POLITEHNICA UNIVERSITY OF BUCHAREST

Doctoral School of Electronics, Telecommunications and Information Technology

Decision No. ____ from DD-MM-YYYY

Ph.D. THESIS SUMMARY

Ing. Ioan-Sorin ȘORLEI

CONTROL, OPTIMIZARE, DIAGNOZĂ ȘI ÎNTREȚINERE PREDICTIVĂ A SISTEMULUI ELECTRIC HIBRID DE ENERGIE DIN VEHICULE ELECTRICE CU PILE DE COMBUSTIBIL

CONTROL, OPTIMIZATION, DIAGNOSIS AND PREDICTIVE MAINTENANCE OF THE HYBRID ELECTRIC POWER SYSTEM IN FUEL CELL ELECTRIC VEHICLES

THESIS COMMITTEE

Prof. Dr. Ing. Gheorghe BREZEANU Politehnica Univ. of Bucharest	Preşedinte
Prof. Dr. Ing. Nicu BIZON Politehnica Univ. of Bucharest	Conducător de doctorat
Prof. Dr. Ing. Radu-Emil PRECUP Politehnica Univ. of Timisoara	Referent
Prof. Dr. Ing. AIORDACHIOAIEI "Lower Danube" University of Galati	Referent
Prof. Dr. Ing. Dan Alexandru Stoichescu Politehnica Univ. of Bucharest	Referent

BUCHAREST 2025

Content

Chapter 1

Introduction

The global economic context, green policies, the Euro 7 pollution standard and the application of the Corporate Average Fuel Economy (CAFE) standard have led major car companies to invest more and more in Fuel Cell Electric Vehicles (FCEVs) in addition to hybrid, plug-in hybrid and electric models.

In this sense, this paper addresses the above challenges, by implementing advanced control techniques to reduce fuel consumption, increase overall energy efficiency and durability.

1.1 Presentation of the field of the doctoral thesis

The PhD thesis is focused on the applications of advanced software algorithms in the automotive industry for the research and development of Fuel Cell Electric Vehicles to reduce hydrogen consumption, improve overall energy efficiency and increase the lifetime of energy storage systems.

1.2 Scope of the doctoral thesis

The main goal of this research paper is to develop and test a new software algorithm, SWA_RTO, in order to achieve both hydrogen fuel economy and to improve hybrid electric system performance indicators by applying real-time control strategies and techniques in a European Extra-Urban Driving Cycle (EUDC).

1.3 Content of the doctoral thesis

This thesis aims to introduce new technologies in terms of control and mechanisms for the optimization and predictive maintenance of FCHEVs taking into account energy management strategies.

In this regard, the study in Chapter 2 was based on the analysis of recent research in the field to reflect on the need to implement new optimization and control algorithms for both reducing fuel consumption and improving the performance of fuel cell vehicles.

To highlight the system performance using real-time optimization (RTO) strategies based on the Global Extremum Seeking Control (GES) algorithm, in Chapter 3, load threshold sensitivity analysis was used to determine the best values of the calibratable parameters of the optimization function and GES algorithm.

The main contribution of Chapter 4 focuses on the development of a Model In The Loop (MIL) test model in the Matlab/Simulink software application to test the vehicle performance in an EUDC driving cycle by means of a novel real-time control (SW_RTO) for fuel economy and state of charge optimization of the energy storage system, consisting of batteries and ultracapacitors.

In Chapter 5, previous results were improved by a new SWA_RTO algorithm, applied to a fuel cell hybrid power system in order to achieve much lower fuel consumption. Simulation tests were performed for the profiles: urban driving cycle (ECE-15), extra-urban driving cycle (EUDC) and urban + extra-urban driving cycle (NEDC).

Chapters 6 and 7 conclude the paper with a number of positive conclusions demonstrating the ability of the GES algorithm to integrate it into a number of real-time optimization strategies to meet performance indicators. At the same time, the limitations that the algorithm has in adapting to new control units for fuel cell systems with different power outputs, limitations that are related to the tuning and calibration of software parameters, should not be neglected.

Chapter 2

Energy management strategies for the main propulsion system topologies for a fuel cell electric vehicle

FCEVs and fuel cell hybrid electric vehicles (FCHEVs) use a combination of the fuel cell (FC), the battery system (B) and the ultracapacitor (UC) system. In order to increase power density and meet power load demand, the integration of an energy management system (EMS) is required [1].

2.1 Fuel cell propulsion systems and DC/DC converter topologies

All electric vehicles (AEVs) use only electricity for the propulsion system of the vehicles. They may use a battery system, fuel cells or a hybrid solution as a backup power source.

2.1.1 Fuel Cell Electric Vehicles (FCEVs)

FCEVs use a full electric propulsion system and the main energy source is based on the fuel cell system.

The propulsion system of FCEVs/FCHEVs can be realized in three modes: fuel cell + battery (FC + B), fuel cell + ultracapacitor (FC + UC) and fuel cell + battery + ultracapacitor (FC + B + UC) [2].

2.1.2 Fuel Cell Hybrid Electric Vehicles (FCHEVs)

Figure 2.2 shows the type of configuration: fuel cell + battery system + ultracapacitors that an FCHEV can have.

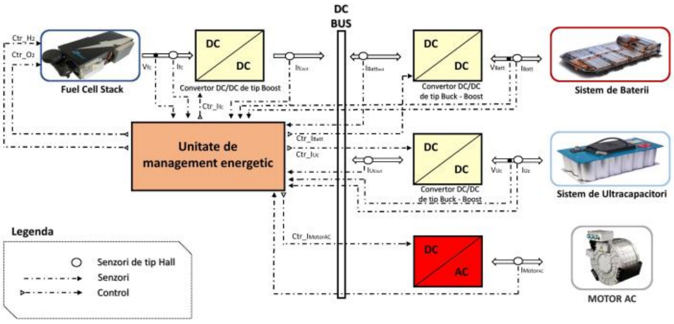

__Figure 2.2__ Fuel cell hybrid electric vehicle topology (T5 topology)

2.1.3 State-of-the-art fuel cell technologies in the automotive industry

Over time, different car manufacturers in different countries have approached the development of FCEVs as follows [3]: Germany (Europe), Japan, Korea and China (Asia) and the USA (North America) (see Figure 2.3).

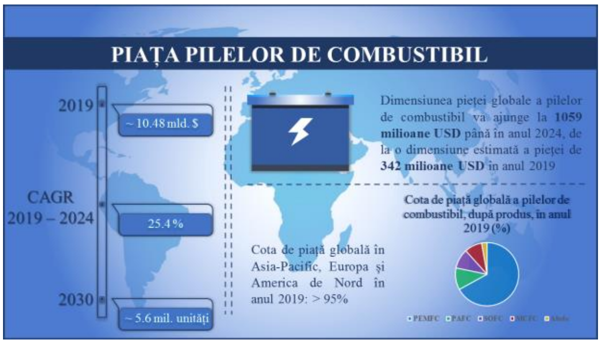

__Figure 2.3__ Fuel cell market

2.1.4 DC/DC Converters for Fuel Cell Electric Vehicles

DC/DC converters are electronic devices that convert an electrical voltage level, usually unstable at the input, into a stable electrical voltage at the output. In the automotive field, the electrical voltage useful for electric propulsion is in the range 400-700 V. DC/DC converter topologies are divided into two categories: non-isolated and isolated [4].

2.1.4.1 Uninsulated DC/DC converters

The first topology of non-isolated DC/DC converters is the boost type converter with an efficiency of about 95% suitable to serve as an interface between the fuel cell and the DC bus. The second topology is the buck type DC/DC converter - the main characteristic is to produce a lower output voltage than the input voltage and is designed to provide a low output ripple current. The third topology is the buck-boost converter - it increases or decreases the output voltage and reverses the polarity of the input voltage.

For interfacing renewable energy sources, the three-port non-isolated buck-boost DC/DC converter is presented in the paper.

2.1.4.2 Isolated DC/DC converters

Isolated DC/DC converters are converters that have a transformer built into their structure to achieve DC isolation between input and output. The transformer operates at the switching frequency of the converter up to hundreds of kHz [5].

2.1.4.3 DC/DC Converters - New topologies

With the development of new automotive technologies for EV, HEV, FCEV, FCHEV and AEV applications, the main objective of researchers is to find new technological solutions to meet the challenges of this segment. There are many underlying factors that increase the performance of a converter, such as the suppression of electrical noise in the system, low ripple voltage value of capacitors (< 1%), ripple current value, switching losses or the implementation of new active or passive components, increase the efficiency of the system [6].

2.2 Energy management strategy for fuel cell electric vehicles

Reducing hydrogen consumption by optimizing energy consumption is the subject of much research. In addition to assessing fuel consumption, control strategies play a role in preventing degradation of energy storage systems, batteries and ultracapacitors.

2.2.1 Analysis of Rule-Based Strategies in FCEVs

Control based on rule sets has very good efficiency consistent with embedded processors, but they are usually based on empirical laws, and the results are not optimal.

2.2.2 Analysis of Optimisation-Based Strategies in FCEV

2.2.2.1 Global Optimization Strategy

Global optimization strategies are often used to reduce fuel consumption by optimizing the power flow of the propulsion system. Some examples of the implementation of algorithms, used for fuel economy, in the sphere of global optimisation strategies are highlighted [7].

2.2.2.2 Real-Time Optimization Strategy

The most important feature of real-time optimization strategies is the processing power of the information collected from the ESS for the purpose of automating energy control to prevent component aging. Even though the design of such algorithms is more difficult to realize, compared to other energy management strategies, real-time strategies are important because the development of FCEVs must have a competitive end in the global market [8].

2.2.3 Analysis of Learning Based Strategies in FCEV

LB strategies rely on large datasets with historical information and real-time data to achieve optimal control. The main advantage of these strategies is the learning and adaptive capability as well as model-free control [9].

2.3 Discussion and Perspectives

The lifecycle of a fuel cell stack can be categorized from a techno-economic point of view into a manufacturing stage and an end-user stage. Thus the total cost of an 80 kWnet fuel cell system is between 20 - 30 USD/kW.

The main challenges in adopting FC technologies as automotive propulsion systems are the following:

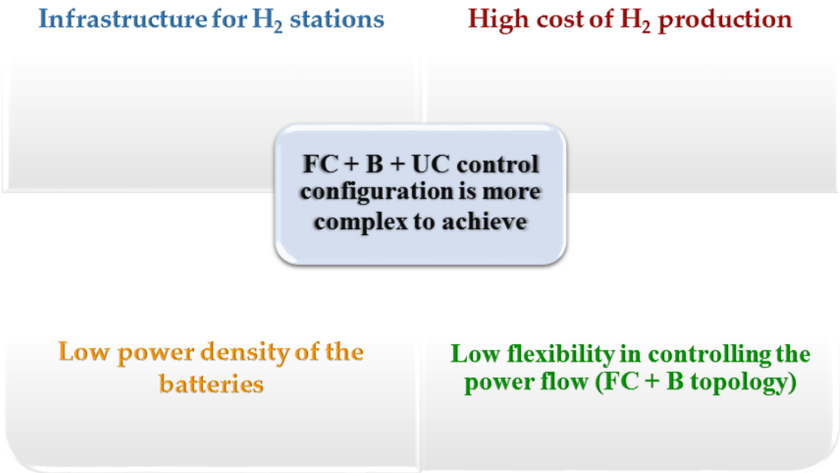

Figure 2.11 *Main challenges in the adoption of Fuel Cell (FC) technologies as automotive propulsion system*

2.4 Summary and conclusions

In order to improve energy performance, a number of energy management strategies have been analyzed, presenting the fundamentals of existing techniques with the advantages and disadvantages of their use, with the objectives of reducing hydrogen consumption and preventing degradation of the ESS system.

Thus, the progress made by software developers in the field of artificial intelligence offers researchers the possibility to have a maximum potential in the design abilities of new control algorithms by hybridizing with existing techniques to eliminate uncertainties in the robustness of the EMS.

Chapter 3

Modeling the chosen fuel cell electric vehicle architecture and analyzing energy management strategies

The issue of PEMFC performance optimization is the efficiency of the system through a number of parameters. Thus, particular attention must be paid to the airflow to ensure efficient, durable and reliable operation [186]. The defining parameter in the dynamic response of the system's variable airflow is the excess oxygen ratio (OER) [10].

3.1 Fuel cell hybrid energy system

The overall energy efficiency of the HPS FC/ESS could be maximized by identifying the best degree of hybridization and the appropriate multi-source and multi-load energy management strategy.

3.1.1 Fuel Cell System model

For the modeling of the chosen architecture a default model of a 6 kW - 45 V PEMFC PEMFC stack from the SimPowerSystem® toolbox of Matlab/Simulink software.

3.1.1.1 Air flow control

PEMFC airflow must be controlled quickly, but robust and efficient. MPP tracking using ES (extremum seeking) control based on a computational scheme is used to obtain the optimum value of oxygen stoichiometry reference stoichiometry [11].

3.1.1.2 Hydrogen flow control

The fuel cell power can be adjusted directly by controlling the hydrogen supply. The current regulation is limited by the fuel cell size (which sets a minimum internal impedance) and the dynamic range of the mass flow controllers. The control loops, of the reactant feeders, must achieve a fast response of the FCHPS to load changes.

3.1.1.3 Feed flow control

In this paper, FuelFr and AirFr are the inputs controlled by the fuel (3.1) and air (3.2) controllers, respectively:

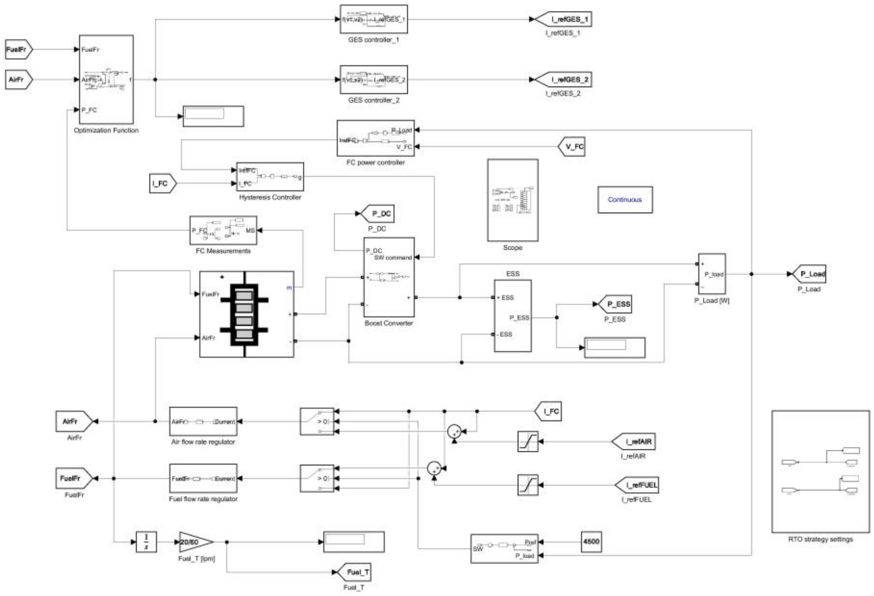

Figure 3.3 *FCHPS architecture based on Global Extremum Seeking Control (GES)*

$$I_{ref(Fuel)} = \begin{cases} I_{FC}, \ if \ P_{DCreq} \leq P_{ref} \\ I_{FC} + I_{ref(GES\_2)}, \ if \ P_{DCreq} > P_{ref} \end{cases} \tag{3.3}$$

$$I_{ref(Air)} = \begin{cases} I_{FC} + I_{ref(GES\_1)}, \ if \ P_{DCreq} \leq P_{ref} \\ I_{FC}, \ if \ P_{DCreq} > P_{ref} \end{cases} \tag{3.4}$$

The optimal P_{ref} threshold for the best fuel economy will be found by the sensitivity analysis performed for this parameter.

3.1.2 Energy Storage System (ESS)

In this study, the semi-active ESS topology utilizes the 100 Ah lithium-ion battery system (connected directly to 200 V DC) and the 50F ultracapacitor system (connected through a bidirectional buck-boost converter).

3.1.2.1 Batteries

For a 100 Ah lithium-ion battery, its capacity (CBat) can be estimated with equation (3.11):

$$C_{Bat} = \frac{\Delta P_{load} * n_{cycle} * T_{cycle(Bat)}}{\Delta V_{Bat}} \tag{3.11}$$

, where the stored energy pulse ($\Delta P_{load} \cdot T_{cycle(Bat)}$=4800 Ws) will give a voltage drop down to ΔV_{Bat} (= 1,5%V_{Bat} = 3 V) during each charge cycle (n_{cycle}=100).

3.1.2.2 Capacitors and ultracapacitors

Capacitors and ultracapacitors are used to attenuate power pulses during 100 load cycles (n_{cycle}=100), dynamically compensating the instantaneous power flow balance.

3.1.3 FCHPS variable load

The variable load demand is based on a step (up and down) profile, with power levels of 3000 W, 4000 W, 5000 W, 6000 W, 7000 W, 6000 W, 5000 W, 4000 W, 3000 W are examined for the time sequence of 0-2 s, 2-4 s, 4-8 s, 8-10 s, 10-12 s, 12-14 s, 14-16 s, 16-18 s, 18-20 s.

3.1.4 The optimization function formulation problem

The optimization function formulation problem for FCHPS is defined in relation (3.14):

Maximize:

$$f(x, AirFr, FuelFr, P_{load}) = k_{net} * P_{FCnet} + k_{fuel} * Fuel_{eff} \tag{3.14}$$

where P_{load} is the power on load, AirFr and FuelFr are the stack fuel flow rates, P_{FCnet} is the FC net power, $Fuel_{eff}$ is the fuel consumption efficiency ($Fuel_{eff}$ = P_{Fcnet} / FuelFr), and K_{net} and K_{fuel} are two weighting coefficients that can be selected or adjusted based on the objective set for the Energy Management Unit (EMU).

3.2 Energy management strategy for fuel cell hybrid power system

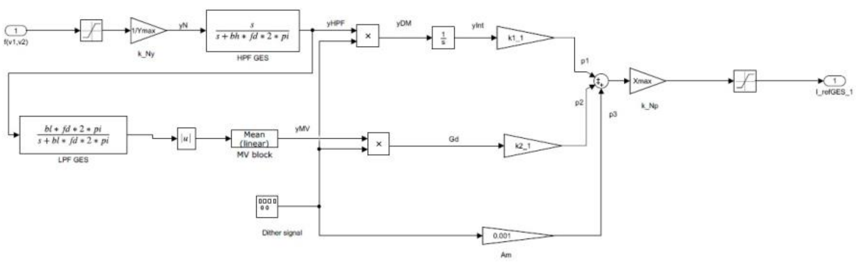

Figure 3.10 *Controller GES (Global Extremum Seeking)*

The tracking loop of the proposed GHG scheme operates during the localisation of the optimum, MEP (Maximum Efficiency Point) for the FCHPS. In order to show the effect of the weighting coefficients on the total fuel consumption, three cases will be analyzed: case A (K_{net}=0.5, K_{fuel}=20), case B (K_{net}=0.5, K_{fuel}=35) and case C (K_{net}=0.5, K_{fuel}=50).

Table 3.1 *Establishment of the RTO strategies and the sFF (Static Feed-Forward) reference strategy for the fuel cell hybrid power system model*

Reference \ Strategies	RTO_1	RTO_2	RTO_3	RTO_4	RTO_5	RTO_6	RTO_7	sFF
$I_{ref(Air)}$	I_{FC}	$I_{FC}+I_{GES1}$	I_{ref}	I_{FC}	I_{ref}	$I_{FC}+I_{GES2}$	$I_{FC}+I_{GES1}$	I_{FC}
$I_{ref(Fuel)}$	$I_{FC}+I_{GES1}$	I_{FC}	I_{FC}	I_{ref}	$I_{FC}+I_{GES2}$	I_{ref}	$I_{FC}+I_{GES1}$	I_{FC}
$I_{ref(Boost)}$	I_{ref}	I_{ref}	I_{GES1}	I_{GES1}	I_{GES1}	I_{GES1}	I_{ref}	I_{ref}

The optimality of the optimization function will be pursued by the GES-based RTO_1 - RTO_7 strategy for three sets of weighting coefficients K_{net} and K_{fuel}: (0.5, 20), (0.5, 35) and (0.5, 50). The value of the performance indicators η_{sys}, $Fuel_{eff}$ and $Fuel_T$ using the RTO strategies compared to the sFF strategy are presented in Table 3.4.

Table 3.4. *Fuel economy of RTO strategies compared to the sFF reference strategy for t = 20 s.*

Knet = 0.5; GES$_1$=50 Hz; GES$_2$=100 Hz						
Nr. Crt.	K_{fuel}	$Fuel_{T\_SFF}$ [liters/h]	$Fuel_{T\_RTO}$ [liters/h]	Δ_{FuelT} [liters/h]	$Fuel_{eff}$ [W/lpm]	η_{sys} [%]
RTO_1	35	294	280.9	13.1	116	89.36
RTO_2	35	294	282.7	11.3	114.6	87.72
RTO_3	20	294	276.3	17.7	113.8	88.51
RTO_4	20	294	273.2	20.8	114.4	88.99
RTO_5	20	294	288.6	5.4	108.7	88.63
RTO_6	20	294	276.8	17.2	115.6	89.14
RTO_7	20	294	290	4	113.3	87.84

3.3 Summary and conclusions

The difference in fuel economy could be up to 20.8 liters for the variable load cycle compared to the sFF strategy for the RTO_4 strategy, while also supported by the performance indicators η_{sys} and ΔfuelT.

The performance in all indicators depends on the values of the weighting coefficients due to the change in the optimization function and this can be an advantage for the FCHPS, as the system can select the appropriate strategy related to the load profile.

Chapter 4

Advanced control, optimization and diagnostic techniques for fuel cell electric vehicle systems - design and simulation

The novelty and main contribution of this chapter focuses on improving vehicle performance in the EUDC driving cycle through innovative control for fuel economy and optimizing the state of charge of the energy storage system [12].

4.1 Topology of the FCHEV architecture

The FCHEV is made of three energy sources: the Proton Exchange Membrane Fuel Cell (PEMFC) as the main energy source and the Energy Storage System (ESS) consisting of Li-ion batteries and ultracapacitors.

4.1.1 Vehicle powertrain model

In order to model the powertrain in Matlab/Simulink, a three-degrees-of-freedom (3DOF) rigid body model with configurable axle stiffness was implemented to calculate longitudinal, vertical and tilt motion.

4.1.1.1 Driver model

The driver model implements a parametric longitudinal speed tracking controller for generating normalized acceleration and braking commands based on reference and feedback speeds.

4.1.1.2 Direct Current Electric Motor (DC Motor)

The electric motor used in this study is a direct current motor/generator (DC Motor). Static operating conditions in the linear domain of the motor are considered and the model can be used for dynamic simulations.

Using an efficiency map, one can estimate electrical power from mechanical torque demand:

$$P_e = P_{mec}\eta^k \tag{4.10}$$

, where P_e is the electrical power, P_{mec} – mechanical power, η – efficiency of conversion of electrical power from mechanical torque demand, and k represents:
$k = -1$, if used in engine mode ≥ 0,

$k = 1$, if used in generator mode < 0.

4.1.1.3 European Extra-City Driving Cycle (EUDC)

To analyze the performance of an urban vehicle, the use of a driving cycle is unavoidable. The maximum speed of the EUDC cycle is 120 km/h, with a total duration of 400 s (6 minutes 40 s seconds), and the theoretical distance is 6956 meters, with an average speed of 62.6 km/h.

4.1.2 Fuel cell System

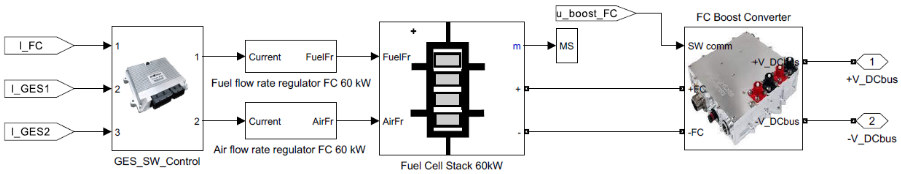

Figure 4.9 *Fuel cell system model connected to the DC bus via a one-way boost converter*

A 60 kW FC system has been chosen as the main power source in order to realize a model that comes close to the real conditions of a fuel cell vehicle.

It should be noted that in addition to fuel savings ($Fuel = \int FuelFr(t)dt$) during the EUDC cycle, the model also tracks other performance indicators such as fuel efficiency ($Fuel_{eff} = P_{FC_{net}}/FuelFr$) and electrical efficiency of the FC system ($\eta_{sys} = P_{FC_{net}}/P_{FC}$), where P_{FC} is the FC power and $P_{FC_{net}}$ is the net FC power.

4.1.3 Energy Storage System (ESS)

The ESS topology consists of a 232 Ah, 212 V Li-ion battery system and a 38.5 F, 200 V ultra-capacitor system connected in parallel to the DC bus via 2 bidirectional buck-boost DC/DC converters to dynamically compensate the power on the DC bus and stabilize the voltage at 400 V.

4.1.4 Proposed energy management strategy

The energy management and control strategy (Figure 4.13) was developed to minimize fuel consumption, within an EUDC cycle, to extend the ESS system lifetime, and to maximize the overall efficiency of the FCHEV.

The power management algorithm, which generates the drive motor torque, for controlling the PEM fuel cell, implements an LFC controller to maintain the full range of the power demand so that the variation of the battery and ultracapacitor energy is permanently in a narrow band, operating in the sustained charge (CS) mode. Therefore, the drive current of the FC system is calculated according to Eq $I_{FCCurrCmd} \cong \frac{P_{ve\square.MV}}{\eta_{FC_{boost}} V_{FC_{MV}}}$.

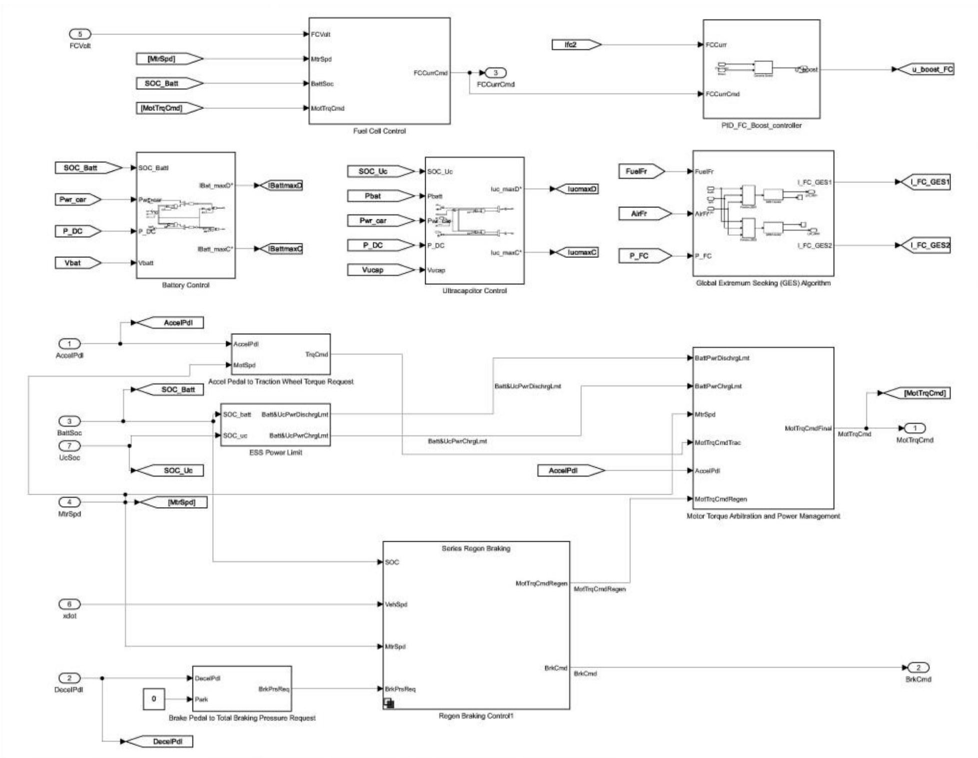

Figure 4.13 *Energy management and control strategy for FCHEV energy sources*

4.2 FCHEV architecture simulation results with real-time GES control strategy

The optimality of the optimization function will be tracked by the GES-RTOk strategy with a sinusoidal search signal $S_d = \sin(\omega t)$, where $\omega = 2\pi f_d$ ($f_{d_1} = 500\ Hz$ and $f_{d_2} = 1000\ Hz$) to compare the fuel savings achieved for FCHPS under the strategies sFF, RTO_1, RTO_2, RTO_3, SW_RTO_1/2 (with five values of $P_{ref} = [11\ kW;\ 21\ kW;\ 31\ kW; 41kW;\ 51\ kW]$). Weighting coefficients k_{net} and k_{fuel} have been set to 0.5 respectively [20; 37].

Fuel savings are obtained in this study for all GES_RTO strategies compared to the sFF baseline strategy, and validate the results obtained for variable load demand in the extra-urban cycle.

Table 4.8 *Fuel economy of RTO strategies compared to the sFF baseline strategy for the EUDC cycle (t = 400 s).*

Knet = 0.5; GES$_1$=500 Hz; GES$_2$=1000 Hz						
Nr. Crt.	K_{fuel}	$Fuel_{T\_sFF}$ [liters/h]	$Fuel_{T\_RTO}$ [liters/h]	Δ_{FuelT} [liters/h]	$Fuel_{eff}$ [W/lpm]	η_{sys} [%]
RTO_1	20	1753.33	1721.11	32.22	100.8	98.14
RTO_2	37	1753.33	1741.11	12.22	111.9	98.64
RTO_3	20; 37	1753.33	1713.33	40.00	108.7	98.81
SW_RTO_1/2	20; 37	1753.33	1702.22	51.11	105.0	98.71

Figure 22 shows the strategy with the best reference economy SW_RTO_1/2, $P_{ref} = 21\ kW$, in the EUDC extra-urban cycle and the power profiles of the $P_{veh.}$, P_{FC}, P_{Bat} şi P_{UC}.

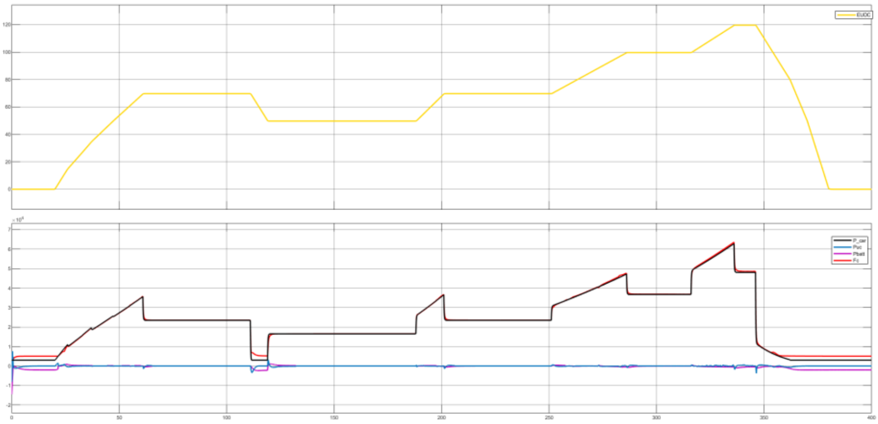

Figure 4.22 *Power profiles of $P_{veh.}$, P_{FC}, P_{Bat} and P_{UC} in an extra-urban EUDC cycle for the strategy SW_RTO_1/2, $P_{ref} = 21\ kW$*

Note that, the RTO_3 and SW_RTO_1/2 strategies use two GES controllers instead of one controller for the RTO_1 and RTO_2 strategies, so the first variants are more complex to implement.

4.3 Summary and conclusions

The switch strategy is proposed to further increase fuel economy for an extra-urban profile by using P_{ref} in the range $[11kW; 21kW; 31kW; 41kW; 51kW]$, to find the best threshold for switching. Thus, the best economy was achieved for $P_{ref} = 21kW$, with 2.5 kW upper switching threshold and 1 kW lower switching threshold.

Chapter 5

Algorithms for reducing hydrogen consumption in fuel cell electric vehicles - design and testing

In this chapter, previous results have been improved by a new SWA_RTO algorithm, by algorithmically calculating an A-factor, which selects the best optimization strategy, applied to a fuel cell hybrid power system in order to reduce fuel consumption.

5.1 Fuel economy algorithms in FCHEV

The SWA_RTO algorithm, SWA_RTO, switches between the oxygen and hydrogen controllers of the FC system, depending on the total power on the DC bus (P_car) and the set reference power (P_ref).

Evaluation of total fuel consumption for the SWA_RTO strategy (with parameters $K_{fuel} = 20$, $K_{net} = 0.5$, $f_{GES1} = 500$ Hz, $f_{GES2} = 1000$ Hz) using FCHPS with the appropriate settings mentioned, has been carried out in two steps and takes into account a number of cases for determining the best values of vector A.

Table 5.2 *Step 1 of the SWA_RTO strategy and determination of vector A in each case for the EUDC cycle (t = 400 s).*

P_{car1} $[kW]$	3 6 12	18 21 24	30 36 42	48 54 60	A
Case1	RTO1	RTO1	RTO1	RTO2	*[20 10 5 3.33 2.85 2.5 2 1.66 1.43 0.0625 0.0555 0.05]*
Case2	RTO1	RTO1	RTO2	RTO2	*[20 10 5 3.33 2.85 2.5 0.1 0.083 0.071 0.0625 0.0555 0.05]*
Case3	RTO1	RTO2	RTO2	RTO2	*[20 10 5 0.167 0.143 0.125 0.1 0.083 0.071 0.0625 0.0555 0.05]*
Case4	RTO1	RTO2	RTO1	RTO2	*[20 10 5 0.167 0.143 0.125 2 1.66 1.43 0.0625 0.0555 0.05]*
Case5	RTO1	RTO2	RTO2	RTO1	*[20 10 5 0.167 0.143 0.125 0.1 0.083 0.071 1.25 1.11 1]*
Case6	RTO2	RTO2	RTO2	RTO1	*[1 0.5 0.25 0.167 0.143 0.125 0.1 0.083 0.071 1.25 1.11 1]*
Case7	RTO2	RTO2	RTO1	RTO1	*[1 0.5 0.25 0.167 0.143 0.125 2 1.66 1.43 1.25 1.11 1]*
Case8	RTO2	RTO1	RTO1	RTO1	*[1 0.5 0.25 3.33 2.85 2.5 2 1.66 1.43 1.25 1.11 1]*
Case9	RTO2	RTO1	RTO2	RTO1	*[1 0.5 0.25 3.33 2.85 2.5 0.1 0.083 0.071 1.25 1.11 1]*
Case10	RTO2	RTO1	RTO1	RTO2	*[1 0.5 0.25 3.33 2.85 2.5 2 1.66 1.43 0.0625 0.0555 0.05]*

Table 5.3 *Step 2 of the SWA_RTO strategy and determination of vector A in each case for the EUDC cycle (t = 400 s).*

P_{car2} [kW]	11	13	15	17	19	21	A
Case1	RTO1	RTO1	RTO2	RTO2	RTO1	RTO1	*[20 10 5.45 4.62 0.2 0.176 3.16 2.86 0.125 0.1 0.083 0.071 0.0625 0.0555 0.05]*
Case2	RTO1	RTO2	RTO2	RTO2	RTO1	RTO1	*[20 10 5.45 0.23 0.2 0.176 3.16 2.86 0.125 0.1 0.083 0.071 0.0625 0.0555 0.05]*
Case3	RTO1	RTO1	RTO2	RTO2	RTO2	RTO1	*[20 10 5.45 4.62 0.2 0.176 0.158 2.86 0.125 0.1 0.083 0.071 0.0625 0.0555 0.05]*
Case4	RTO1	RTO2	RTO2	RTO2	RTO2	RTO1	*[20 10 5.45 0.23 0.2 0.176 0.158 2.86 0.125 0.1 0.083 0.071 0.0625 0.0555 0.05]*
Case5	RTO1	RTO2	RTO1	RTO2	RTO1	RTO2	*[20 10 5.45 0.23 4 0.176 3.16 0.143 0.125 0.1 0.083 0.071 0.0625 0.0555 0.05]*
Case6	RTO2	RTO2	RTO1	RTO1	RTO2	RTO2	*[20 10 0.27 0.23 4 3.53 0.158 0.143 0.125 0.1 0.083 0.071 0.0625 0.0555 0.05]*
Case7	RTO2	RTO1	RTO1	RTO1	RTO2	RTO2	*[20 10 0.27 4.62 4 3.53 0.158 0.143 0.125 0.1 0.083 0.071 0.0625 0.0555 0.05]*
Case8	RTO2	RTO2	RTO1	RTO1	RTO1	RTO2	*[20 10 0.27 0.23 4 3.53 3.16 0.143 0.125 0.1 0.083 0.071 0.0625 0.0555 0.05]*
Case9	RTO2	RTO1	RTO1	RTO1	RTO1	RTO2	*[20 10 0.27 4.62 4 3.53 3.16 0.143 0.125 0.1 0.083 0.071 0.0625 0.0555 0.05]*
Case10	RTO2	RTO1	RTO2	RTO1	RTO2	RTO1	*[20 10 0.27 4.62 0.2 3.53 0.158 2.86 0.125 0.1 0.083 0.071 0.0625 0.0555 0.05]*

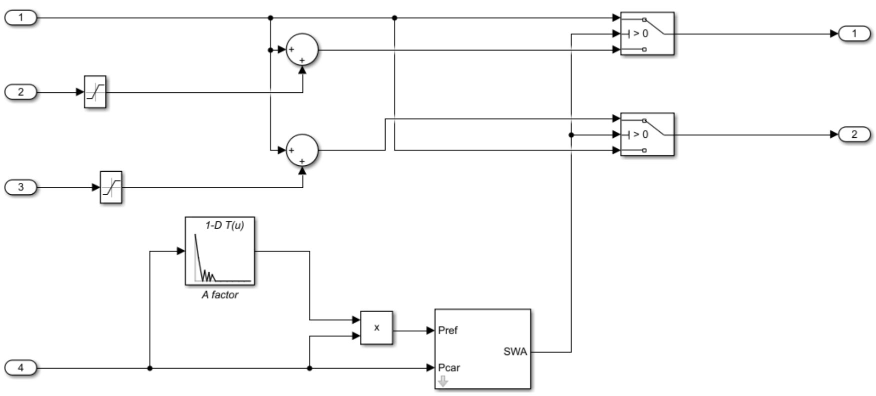

Figure 5.3 *Global Extremum Seeking (GES) based on real-time SWA_RTO algorithm*

The threshold value P_ref is set optimally for two different calculation steps: the first step (Et.1) defines the vector A in intervals over the entire power range, 3 - 60 [kW], and the second step (Et.2) defines the vector A in intervals over the power range, 11 - 21 [kW].

5.2 Experimental results of the new real-time switch algorithm in European test runs

Based on the positive results obtained on the European test cycles, for the SW_RTO_1/2 strategy, the new SWA_RTO strategy was validated, respecting the same parameters for the search of the optimality of the optimization function: K_{fuel} = 20, K_{net} = 0.5, f_{GES1} = 500 Hz, f_{GES2} = 1000 Hz.

Table 5.8 *Fuel economy for the SWA_RTO strategy, for the EUDC cycle (t = 400 s), in Stage 1*

Caz	$Fuel_{T\_sFF}$ [liters/h]	$Fuel_{T\_SWA\_RTO}$ [liters/h]	Δ_{FuelT} [liters/h]
Caz_1	1753.33	1721.11	32.22
Caz_2	1753.33	1701.11	52.22
Caz_3	1753.33	1701.11	52.22
Caz_4	1753.33	1716.67	36.67
Caz_5	1753.33	1720.00	33.33
Caz_6	1753.33	1721.11	32.22
Caz_7	1753.33	1761.11	-7.78
Caz_8	1753.33	1743.33	10
Caz_9	1753.33	1728.88	24.45
Caz_10	1753.33	1721.11	32.22

Table 5.9 *Fuel economy for the SWA_RTO strategy, for the EUDC cycle (t = 400 s), in Stage 2*

Caz	$Fuel_{T\_sFF}$ [liters/h]	$Fuel_{T\_SWA\_RTO}$ [liters/h]	Δ_{FuelT} [liters/h]
Caz_1	1753.33	1700.00	53.33
Caz_2	1753.33	1700.00	53.33
Caz_3	1753.33	1700.00	53.33
Caz_4	1753.33	1701.11	52.22
Caz_5	1753.33	1701.11	52.22
Caz_6	1753.33	1700.00	53.33
Caz_7	1753.33	1701.11	52.22
Caz_8	1753.33	1701.11	52.22
Caz_9	1753.33	1700.00	53.33
Caz_10	1753.33	1700.00	53.33

5.3 Summary and conclusions

In conclusion, the new switch strategy proposed in this paper improves the fuel economy of the fuel cell system and increases the lifetime of the energy storage system (ESS) over the whole EUDC extra-urban cycle. The chosen solution has demonstrated encouraging results in hydrogen economy and can be extrapolated over all driving cycles: NEDC, WLTP, FTP, etc.

Chapter 6

Perspectives and limitations on the applicability of advanced control and optimization techniques based on GES algorithms

To evaluate and analyze the potential limitations of the energy management system, two PEM fuel cell systems of 30 kW and 100 kW were selected for comparison with the 60 kW FCS.

6.1 Experimental results of the 30 kW PEM fuel cell energy management system

A 24 kW/80 V PEMFC system was used to evaluate the system performance, which can supply the load demand up to 30 kW.

The fuel economy, in the EUDC cycle, for the selected RTO strategies in Table 6.4 is not met on all criteria compared to the sFF baseline strategy, with the best results being presented by the RTO_2 and SW_RTO_1/2 strategies. It can be observed that, there is a higher ΔFuel_T for both RTO_1 and RTO_3 strategies.

Table 6.4 *Fuel economy of the RTO strategies, compared to the sFF baseline strategy, for the EUDC cycle (t = 400 s) and 30 kW PEMFC.*

Knet = 0.5; GES_1=500 Hz; GES_2=1000 Hz						
Nr. Crt.	K_{fuel}	$Fuel_{T\_sFF}$ [liters/h]	$Fuel_{T\_RTO}$ [liters/h]	Δ_{FuelT} [liters/h]	$Fuel_{eff}$ [W/lpm]	η_{sys} [%]
RTO_1	37	8757	10170	-1413	99.02	97
RTO_2	37	8757	8744	13	112.4	98.24
RTO_3	20; 37	8757	10200	-1443	117.4	96.13

SW_RTO_1/2	20; 37	8757	7714	1043	105.9	96.74

6.2 Experimental results of the 100 kW PEM fuel cell energy management system

In this sub-chapter, the study continued with the implementation of an 85.5 kW/300 V PEMFC system that can supply load demand scaled up to 100 kW power.

Fuel economy $Fuel_{T(SW\_RTO\_1/2)}$, is presented in Table 6.9 and shows that the best saving is obtained for the value $P_{ref} = 71\ kW$. It can be seen that there is a $\boldsymbol{\Delta Fuel_T}$ higher for both RTO_1 and RTO_3 strategies.

Table 6.9 *Fuel economy of the RTO strategies, compared to the sFF baseline strategy, for the EUDC cycle (t = 400 s) and 100 kW PEMFC.*

Knet = 0.5; GES$_1$=500 Hz; GES$_2$=1000 Hz						
Nr. Crt.	K_{fuel}	$Fuel_{T\_sFF}$ [liters/h]	$Fuel_{T\_RTO}$ [liters/h]	Δ_{FuelT} [liters/h]	$Fuel_{eff}$ [W/lpm]	η_{sys} [%]
RTO_1	37	4002	4612	-610	67.2	95.14
RTO_2	37	4002	3984	18	82.7	94.41
RTO_3	20; 37	4002	4614	-612	66.39	94.84
SW_RTO_1/2	20; 37	4002	3970	32	82.62	94.06

6.3 Summary and conclusions

In conclusion, the real-time switch strategy proposed in this paper considerably improves the fuel economy of the PEMFC system and increases the lifetime of the energy storage system (ESS) over the entire EUDC extra-urban cycle. Future prospects hold new solutions to improve the current algorithm by hybridizing it with Machine Learning based algorithms to ensure lower development and implementation time without creating diversity and low cost to meet the main objectives of this study, fuel economy and performance improvement of PEMFC and ESS systems through an optimal and predictive way.

Chapter 7

General conclusions

Ensuring the overall performance of the hybrid propulsion system in the FCHEV was achieved using new energy management strategies and a new SWA_RTO algorithm, SWA_RTO, for interval switching by determining the A-factor as a function of the total power demand on the DC bus (P_{car}) and the optimally defined reference threshold power (P_{ref}). The new switching algorithm utilized the best GES_RTO strategy, adjusting the power levels over the whole driving cycle, for the air regulator and the fuel regulator, providing the best economy, thus demonstrating the efficiency and software integrability on any energy management unit.

Future perspectives on the improvement of the current strategy, SWA_RTO based on the GES algorithm will be realized by hybridization with Machine Learning based algorithms to ensure deployment on any type of fuel cell hybrid vehicle.

7.1 Obtained results

Results obtained are presented below, with objectives achieved on each chapter, fulfilling the purpose of this research work, within the Doctoral School of Electronics, Telecommunications and Information Technology, SD-ETTI:

- **O1. Analysis of recent research in the field, based on selected reference works**
- **O2. Selection and presentation of energy management strategies based on the analysis in Chapter 2**
- **O3. Design and simulation of a MIL test model in order to evaluate the FCHEV in a European EUDC driving cycle**
- **O4. Design and test a new switching algorithm to reduce hydrogen consumption**
- **O5. Perspectives and limitations on the applicability of real-time optimization strategies based on GES algorithms**

7.2 Original contributions

The main contributions made in Chapter 2 are the following:

1. Analysis and description of FCEV/FCHEV topologies, focusing on advantages/disadvantages, control type and applications [2S];

2. Case study in order to classify EMS energy management strategies and characterize them according to the performance and benefits of each strategy [2S];

The main contributions made in Chapter 3 are the following:
1. Modeling the FCHPS architecture based on global extremum search (GES) control [1S], [8S], [9S];
2. Sensitivity analysis to identify the best values of the weighting coefficients of the optimization function and the influence of the sinusoidal generator frequency on the total fuel consumption [6S], [7S], [10S];
3. Simulation of optimization strategies in real time and identification, based on performance indicators and fuel economy, of the best strategies to implement in EMS [10S], [11S];

The main contributions made in Chapter 4 are the following:
1. Design and simulation of a closed-loop test model, MIL, for validating the energy management unit and RTO strategies with the best-fit identified in Chapter 3 [12S];
2. Proposing a SW_RTO switch strategy among the best identified RTO strategies to further increase hydrogen economy in an extra-urban EUDC test cycle [12S];

The main contributions made in Chapter 5 are the following:
1. Design and testing of a real-time strategy, SWA_RTO, which is based on an A-factor algorithm that switches between the best strategies based on GES algorithms [13S];
2. Sensitivity analysis to identify the best switching factor between modes of the best performing strategies in Chapter 4 [13S];

The main contributions made in Chapter 6 are the following:
1. Modification of the FCHEV model with two FC systems of 30 kW and 100 kW, respectively, to demonstrate the adaptability to a range of systems with different values of electric power generated by the hybrid propulsion system.
2. Analysis of the limitations that the model imposes and evaluation of the prospects for improvement both at the level of optimization algorithm, GES, and at the level of software tuning and calibration.

7.3 List of original publications

Articles published in journals of the main international scientific stream, reflect the research activity in the field of the PhD thesis, through active participation in national and international conferences, as well as publication in ISI indexed/coded journals.

7.3.1 ISI WoS:

[1S]. Bizon, N., Oproescu, M., Thounthong, P., Varlam, M., Carcadea, E., Culcer, M., ... & Sorlei, I. S. (2020). Improving the fuel economy and battery lifespan in fuel cell/renewable hybrid power systems using the power-following control of the fueling regulators. *Applied Sciences*, *10*(22), 8310. https://doi.org/10.3390/app10228310

[2S]. Sorlei, I. S., Bizon, N., Thounthong, P., Varlam, M., Carcadea, E., Culcer, M., ... & Raceanu, M. (2021). Fuel cell electric vehicles—A brief review of current topologies and energy management strategies. *Energies*, 14(1), 252. https://doi.org/10.3390/en14010252

[3S]. Appasani, B., Mishra, S. K., Jha, A. V., Mishra, S. K., Enescu, F. M., Sorlei, I. S., ... & Bizon, N. (2022). Blockchain-enabled smart grid applications: Architecture, challenges, and solutions. *Sustainability*, 14(14), 8801. https://doi.org/10.3390/su14148801

[4S]. Iordache, M., Oubraham, A., Sorlei, I. S., Lungu, F. A., Capris, C., Popescu, T., & Marinoiu, A. (2023). Noble metals functionalized on graphene oxide obtained by different methods—new catalytic materials. *Nanomaterials*, 13(4), 783. https://doi.org/10.3390/nano13040783

[5S]. Oubraham, A., Ion-Ebrasu, D., Vasut, F., Soare, A., Sorlei, I. S., & Marinoiu, A. (2023). Platinum-functionalized graphene oxide: One-pot synthesis and application as an electrocatalyst. *Materials*, 16(5), 1897. https://doi.org/10.3390/ma16051897

[6S]. Hoarcă, I. C., Bizon, N., Șorlei, I. S., & Thounthong, P. (2023). Sizing design for a hybrid renewable power system using HOMER and iHOGA simulators. *Energies*, *16*(4), 1926. https://doi.org/10.3390/en16041926

7.3.2 Baze de date recunoscute de CNADCU

[7S]. Bizon, N., Sorlei, S., Carcadea, E., Culcer, M., Iliescu, M., & Raceanu, M. (2020, June). Sensitivity Analysis Based on the Defined Load Threshold for a new Fuel Economy Strategy used in Fuel Cell Vehicles. *In 2020 12th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)* (pp. 1-6). IEEE. https://doi.org/10.1109/ECAI50035.2020.9223181

[8S]. Oproescu, M., Bizon, N., Carcadea, E., Culcer, M., Iliescu, M., Raceanu, M., & Sorlei, S. (2020, June). Performance of the load-following control switched to the air and hydrogen regulators of the fuel cell system. *In 2020 12th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)* (pp. 1-6). IEEE. https://doi.org/10.1109/ECAI50035.2020.9223155

[9S]. Bizon, N., Oproescu, M., Carcadea, E., Raceanu, M., Raboaca, M. S., & Sorlei, S. (2021, July). Performance of the Fuel Economy Strategies for Fuel Cell Systems under Power Tracking Control. *In 2021 13th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)* (pp. 1-5). IEEE. https://doi.org/10.1109/ECAI52376.2021.9515176

[10S]. Bizon, N., Carcadea, E., Iliescu, M., Raboaca, M. S., Manta, I., & Sorlei, S. I. (2021, July). Estimation of hydrogen consumption for proton-exchange membrane fuel cells systems. *In 2021 13th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)* (pp. 1-7). IEEE. https://doi.org/10.1109/ECAI52376.2021.9515021

[11S]. Bizon, N., Takorabet, N., Thounthong, P., Carcadea, E., Raboaca, M. S., & Sorlei, S. I. (2022, June). Power-following strategy for microgrids based on multiple renewable/fuel cells systems. *In 2022 14th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)* (pp. 1-6). IEEE. https://doi.org/10.1109/ECAI54874.2022.9847467

[12S]. Sorlei, I. S. (2024, June). Fuel economy and overall efficiency optimization of a Fuel Cell Electric Vehicle in a European Extra-Urban Drive Cycle (EUDC). *In 2024 16th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)* (pp. 1-7). IEEE. https://doi.org/10.1109/ECAI61503.2024.10607408

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7.4 Perspectives for further developments

Future perspectives on improving the current strategy with the best fuel reduction, SWA_RTO based on the GES algorithm, are presented below:

- Improving the performance of the hybridization adaptivity algorithm with Machine Learning based algorithms to ensure deployment on any type of fuel cell hybrid vehicle;
- Testing the model on WLTP driving cycles, with a more realistic real-time road characteristic, for the dynamic determination of the A-factor, as the cycles tested did not fully capture all operational dynamic scenarios;
- Increase the long-term durability of both the FC and ESS systems by improving the detection of faults that may occur in the battery membrane or in the electrochemical cells of batteries and ultracapacitors.
- Creating a software executable of the energy management and control unit and integrating it on an ECU to be tested on a HIL (Hardware In The Loop) platform for reliability and validation.

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