xi'an, China, 2012
- [101] Xu L., Hua J., Li X., Meng Q., Li J., Ouyang M., Control strategy optimization of a hybrid fuel cell vehicle with braking energy regeneration, *proc. IEEE Vehicle Power and Propulsion Conf.*, Harbin, China, 2008
- [102] Xu L., Li J., Hua J., Li X., Ouyang M., Adaptive supervisory control strategy of a fuel cell/battery-powered city bus, *J. of Power Sources*, vol. 194, pp. 360-368, 2009
- [103] Xu L., Li J., Hua J., Li X., Ouyang M., Optimal vehicle control strategy of a fuel cell/battery hybrid city bus, *Int. J. of Hydrogen Energy*, vol. 34, pp. 7323-7333, 2009
- [104] Xu L., Yang F., Li J., Ouyang M., Hua J., Real time optimal energy management strategy targeting at minimizing daily operation cost for a plug-in fuel cell city bus, *Int. J. of Hydrogen Energy*, vol. 37, pp. 15380-15392, 2012
- [105] Yu A., Zinger D., Bose A., An innovative optimal allocation strategy for fuel cell, battery and supercapacitor hybrid electric vehicle, *J. of Power Sources*, vol. 196, pp. 2351-2359, 2011
- [106] Zandi M., Payman A., Martin J., Pierfederici S., Davat B., Meibody-Tabar F., Energy management of a fuel cell/supercapacitor/battery power source for electric vehicular applications, *IEEE trans. on Vehicular Technology*, vol. 60, pp. 433-443, 2011
- [107] Zhang X., Mi C.C., Masrur A., Daniszewski D., Wavelet-transform-based power management of hybrid vehicles with

multiple on-board energy sources including fuel cell, battery and ultracapacitor, *J. of Power Sources*, vol. 185, pp. 1533-1543, 2008

- [108] Zhao H., Burke A., Optimum performance of direct hydrogen hybrid fuel cell vehicles, *proc. EVS*, Stavanger, Norway, 2009
- [109] Zhao H., Burke A.F., Fuel cell powered vehicles using supercapacitors-device characteristics, control strategies, and simulation results, *Fuel Cells*, vol. 10, pp. 879-896, 2010
- [110] Zheng C.H., Park Y.I., Lim W.S., Cha S.W., Fuel economy evaluation of fuel cell hybrid vehicles based on optimal control, *Int. J. of Automotive Technology*, vol. 13, pp. 517-522, 2012
- [111] Zheng C.H., Kim N.W., Cha S.W., Optimal control in the power management of fuel cell hybrid vehicles, *Int. J. of Hydrogen Energy*, vol. 37, pp. 655-663, 2012
- [112] Zheng C.H., Oh C.E., Park Y.I., Cha S.W., Fuel economy evaluation of fuel cell hybrid vehicles based on equivalent fuel consumption, *Int. J. of Hydrogen Energy*, vol. 37 pp. 1790-1796, 2012

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