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Energy Management Strategies for Fuel Cell Vehicles

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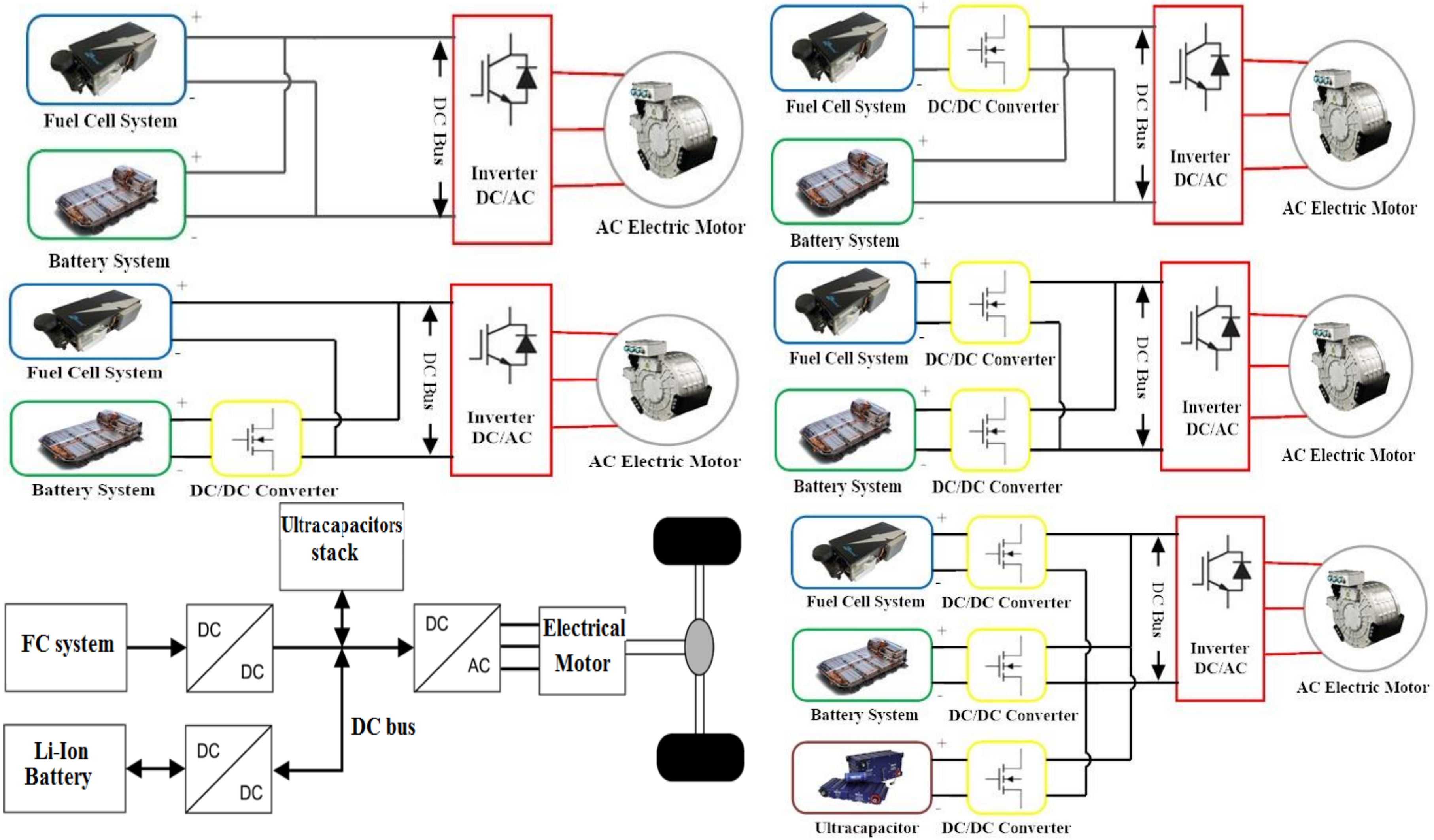
Summary

1. Powertrain architecture of the FC vehicle (FCV)
2. Energy Management Strategies (EMSs) for FCV
3. Load-following based EMSs for FCV
4. Advanced EMSs for FCV
5. Conclusion

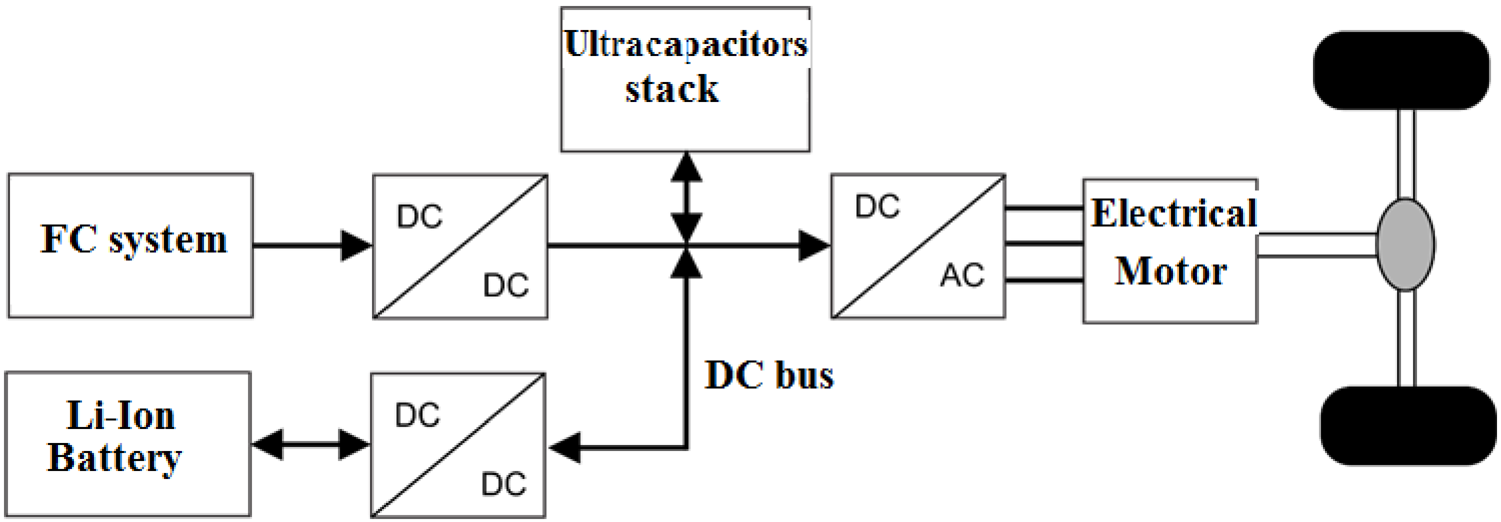
1. Powertrain architecture of the FC vehicle (FCV)

FCV powertrain architectures



1. Powertrain architecture of the FC vehicle (FCV)

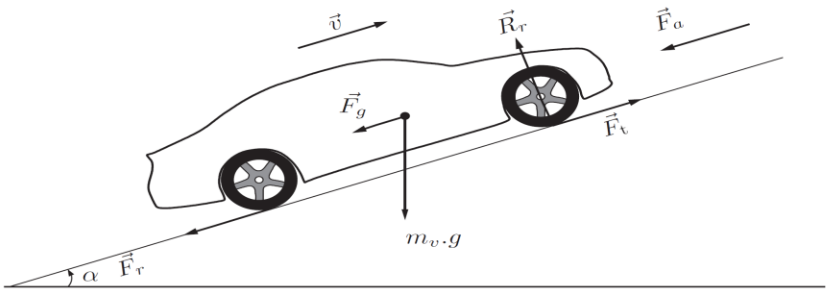
FCV powertrain architecture



FCV powertrain architecture

1. Powertrain architecture of the FC vehicle (FCV)

Modeling of the FCV



The traction force (F_t) is

$$F_t(t) = m_v(t)\frac{d}{dx}(v(t)) + F_a(t) + F_r(t) + F_g(t)$$

where, F_a is the air resistance force, F_r is the rolling resistance, F_g is the gravity force:

$$F_a = 0.5 * \rho * c_W * A * \vartheta^2$$

$$F_r = C_r * m_v(t) * g cos(\alpha)$$

$$F_g = m_v(t) \cdot g \cdot \sin(\alpha)$$

1. Powertrain architecture of the FC vehicle (FCV)

FCV parameters

Parameter	Value
Vehicle weight	1540 kg
Efficiency of the transmission (electric motor \ inverter)	90%
Rolling radius of the wheel	0.25 m
Vehicle frontal area (A)	2.05 m^2
The air drag coefficient (C_W)	0.3
The coefficient of rolling resistance (C_r)	0.01
Air density	1.23 kg/m^3

FCV components

Net power of the FC stack	33 kW
Litiu-ion stack (16 bateries 12.8V - 160Ah)	32,768 kWh
Ultracapacitors (UC) stack (8 Ucs of 12,6F)	57Wh
Power converter efficiency (100% -10% of rated load)	85-92%
Electric motor	75kW

1. Powertrain architecture of the FC vehicle (FCV)

Modeling of FC vehicle

FCV parameters

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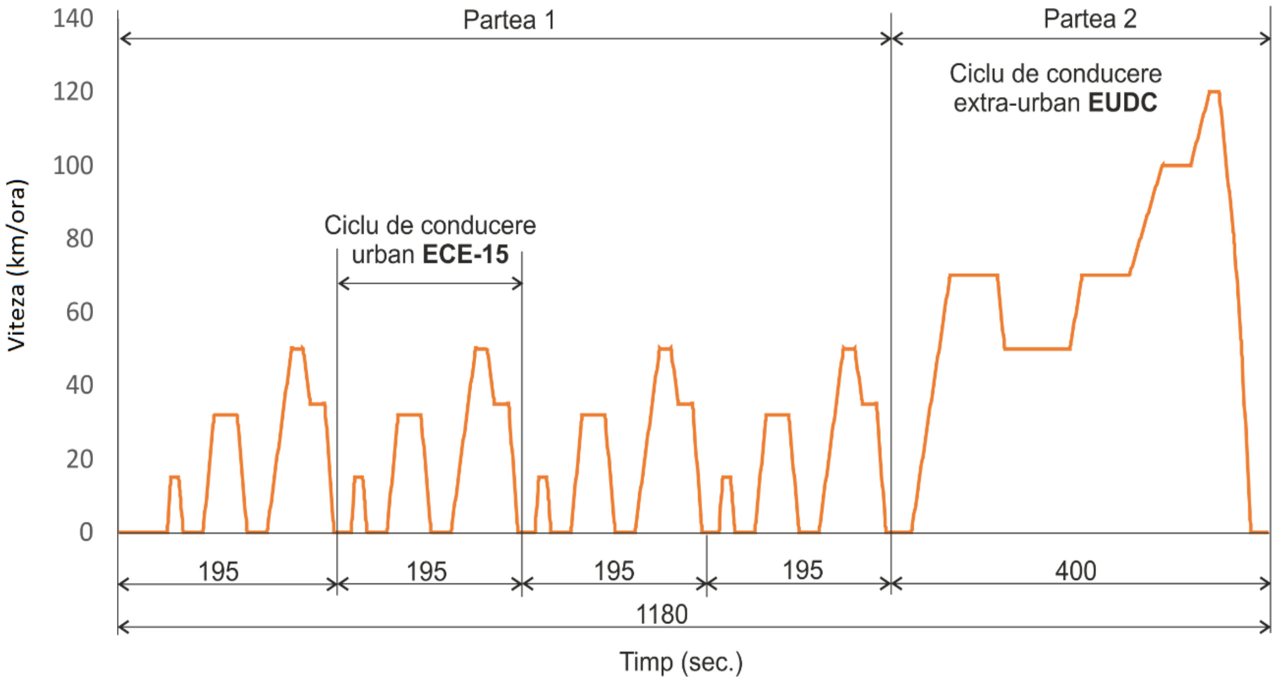
1. Powertrain architecture of the FC vehicle (FCV)

New European Driving Cycle (NEDC)

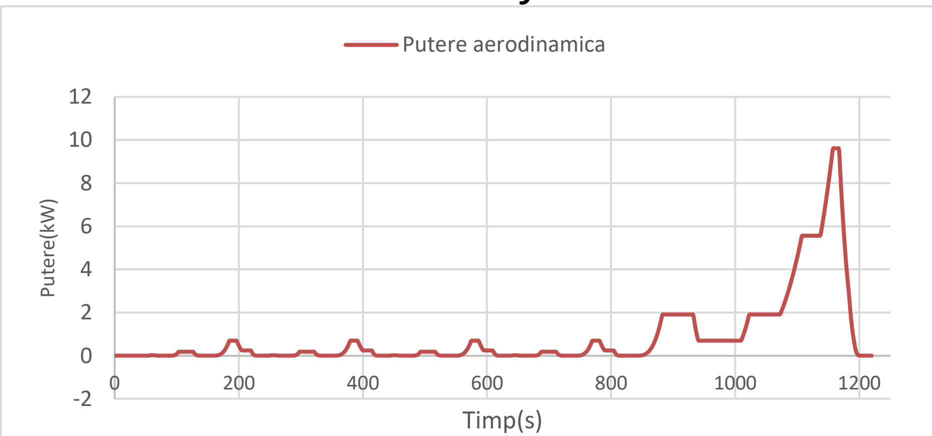


NEDC, European Driving Cycle (EDC) and Extra-Urban Driving Cycle (EUDC) drive cycles

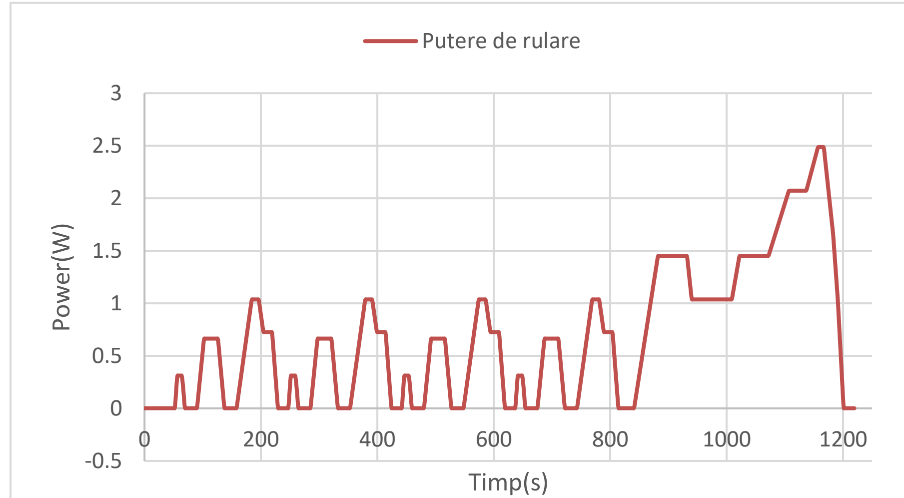
Parameter	ECE-15	EUDC	NEDC
Distance (m)	4 X 994 = 3.976	6.956	10.932
Time (s)	4 x 195 = 780	400	1180
Average speed (km/h)	18.7	62.6	33.6
Maximum speed (km/h)	50	120	120

1. Powertrain architecture of the FC vehicle (FCV)

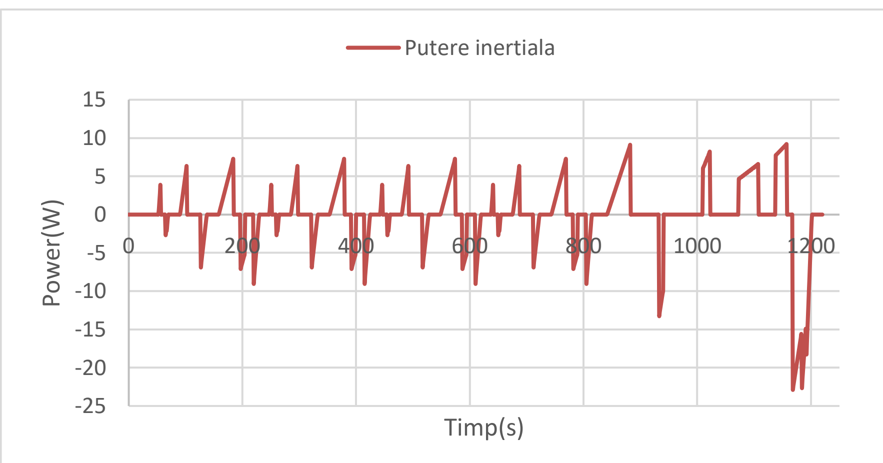
FCV under NEDC cycle



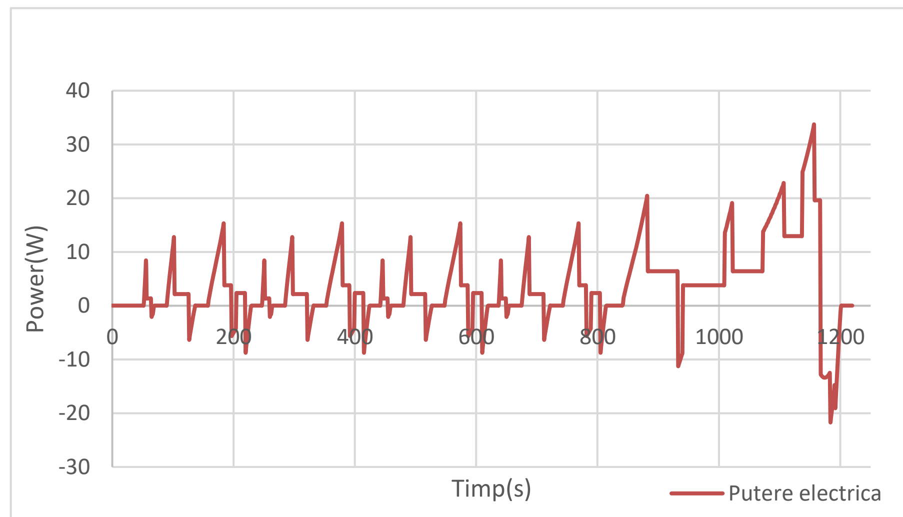
Aerodynamics power during a NEDC cycle



Rolling power during a NEDC cycle



Inertial power during a NEDC cycle



Traction power during a NEDC cycle

2. Energy management strategies (EMS)

Objectives for the EMS unit

- Assuring the load demand
- Operating the FC stack at high efficiency
- Minimizing the fuel consumption
- Protecting the FC stack to fuel starvation
- Protecting the batteries' stack to deep discharge by monitoring the State-Of-Charge (SOC)

The EMS can be mainly classified into rule-based energy management strategy, optimization-based energy management strategy and Learning-based strategies.

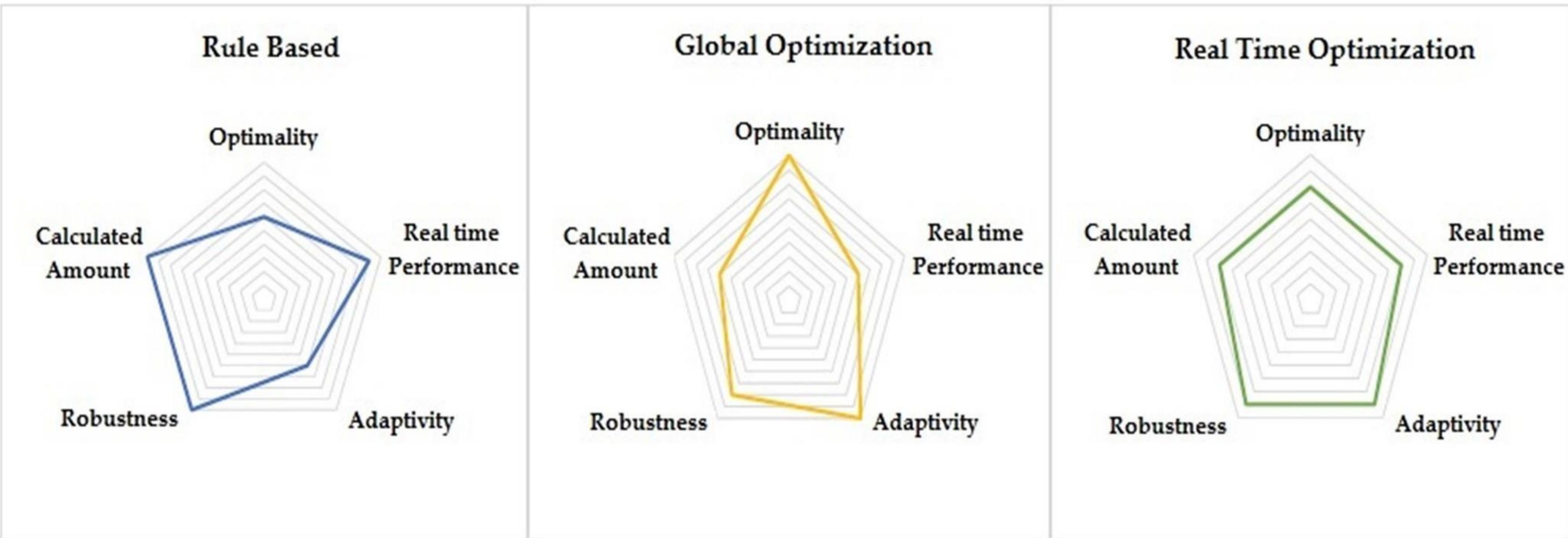
Several energy management control strategies have been already proposed for FC vehicle, such as heuristic strategies, equivalent consumption minimization strategy (ECMS) and strategies based on optimal control theory.

Not all objectives mentioned above can be optimized simultaneously.

2. Energy management strategies (EMS)

Rule-based strategies		▪ Fuzzy control strategy ▪ State machine control strategy ▪ Classical PI control strategy ▪ Frequency decoupling and fuzzy logic strategy (FDFL) ▪ Power prediction
Optimisation-based strategies	Global optimisation	▪ Linear programming (LP) ▪ Dynamic programming (DP) ▪ Global extremum seeking (GES) ▪ Genetic algorithm (GA)
	Real-time optimisation	▪ Pontryagin's minimum principle (PMP) ▪ Quadratic programming (QP) ▪ Multi-agent system (MAS) ▪ Stochastic dynamic programming (SDP) ▪ Convex programming ▪ Multi-mode predictive (Markov driving pattern recognizer) ▪ Soft-run strategy ▪ Fractional order extremum seeking method ▪ Dynamic particle swarm optimisation ▪ Equivalent consumption minimization strategy (ECMS) ▪ External energy maximization strategy (EEMS)
Learning-based strategies		▪ Reinforcement learning ▪ Supervised learning ▪ Unsupervised learning ▪ Neural network ▪ Multi-mode strategy – learning vector quantization (LVQ)

2. Energy management strategies (EMS)



Rule Based EMS can be adaptively adjusted by information of different driving condition

Global driving condition information is used to complete global Based EMS offline calculation

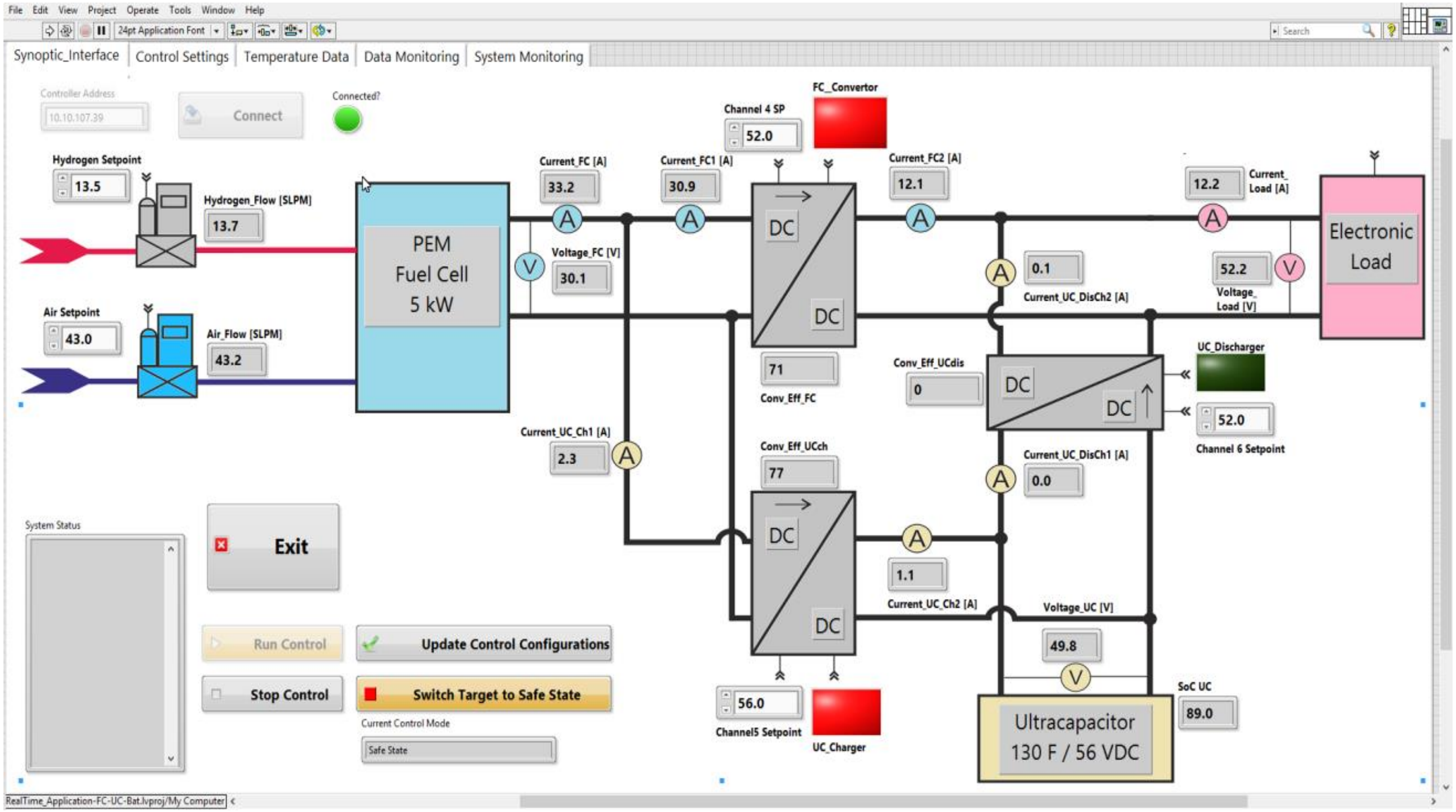
Partial or global driving information is nedded to further optimize Real Time performance of online EMS

2. Energy management strategies (EMS)

EMS type	Main advantages of EMS	Main disadvantages of EMS
Rule-based strategies	▪ Simplicity - It is based on simple sets of rules "if-then-else “ ▪ Using fuzzy algorithms, the system is robust and has very good adaptability and prediction capabilities.	▪ Rule-Based parameters can be strongly affected by the driving conditions ▪ It does not present good performance in reducing fuel consumption.
Optimization-based strategies (Global optimization)	▪ High performance in reducing hydrogen consumption. ▪ Global optimality / Reference for other EMSs	▪ Optimality is not ensured in a limited number of iterations ▪ Need additional information in advance about the driving cycle
Optimization-based strategies (Real-time optimization)	▪ Minimization the total economy consumption: the hydrogen consumption and the battery degradation consumption ▪ An accurate estimation of the variation of the state of charge (SOC) of each system element.	▪ Complex mathematic formulation
Learning-based strategies	▪ It is based on large data sets with historical and real-time information ▪ Model-free control	▪ Time consuming to create database ▪ Requires complex knowledge of artificial intelligence

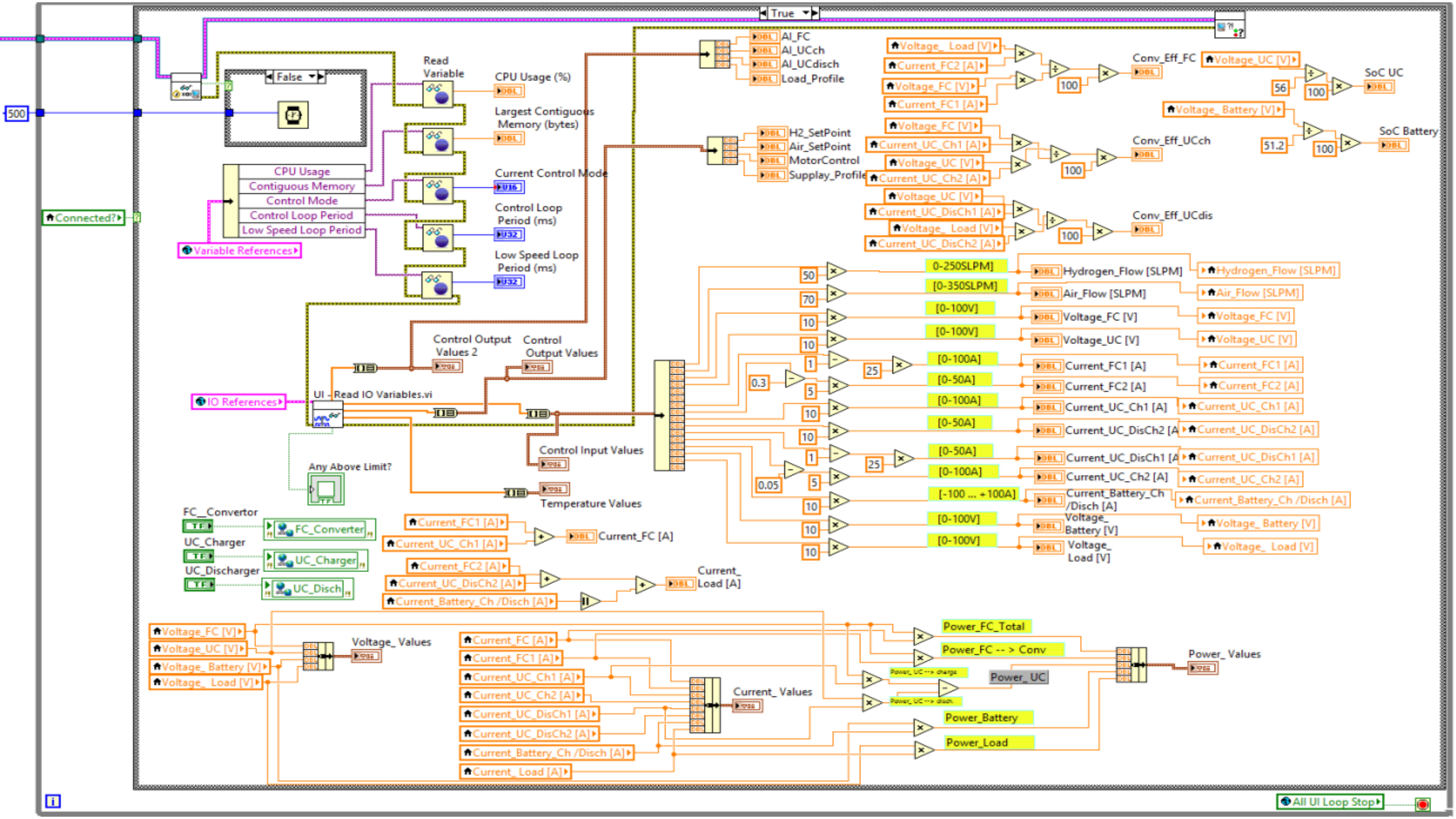
2. Energy management strategies (EMS)

Power split-based Energy Management Strategy (EMS)



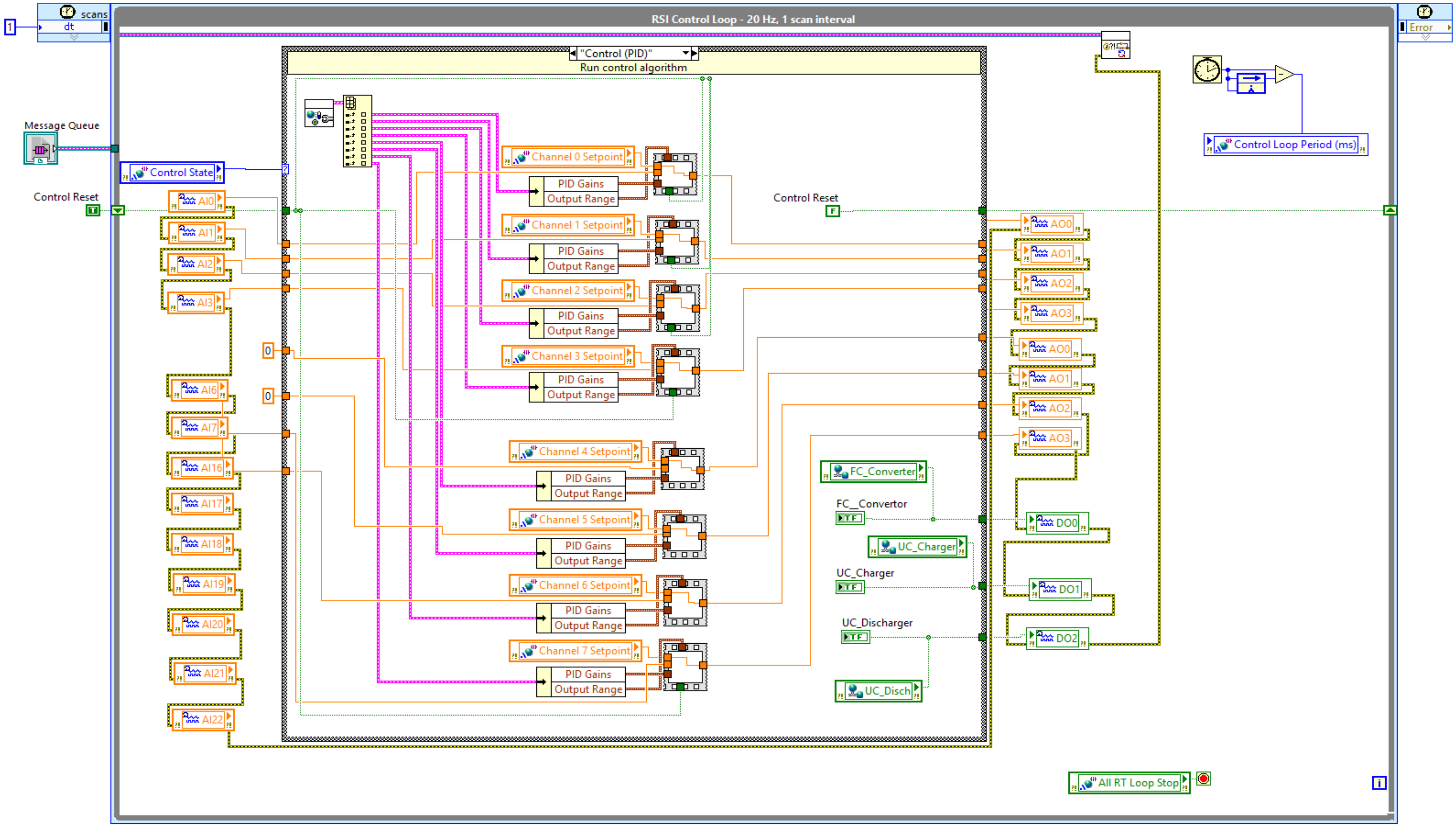
2. Energy management strategies (EMS)

EMS implementation in Real-Time controller

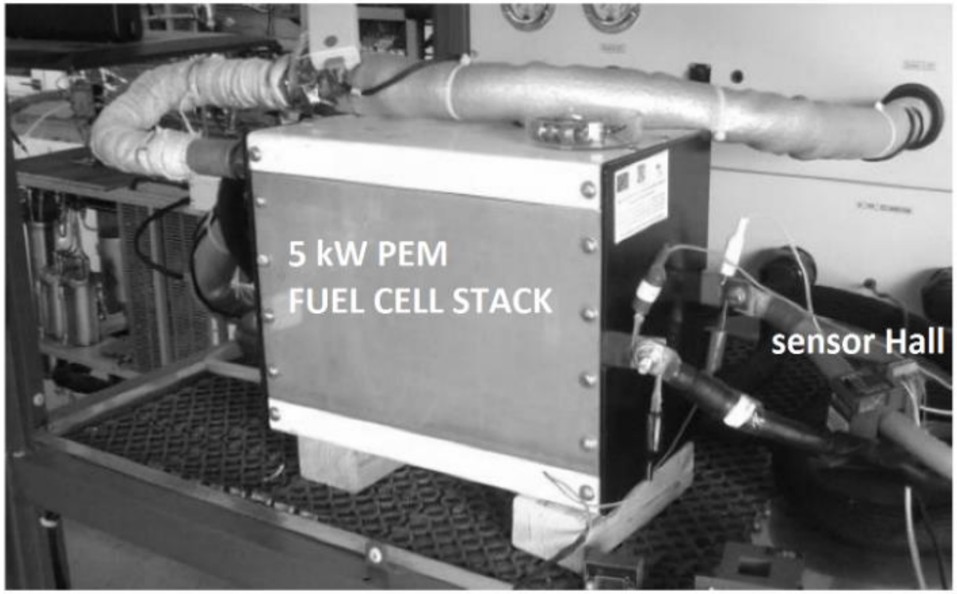


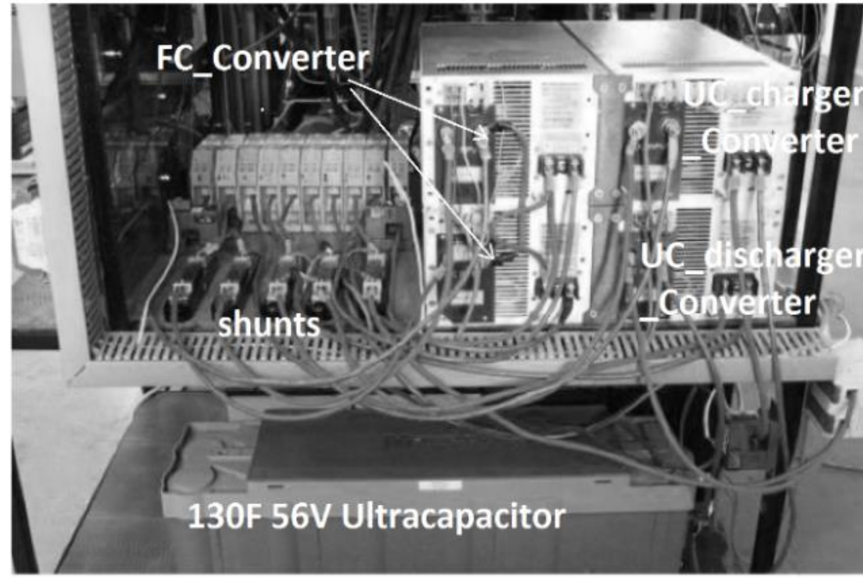
2. Energy management strategies (EMS)

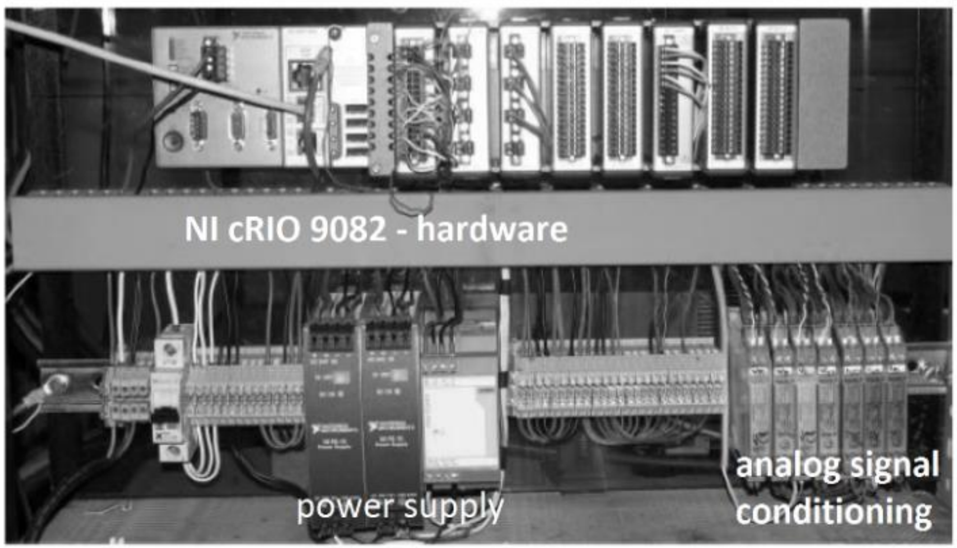
EMS implementation (continue)

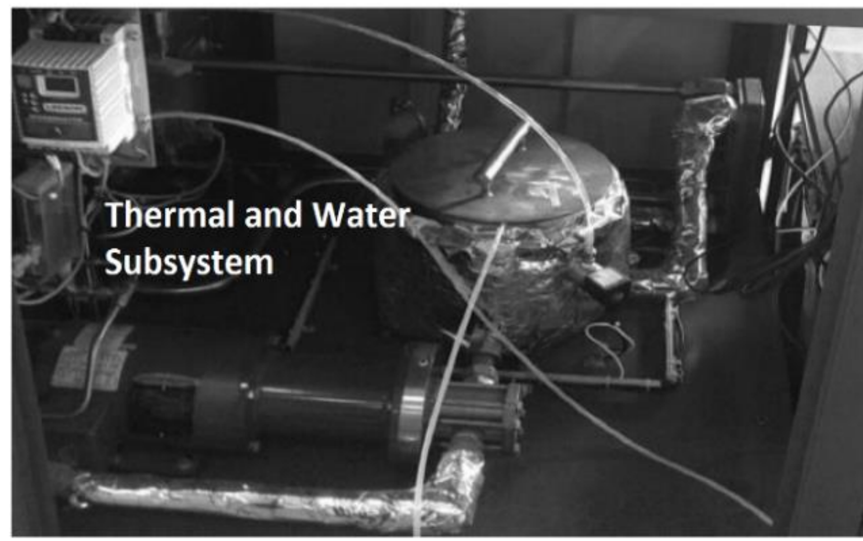


2. Energy management strategies (EMS)







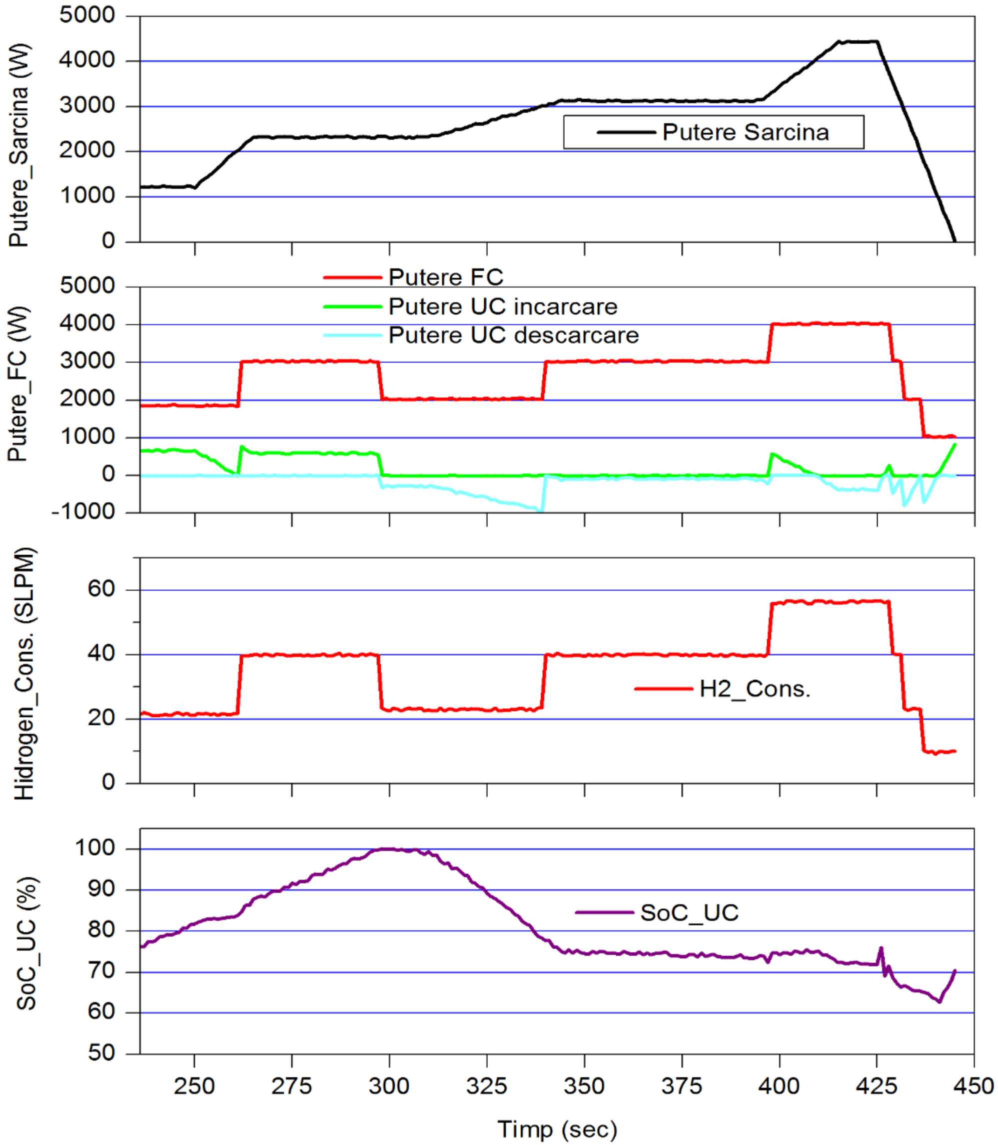


2. Energy management strategies (EMS)

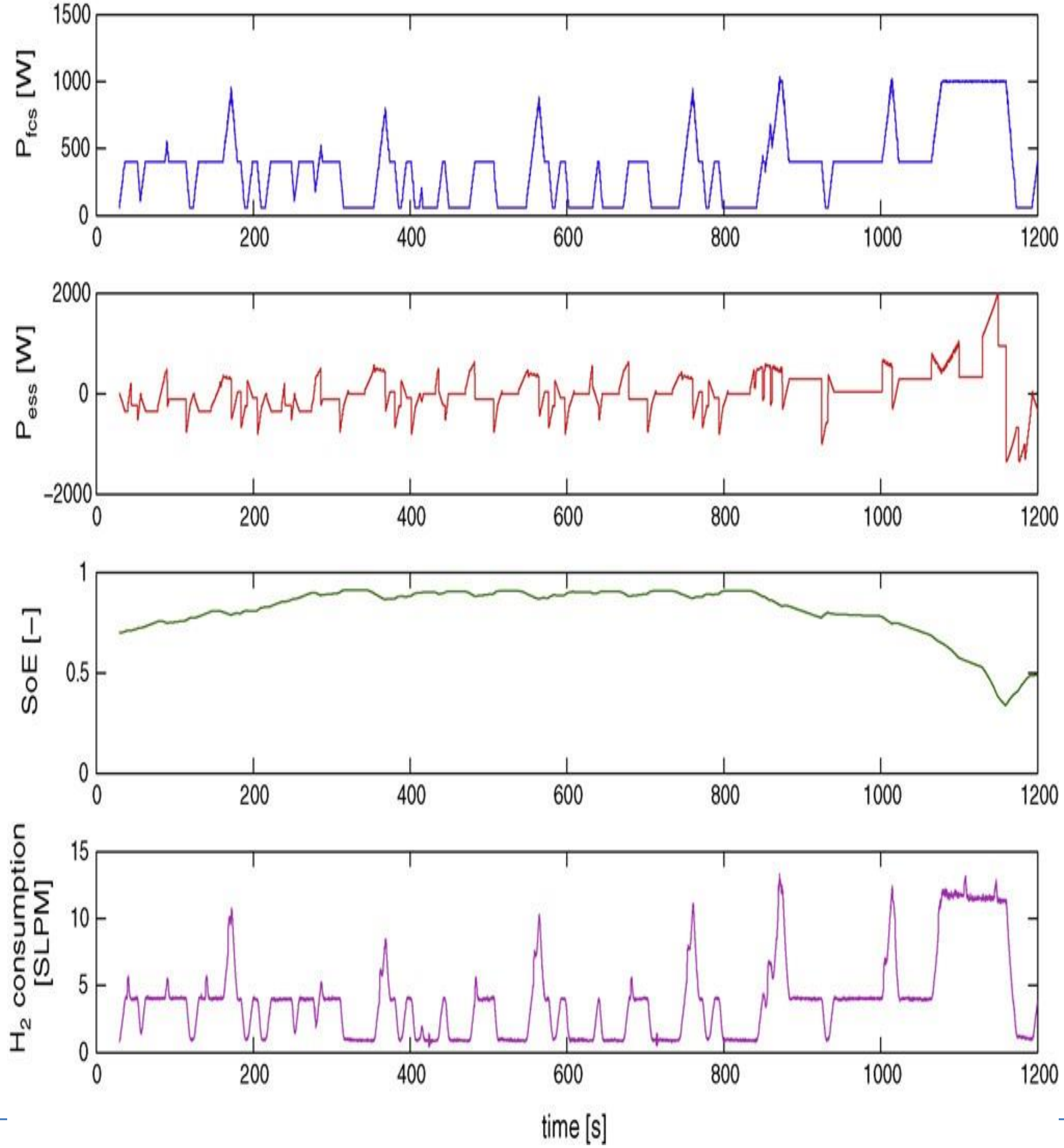
Experimental study for a FC vehicle (2010)

FC vehicle and main subsystems
(a) FCV right side view;
(b) PEM Fuel cells stack;
(c) Dashboard;
(d) Auto-box and electrical panel;
(e) Power Distribution Unit and electrical connections;
(f) Hydrogen supply control system and Electronic load;
(g) DC/DC Converter without housing;
(h) LiPo Battery without housing;
(i) Hydrogen Tank;

2. Energy management strategies (EMS)

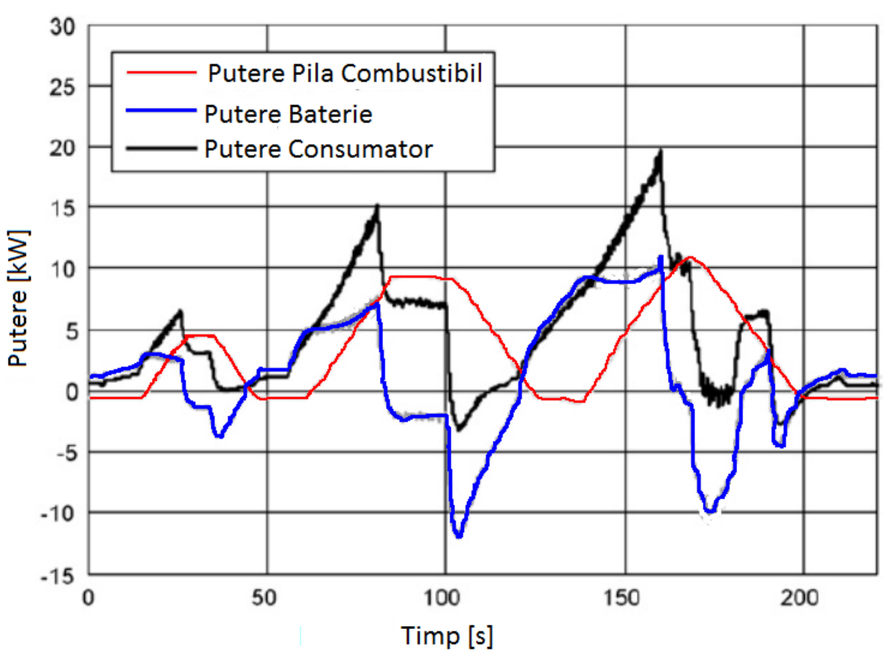


2. Energy management strategies (EMS)



2. Energy management strategies (EMS)

Experimental study for a FC vehicle



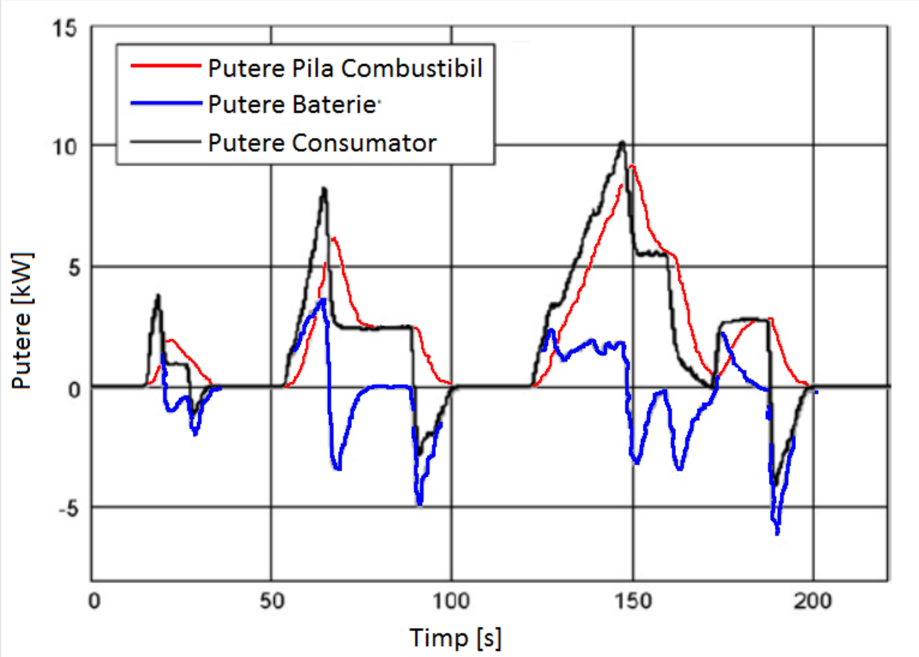


Figure a. Power flow for the FC system, electrical motor and bateries stack with FC current rate limited at 5A/sec

Figura b. Power flow for the FC system, electrical motor and bateries stack with FC current rate limited at 10A/sec

2. Energy management strategies (EMS)

Energy management strategy based on power split technique is tested (2010) for the FC Hybrid Power Source (HPS) .

These results will be the reference for other EMSs proposed in next years:

N. Bizon, FC energy harvesting using the MPP tracking based on advanced extremum seeking control, International Journal of Hydrogen Energy 38(4) (12 February 2013),1952-1966. http://dx.doi.org/10.1016/j.ijhydene.2012.10.112 WOS:000314860600023

N. Bizon, Energy efficiency for the multiport power converters architectures of series and parallel hybrid power source type used in plug-in/V2G fuel cell vehicles. Applied Energy 102 (12 February 2013), 726-734. http://dx.doi.org/10.1016/j.apenergy.2012.08.021 WOS:000314190800078

Mircea RACEANU, Comparative analysis regarding the fuel flow control depending on load for power efficiency and high reliability of the Hybrid Power Source, PhD report 4, 2015

Below, the following two EMS types will be evaluated:
- State machine control strategy;
- PI controllers-based strategies.

2. Energy management strategies (EMS)

EMS based on PI regulator

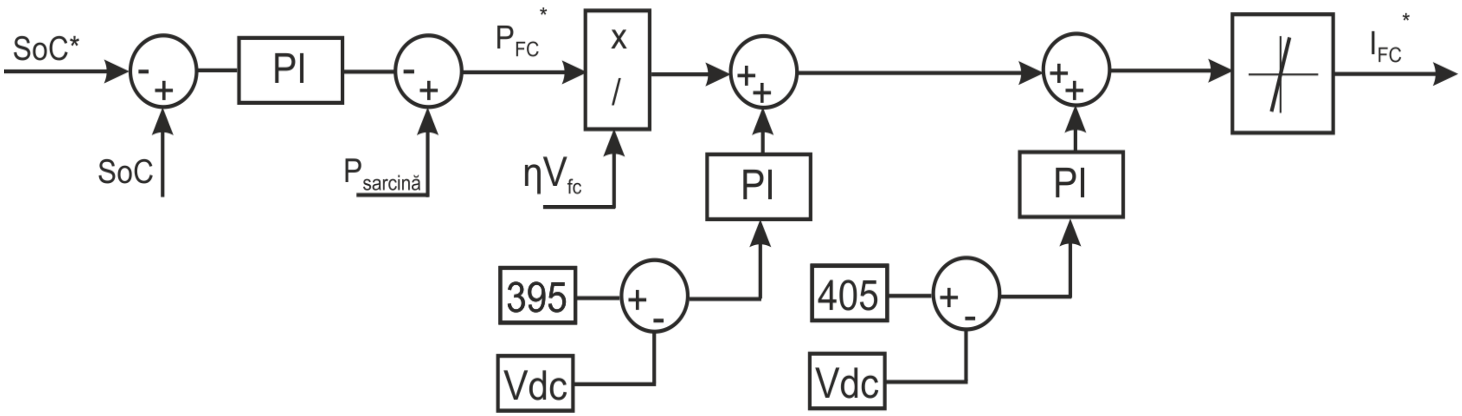
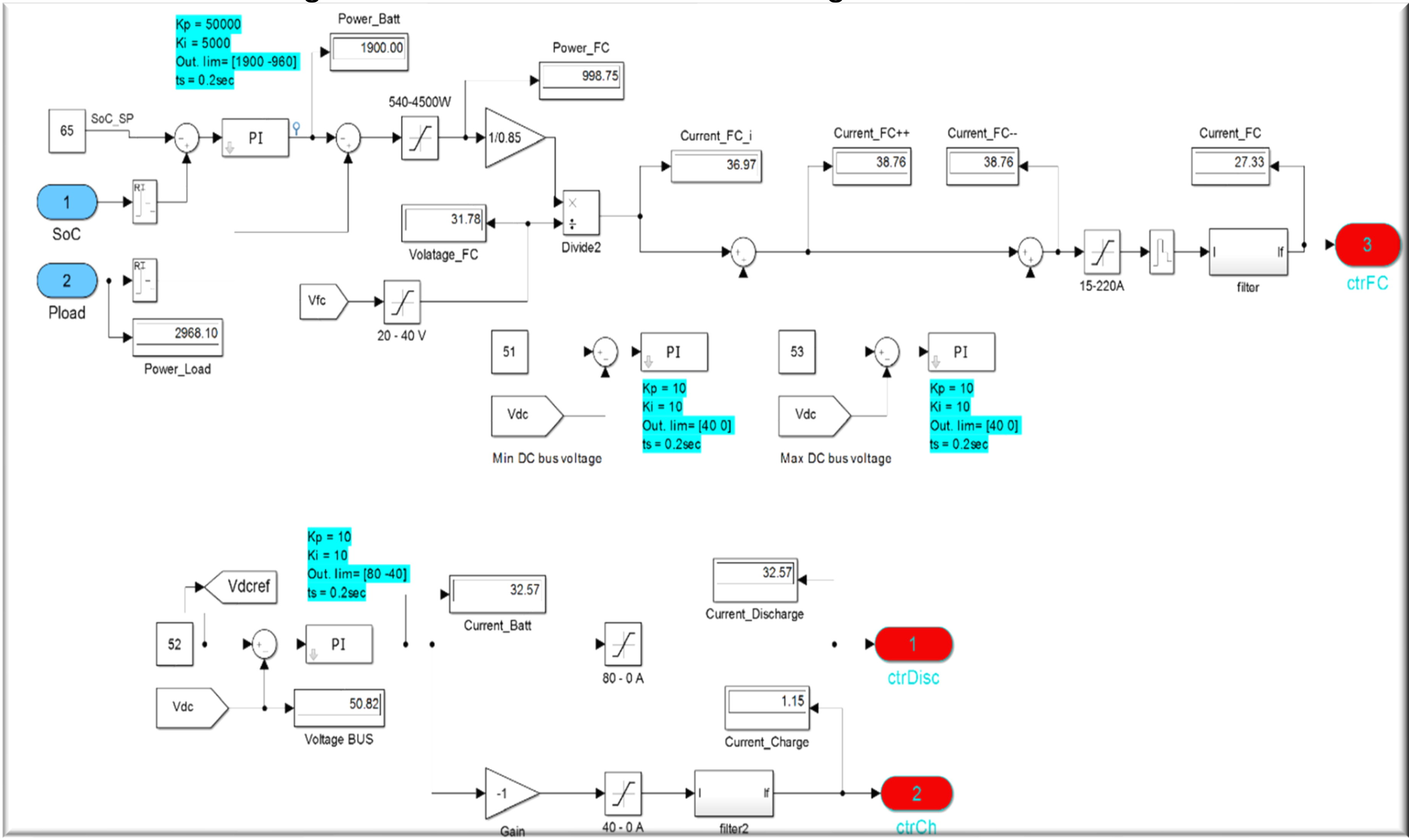


Diagram of the EMS based on PI regulator

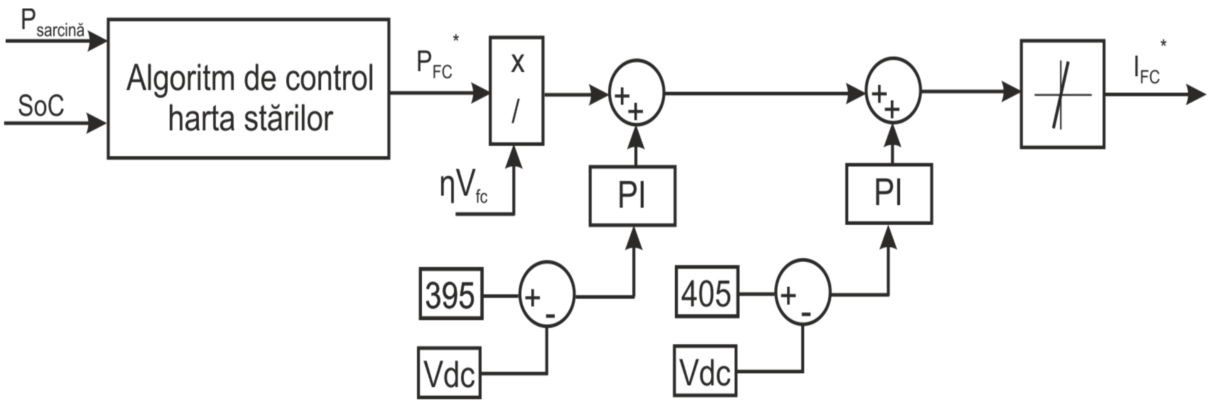
3. Energy management strategies for FC HPS

Matlab-Simulink diagram of the EMS based on PI regulator



3. Energy management strategies for FC HPS

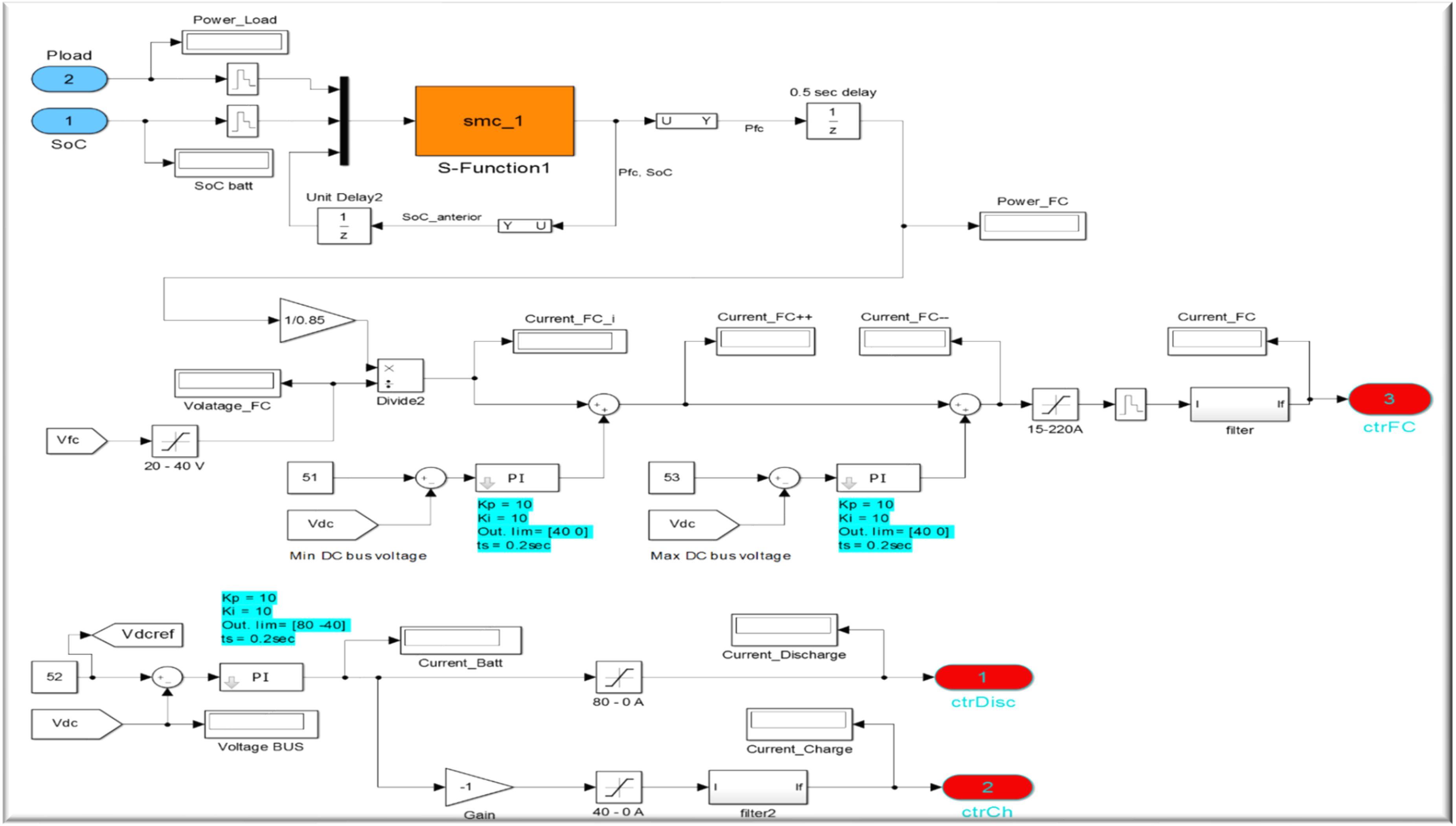
Strategies using the control diagram based on the designed operating states



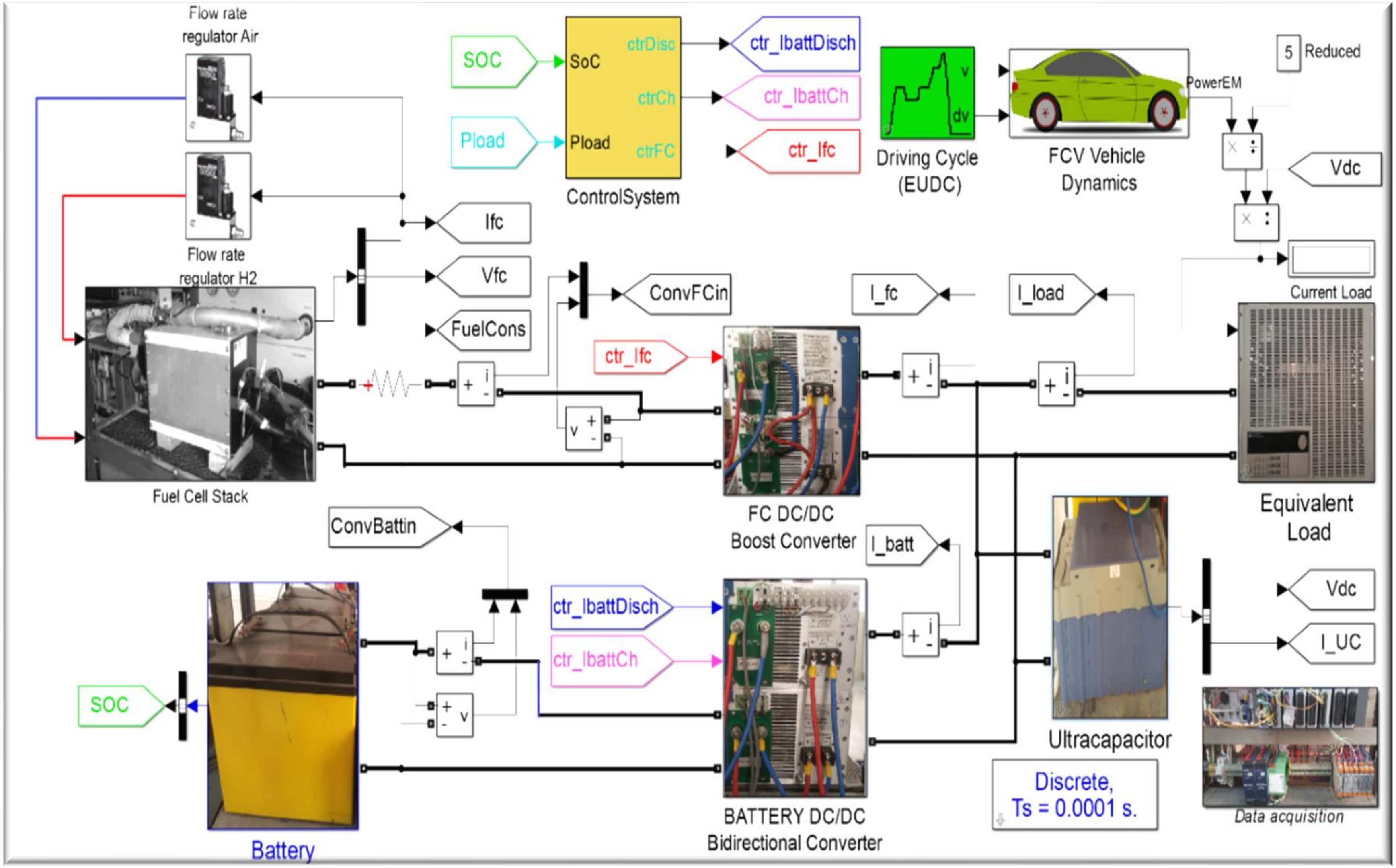
IF $SOC > 90$ & $P_{\mathbf{load}} < Pfc_{min}$	$State = 1$	$Pfc^* = Pfc_{min}$
IF $SOC > 90$ & $P_{\mathbf{load}} \in [Pfc_{min}, Pfc_{max}]$	$State = 2$	$Pfc^* = Pfc_{\mathrm{load}}$
IF $SOC > 90$ & $P_{\mathbf{load}} \geq Pfc_{max}$	$State = 3$	$Pfc^* = Pfc_{max}$
IF $SOC \in [65, 85]$ & $P_{\mathbf{load}} < Pfc_{opt}$	$State = 4$	$Pfc^* = Pfc_{opt}$
IF $SOC \in [65, 85]$ & $P_{\mathbf{load}} \in [Pfc_{opt}, Pfc_{max}]$	$State = 5$	$Pfc^* = Pfc_{\mathrm{load}}$
IF $SOC \in [65, 85]$ & $P_{\mathbf{load}} \geq Pfc_{max}$	$State = 6$	$Pfc^* = Pfc_{max}$
IF $SOC < 60$ & $P_{\mathbf{load}} < Pfc_{max}$	$State = 7$	$Pfc^* = Pfc_{\mathrm{load}} + P_{charge}$
IF $SOC < 60$ & $P_{\mathbf{load}} \geq Pfc_{max}$	$State = 8$	$Pfc^* = Pfc_{max}$

3. Energy management strategies for FC HPS

Matlab-Simulink diagram of the EMS based states' diagram

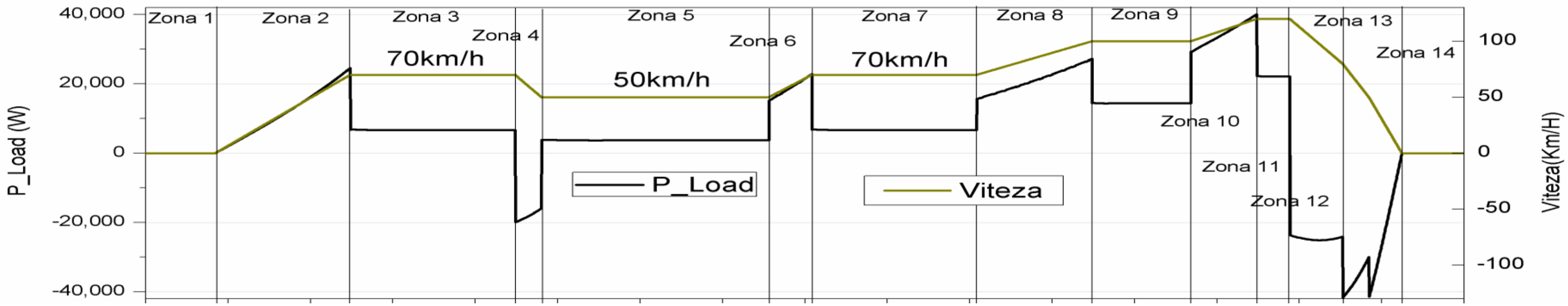


2. Energy management strategies (EMS)



Matlab-Simulink diagram of the FCV

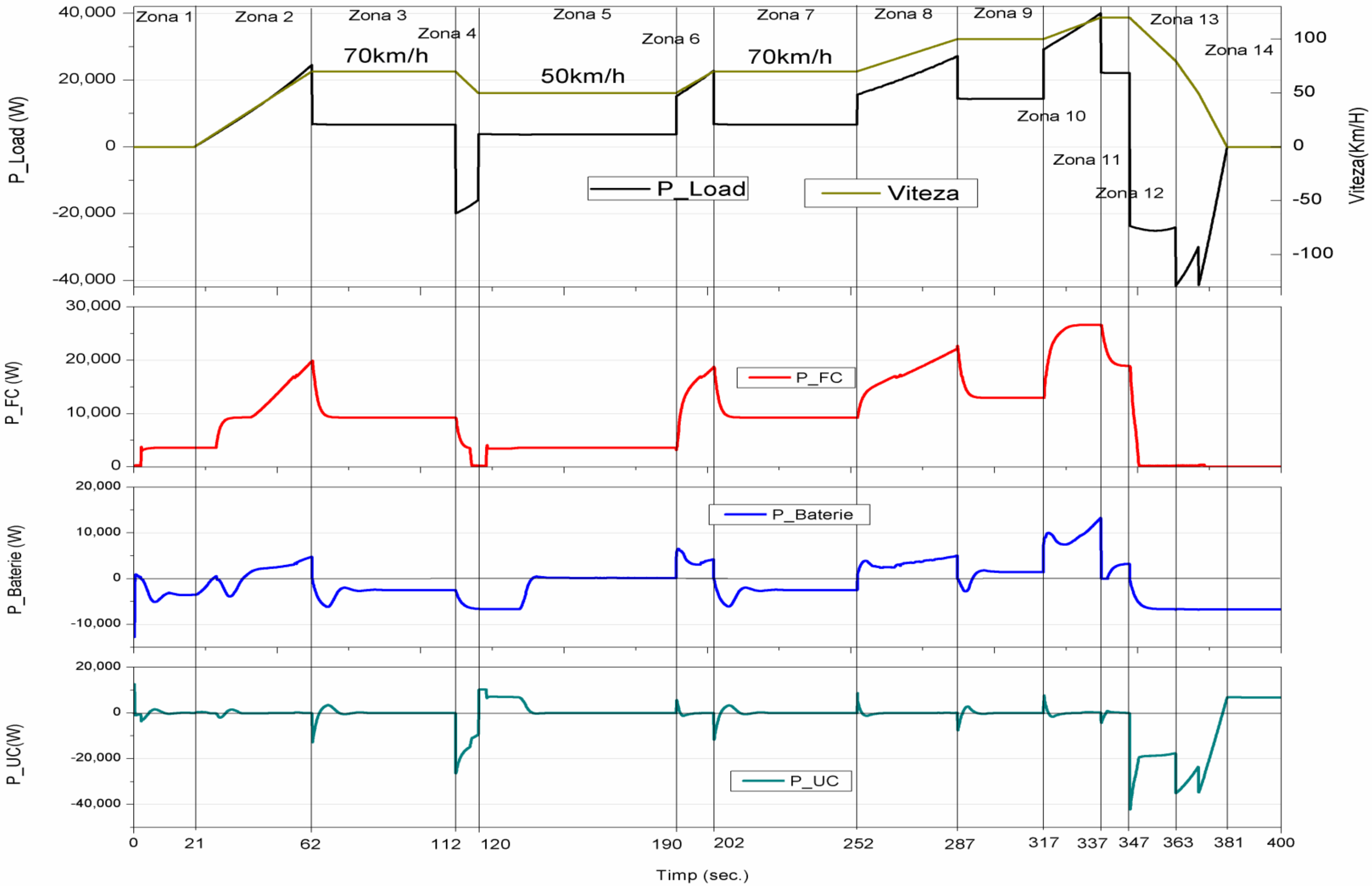
2. Energy management strategies (EMS)



The EUDC driving cycle is divided into 14 areas, which are shown in next Figures.
Zone 1: At first the vehicle is stopped for a period of 20 seconds; in this zone 1 the fuel cell operates at minimum output of 3910W; this power is used to charge the battery system.
Zone 2: the vehicle accelerates slightly to 70 km / h in 41 seconds (simulated vehicle gearbox is automatic). Depending on EMS implemented, the power flows are different.
Zone 3: the vehicle is moving at a speed of 70 km / h for 50 seconds.
Zone 4: the vehicle decelerates to 50 km / h in 8 seconds and then travels at 50 km / h for a period of 69 seconds (zone 5).
Then, the vehicle accelerates slightly to 70 km / h in 13 seconds (zone 6), by moving at a constant speed of 70 km / h for 50 seconds (zone 7).
In zone 8 vehicle reaches 100 km / h in 35 seconds and then keep the cruising speed for 30 seconds (zone 9).
Further, the vehicle accelerates to 120 km / h for 20 seconds (zone 10), followed by a cruising speed of 120 km / h for 10 seconds (zone 11).
Finally, in zones 12 and 13 vehicle brakes in two steps: in step 1, 16 seconds up to 70 km / h and in step 2 the vehicle is stopped in 18 seconds.
In the last zone (zone 14), the vehicle is stopped for 20 seconds.
The total duration of EUDC is 400 seconds and distance covered with an average speed of 62.6 km/h is of 6956m

2. Energy management strategies (EMS)

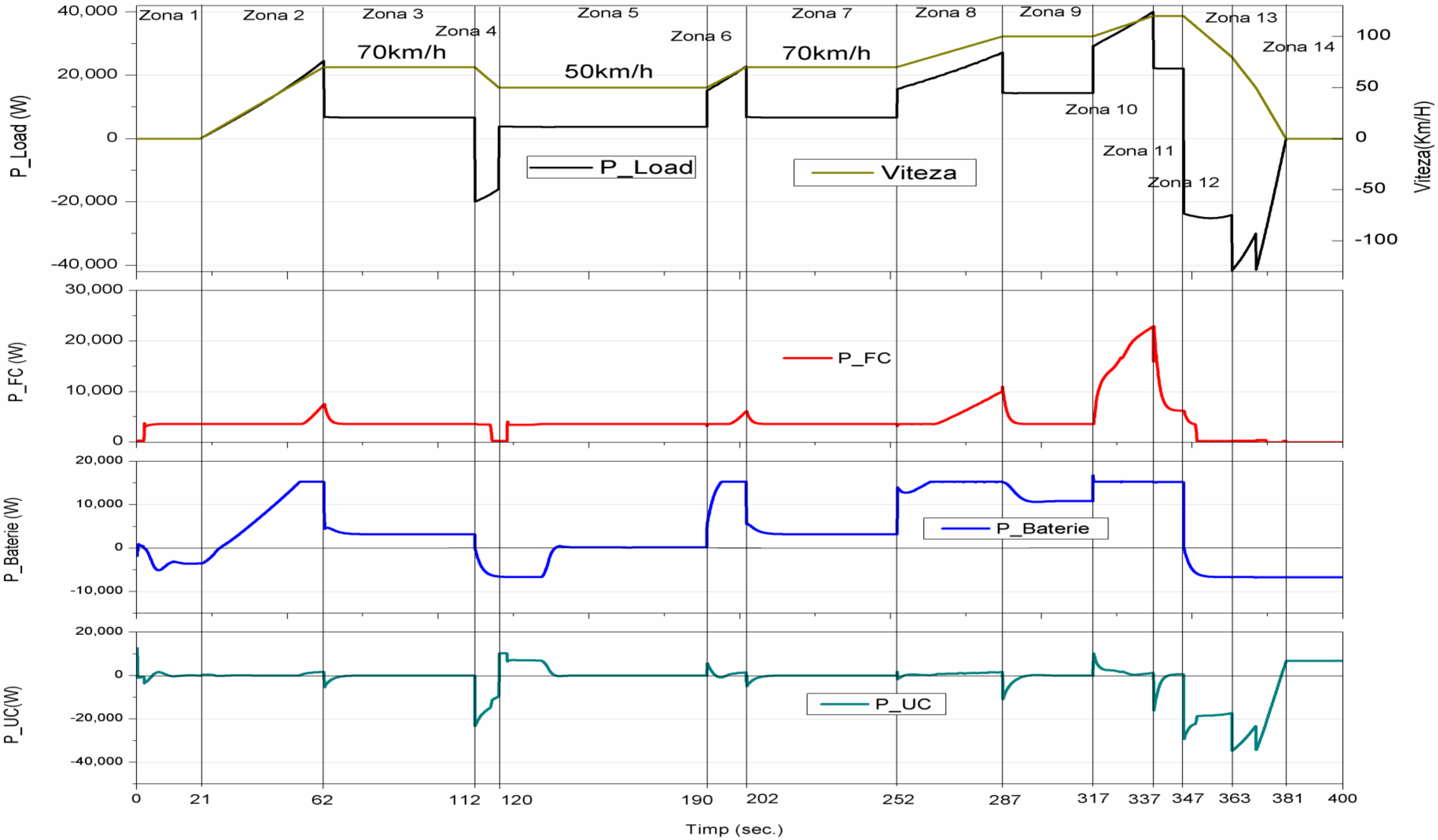
Load power & vehicle speed, FC power, battery power, and UC power



Power flows for EMS based on states' diagram

2. Energy management strategies (EMS)

Load power & vehicle speed, FC power, battery power, and UC power



Power flows for EMS based on PI regulators

2. Energy management strategies (EMS)

Performance indicators:

H2 consumption, efficiency of H2 consumption, FC/HPS energy efficiency

efficiency of H2 consumption

$$eff_{H2} = \frac{100 * P_{FC}^{out}}{LHV * H2_{cons}}$$

FC energy efficiency

$$eff_{FC} = \frac{100 * P_{FCnet}}{P_{FCout}}$$

HPS energy efficiency

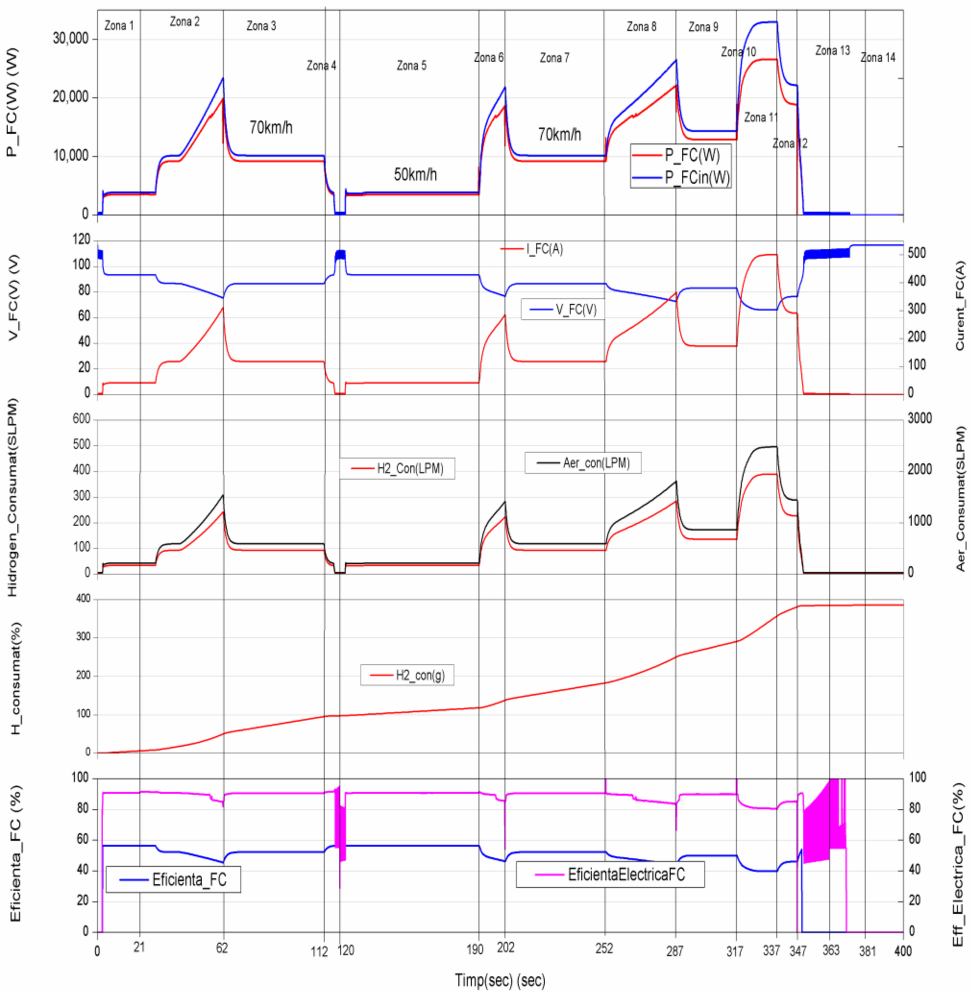
$$eff_{HPS} = \frac{P_{load}}{P_{FC}^{out} + P_{Bat}^{out} + P_{UC}^{out}}$$

H2 consumption

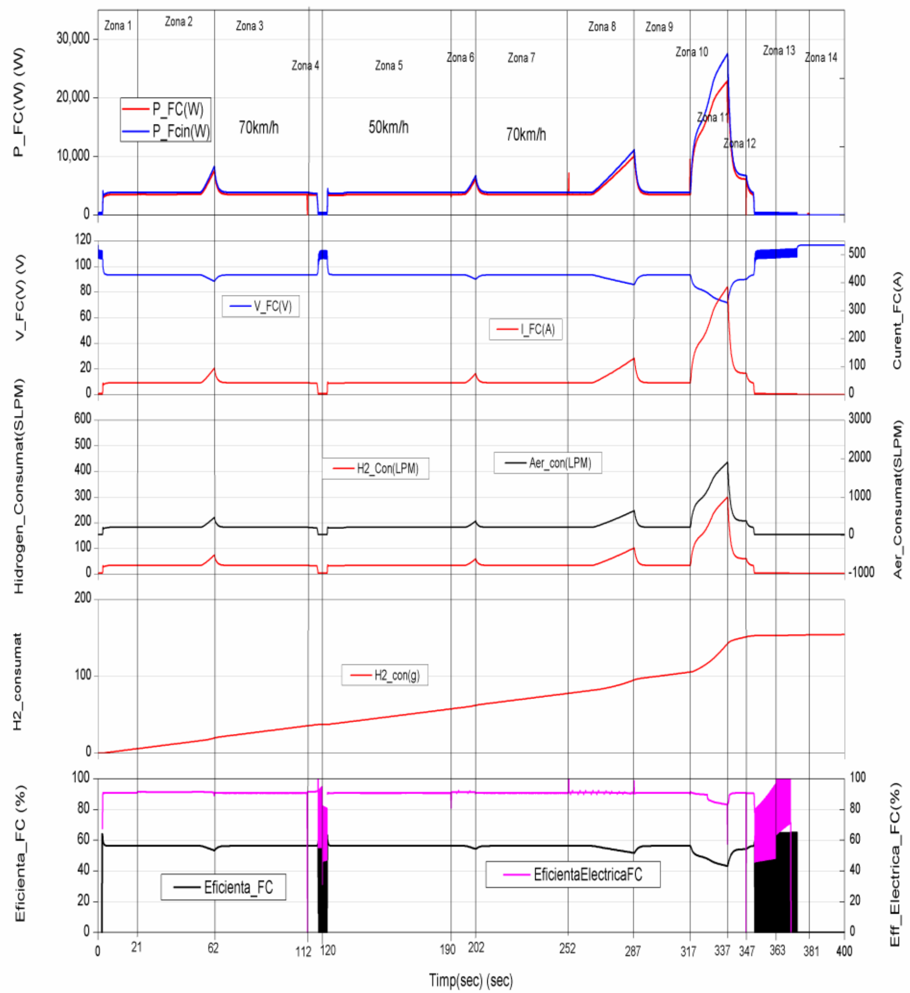
$$H2_{cons} = \frac{N}{F} \int_0^{420} i_{FC} dt$$

2. Energy management strategies (EMS)

Power, voltage & current, H2 & air flows, H2 consumption, efficiency of H2 consumption & FC energy efficiency



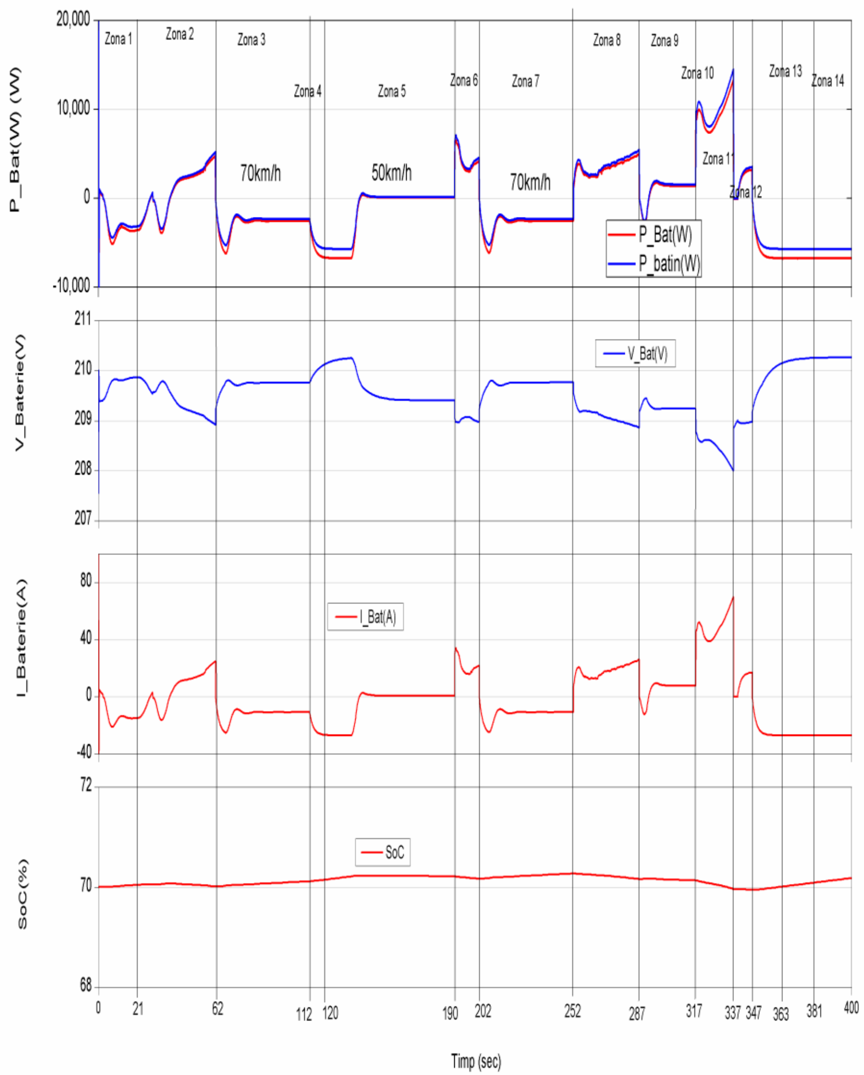
EMS based on states' diagram



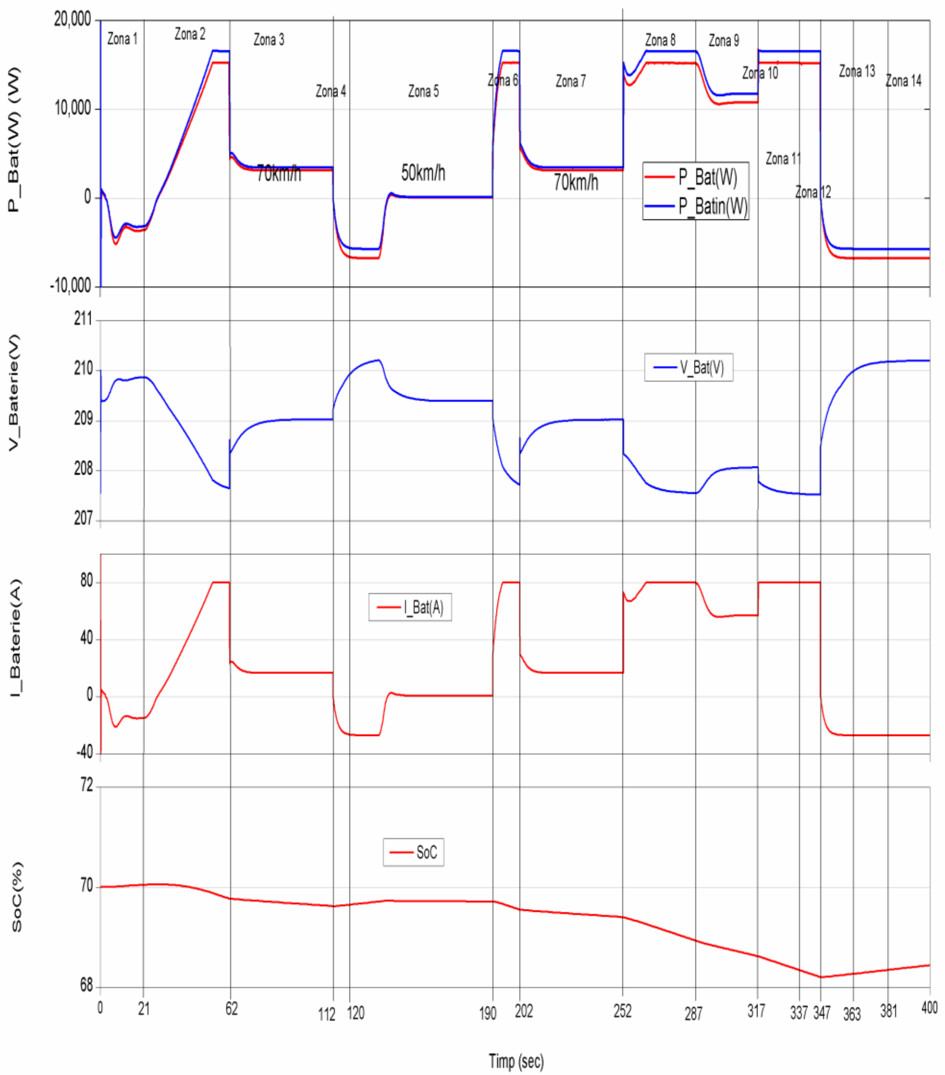
EMS based on PI regulators

2. Energy management strategies (EMS)

Power, voltage, current and SOC for batteries stack



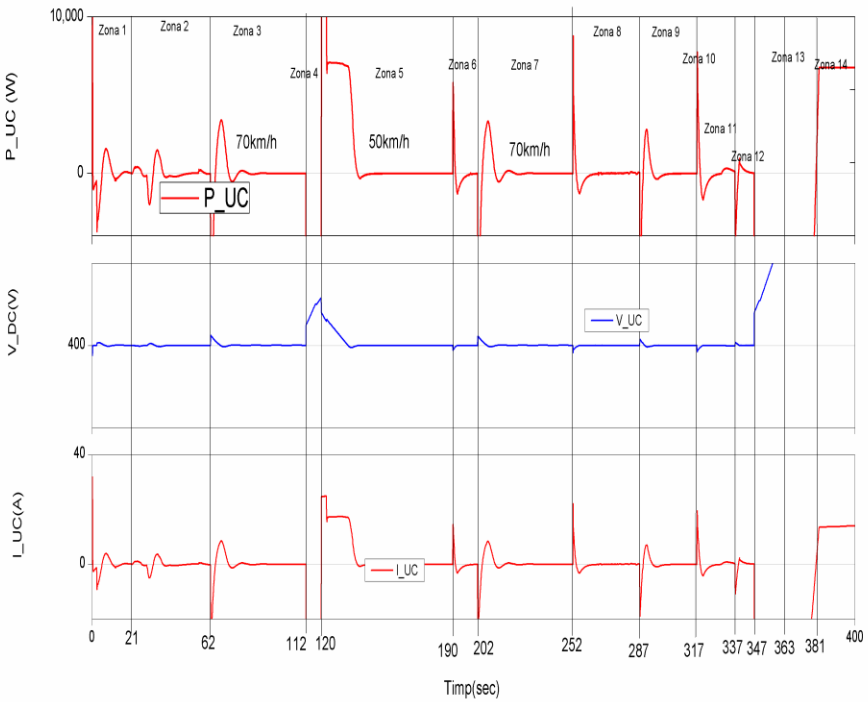
EMS based on states' diagram



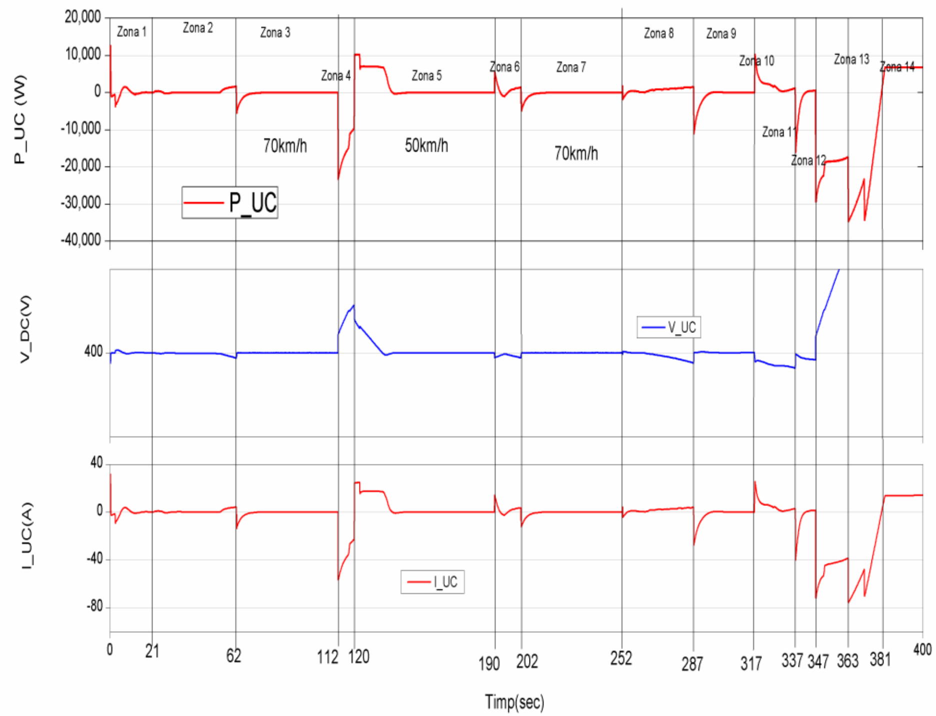
EMS based on PI regulators

2. Energy management strategies (EMS)

UC power, UC voltage, and UC current



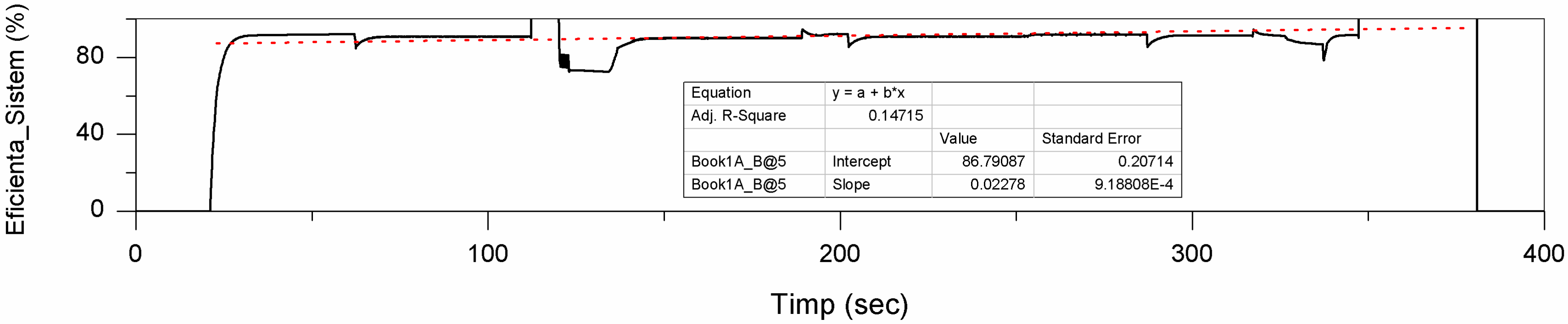
EMS based on states' diagram



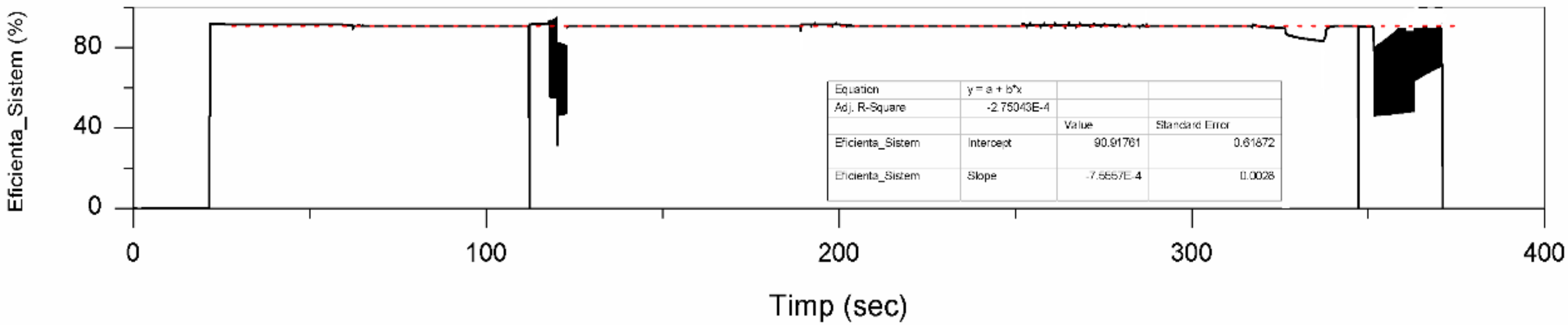
EMS based on PI regulators

2. Energy management strategies (EMS)

HPS energy efficiency



EMS based on states' diagram



EMS based on PI regulators

2. Energy management strategies (EMS)

Performance indicator	States' diagram	PI regulators
Battery SoC	70,2%	68,4%
H2 consumption	385 g	155 g
HPS energy efficiency	86,8%	90,9%

Performance obtained

The EMS based on PI regulators performed better in terms of efficiency, highlighting an overall electrical efficiency with 4% greater in comparison with that obtained with EMS based on states' diagrams, but note that the battery SOC is with 2% lower due to high use (in discharge mode) in the last part of the driving cycle.

The EMS based on PI regulators has achieved but hydrogen consumption noticeably reduced by approx. 40% in comparison with that obtained with EMS based on states' diagrams.

The three criteria adopted for performance comparison of the two control strategies do not allow their hierarchy, because, as has been shown, both strategies shows both advantages and disadvantages during a driving cycle.

Possible solutions for advanced EMS

Suwat Sikkabut, Pongsiri Mungporn, Chainarin Ekkaravarodome, Nicu Bizon, et all. Control of High-Energy High-Power Densities Storage Devices by Li-ion Battery and Supercapacitor for Fuel Cell/Photovoltaic Hybrid Power Plant for Autonomous System Applications. IEEE Transactions on Industry Applications 52(5) (2016):4395-4407, WOS:000384659900078

N. Bizon M. Radut, M. Oproescu, Energy control strategies for the Fuel Cell Hybrid Power Source under unknown load profile, Energy 86 (15 June 2015) 31-41 http://dx.doi.org/10.1016/j.energy.2015.03.118 WOS:000356986300004

N. Bizon, M. Oproescu, M. Raceanu, Efficient Energy Control Strategies for a Standalone Renewable/Fuel Cell Hybrid Power Source, Energy Conversion Management 77 (15 January 2015), 768-772. doi:10.1016/j.enconman.2014.11.002 WOS:000348886800010

N. Bizon, Improving the PEMFC energy efficiency by optimizing the fuelling rates based on extremum seeking algorithm, International Journal of Hydrogen Energy 39(20) (3 July 2014), 10641–10654. http://dx.doi.org/10.1016/j.ijhydene.2014.04.194 WOS:000338388200032

N. Bizon, Tracking the maximum efficiency point for the FC system based on extremum seeking scheme to control the air flow, Applied Energy 129 (15 September 2014) 147–157. http://dx.doi.org/10.1016/j.apenergy.2014.05.002 WOS:000339775400016

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Possible solutions for advanced EMS

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3. Load-following based EMS for FCV

Features of the load-following strategy

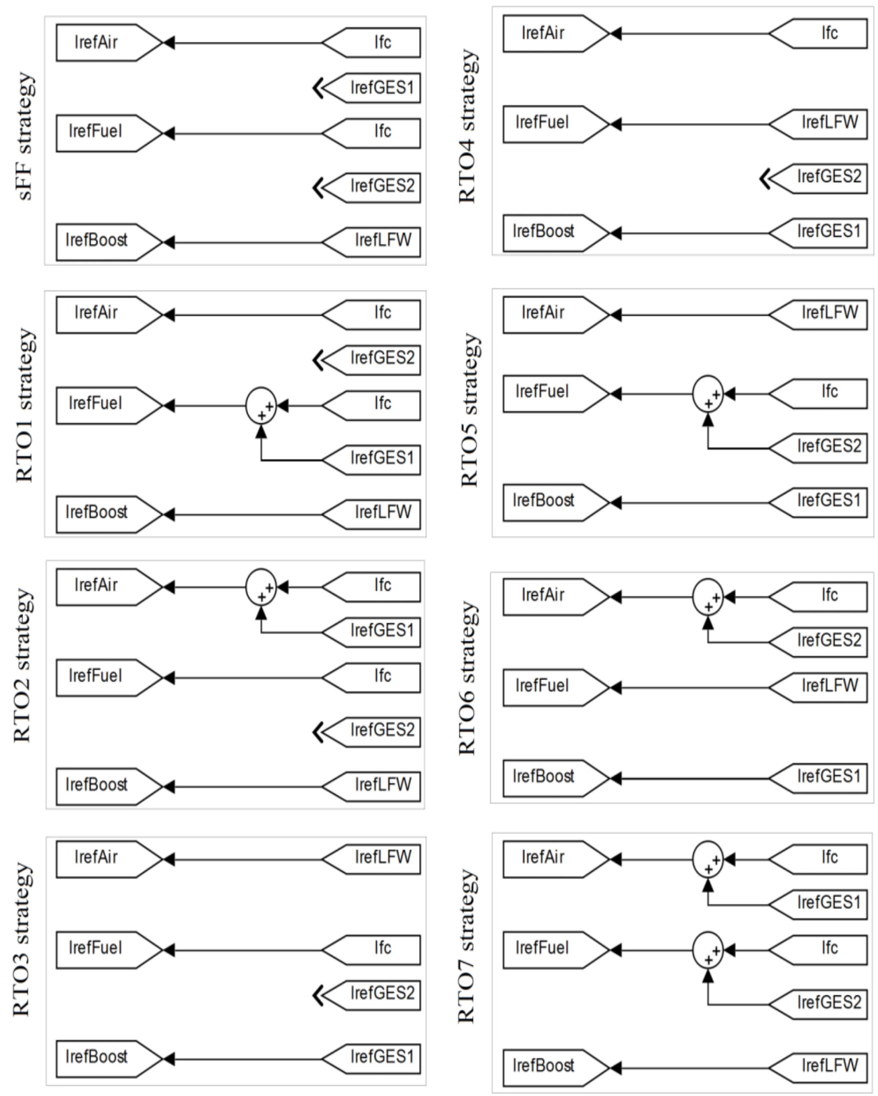
The load-following strategy has the following features:

- The load-following strategy assures the DC power balance using a backup power source, which is the FC system, and battery pack operates in charge-sustained mode;
- Thus a battery stack with lower capacity than in other strategies proposed in the literature is needed due to battery pack operation in charge-sustained mode;
- The load-following strategy avoids frequent charge-discharge cycles of the battery pack, which increases its lifetime and reduces the maintenance costs.

$$\eta_{boost} P_{FCnet} + P_{ESS} - P_{Load} = 0$$

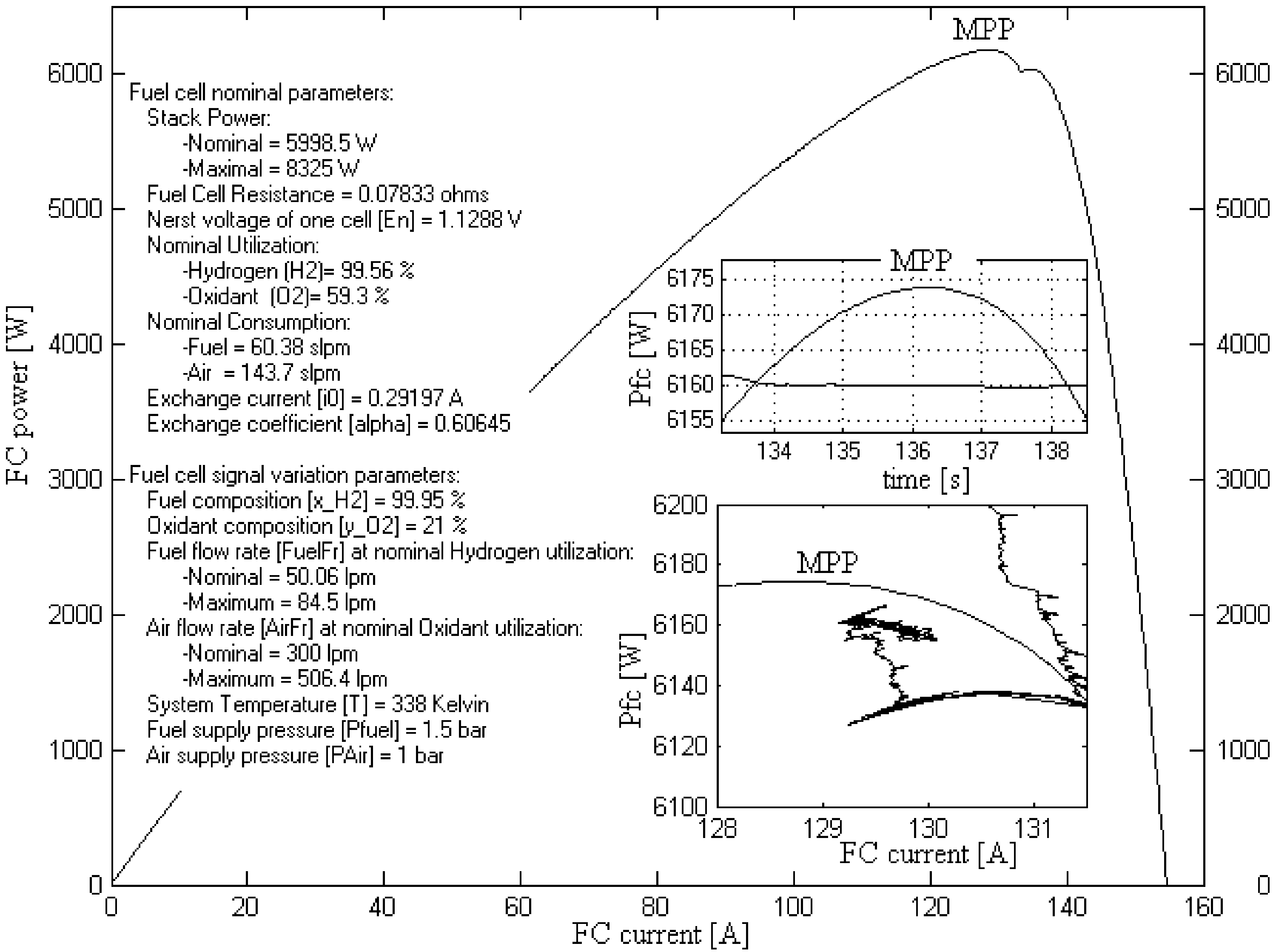
P_{ESS}=0 during a drive cycle

$$I_{refLFW} = I_{FC(AV)} = P_{Load} / (V_{FC} \eta_{boost})$$



3. Load-following based EMS for FCV

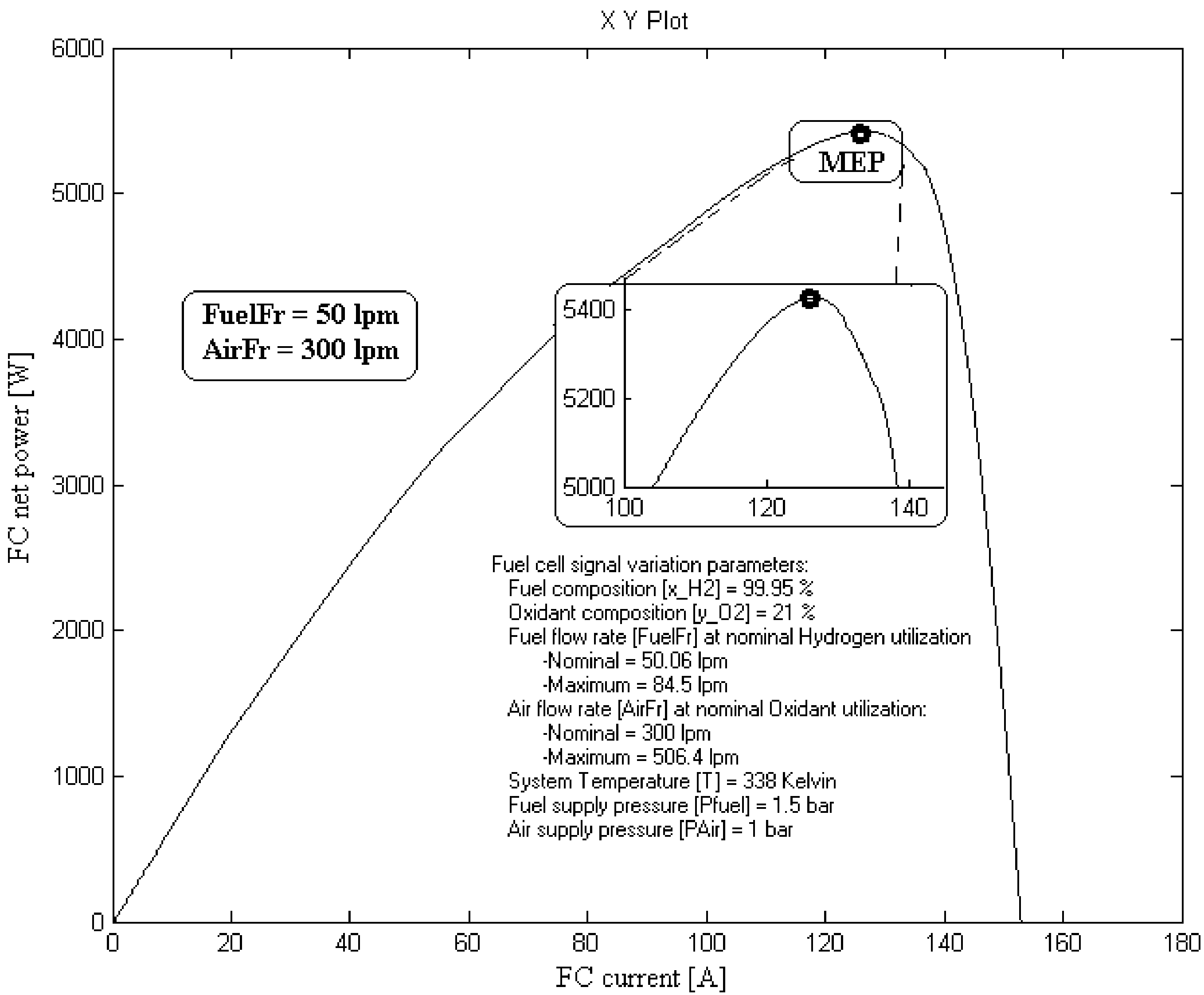
FC Maximum Power Point (MPP) tracking control



The FC parameters, P-I characteristic, and MPP tracking (zooms)

3. Load-following based EMS for FCV

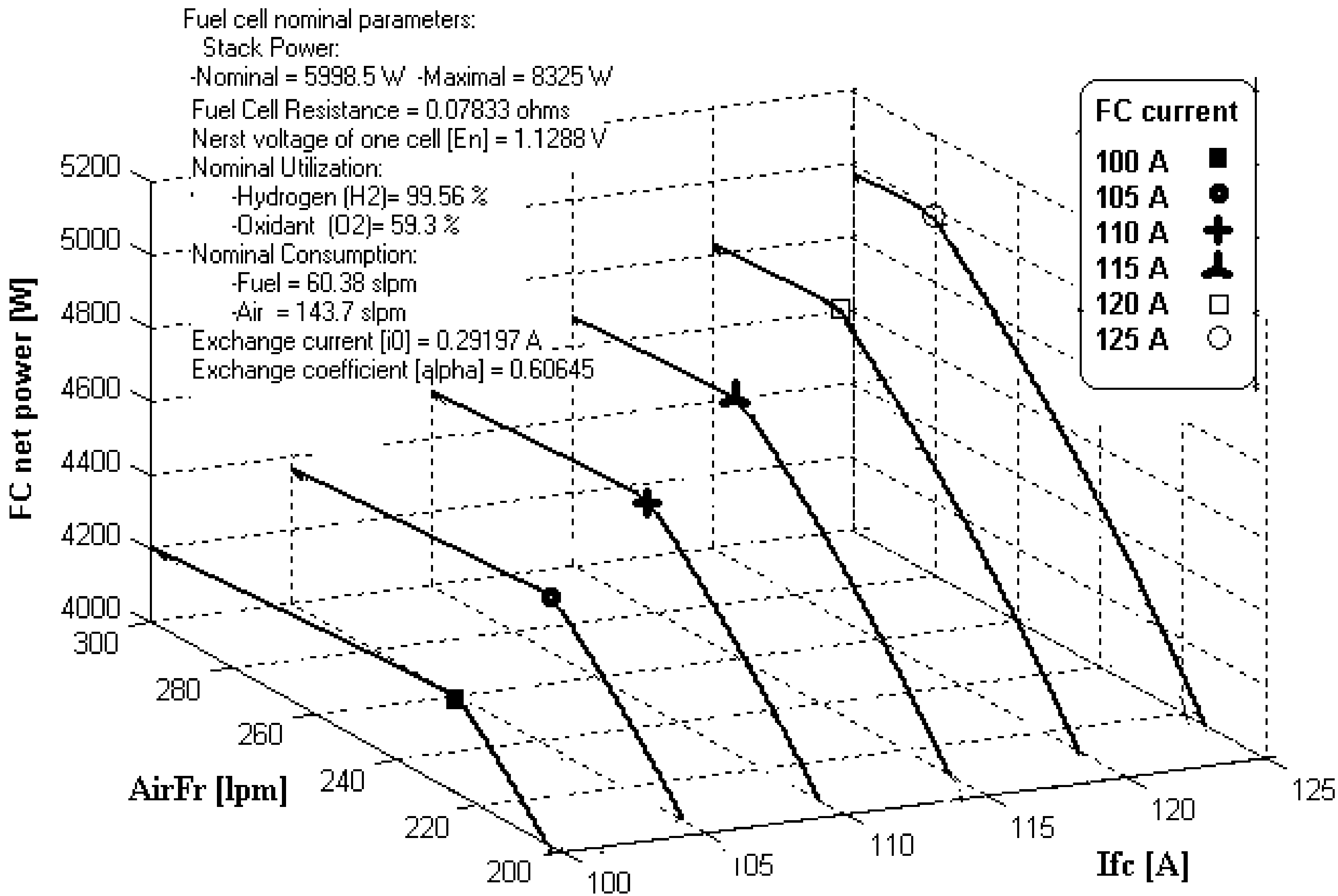
The FC net power characteristics



The FC net power characteristic for the nominal values of fueling rates

3. Load-following based EMS for FCV

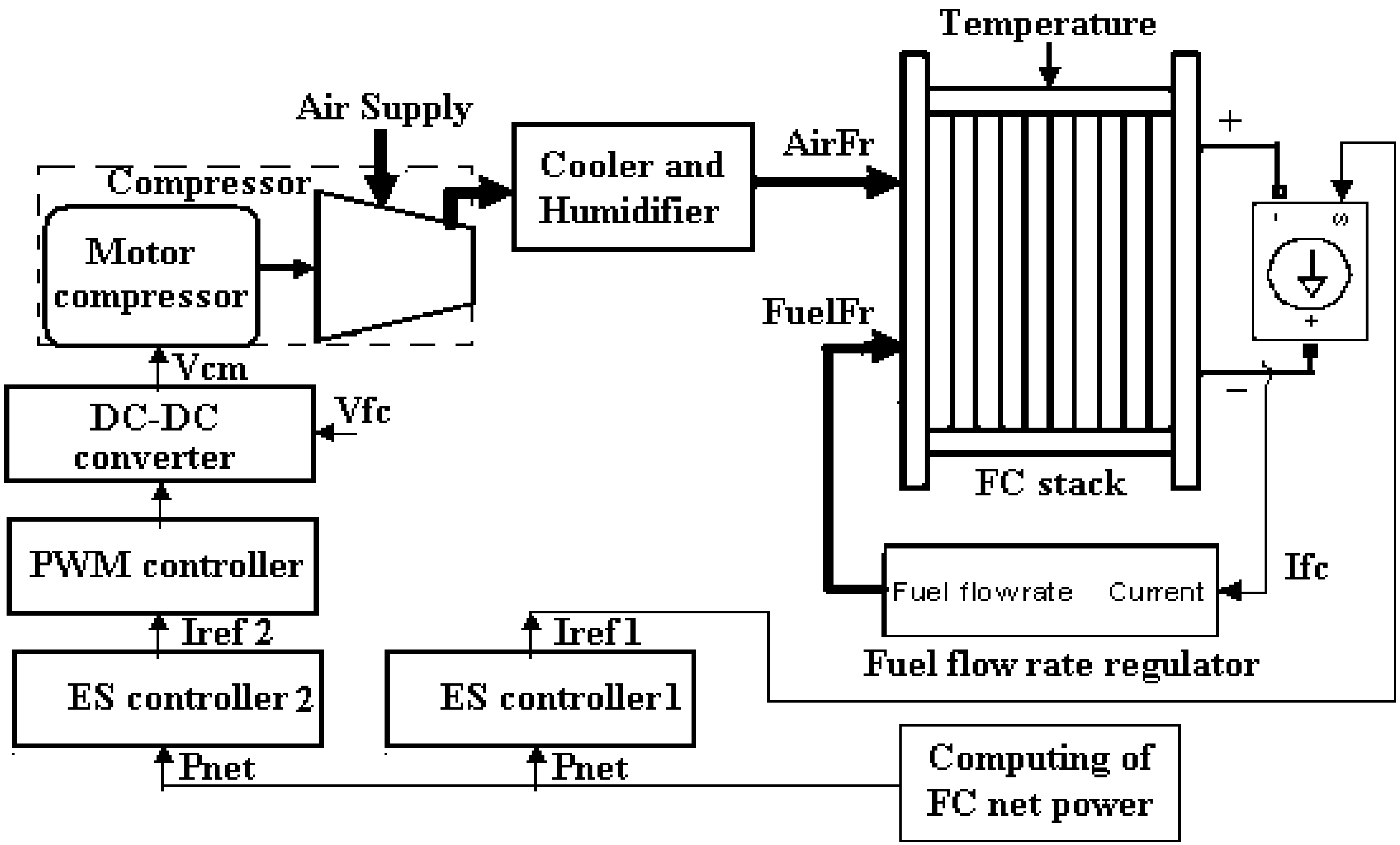
The FC net power characteristics



The FC net power surface

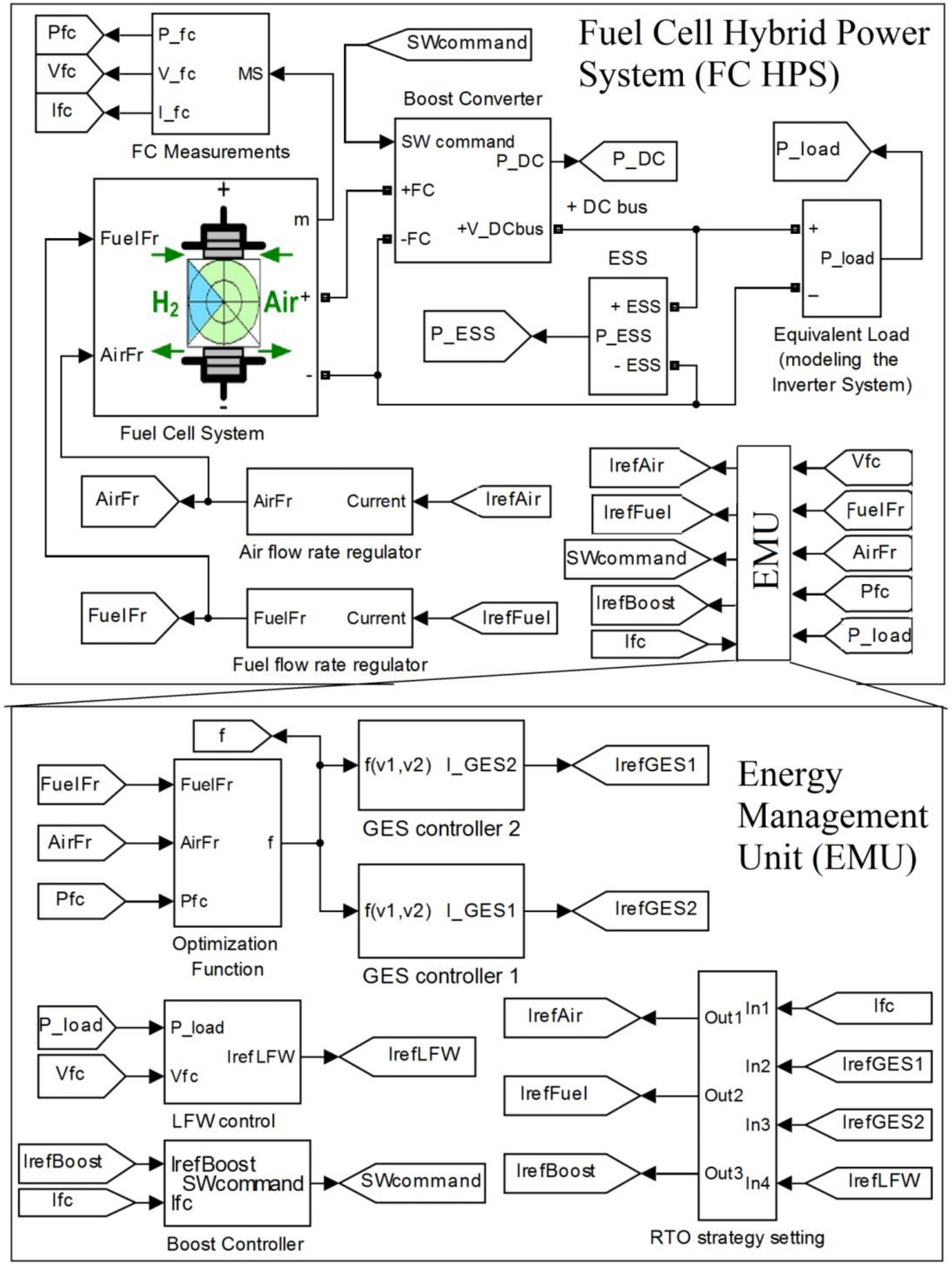
3. Load-following based EMS for FCV

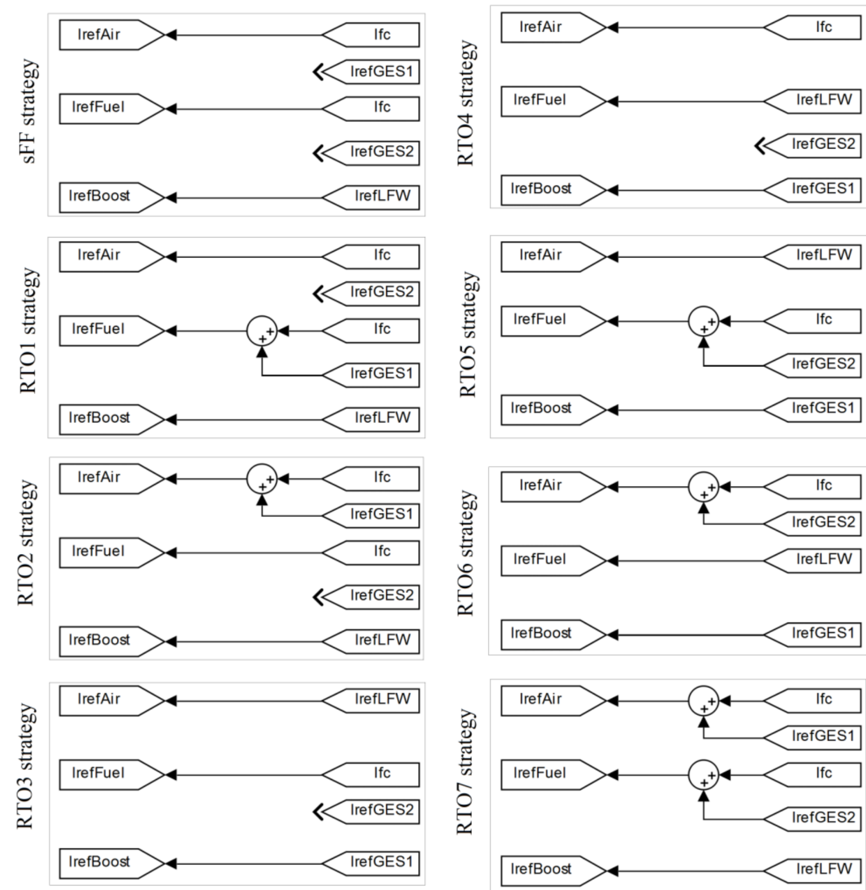
PEMFC system



The Proton Exchange Membrane Fuel Cell (PEMFC) system

3. Load-following based EMS for FCV





RTO strategy setting block

$$\eta_{boost} P_{FCnet} + P_{ESS} - P_{Load} = 0$$

P_{ESS}=0 during a drive cycle

$$I_{refLFW} = I_{FC(AV)} = P_{Load} / (V_{FC} \eta_{boost})$$

The FC HPS and EMU

3. Load-following based EMS for FCV

RTO strategies setting

No.	$I_{ref(Boost)}$	$I_{ref(Air)}$	$I_{ref(Fuel)}$	RTO strategy	Ref	Class
0	I_{LFW}	I_{FC}	I_{FC}	sFF	[0]	
1	I_{LFW}	I_{FC}	$I_{GES1}+I_{FC}$	RTO1	[1]	C1
2	I_{LFW}	$I_{GES1}+I_{FC}$	I_{FC}	RTO2	[2]	C1
3	I_{GES1}	I_{LFW}	I_{FC}	RTO3	[3]	C2
4	I_{GES1}	I_{FC}	I_{LFW}	RTO4	[4]	C3
5	I_{GES1}	I_{LFW}	$I_{GES2}+I_{FC}$	RTO5	[5]	C2
6	I_{GES1}	$I_{GES2}+I_{FC}$	I_{LFW}	RTO6	[6]	C3
7	I_{LFW}	$I_{GES1}+I_{FC}$	$I_{GES2}+I_{FC}$	RTO7	[7]	C1

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3. Load-following based EMS for FCV

The optimization function

$$f(x, AirFr, FuelFr, P_{Load}) = k_{net} \cdot P_{FCnet} + k_{fuel} \cdot Fuel_{eff}$$

$$\dot{x} = g(x, AirFr, FuelFr, P_{Load}),\ x \in X$$

The performance indicators

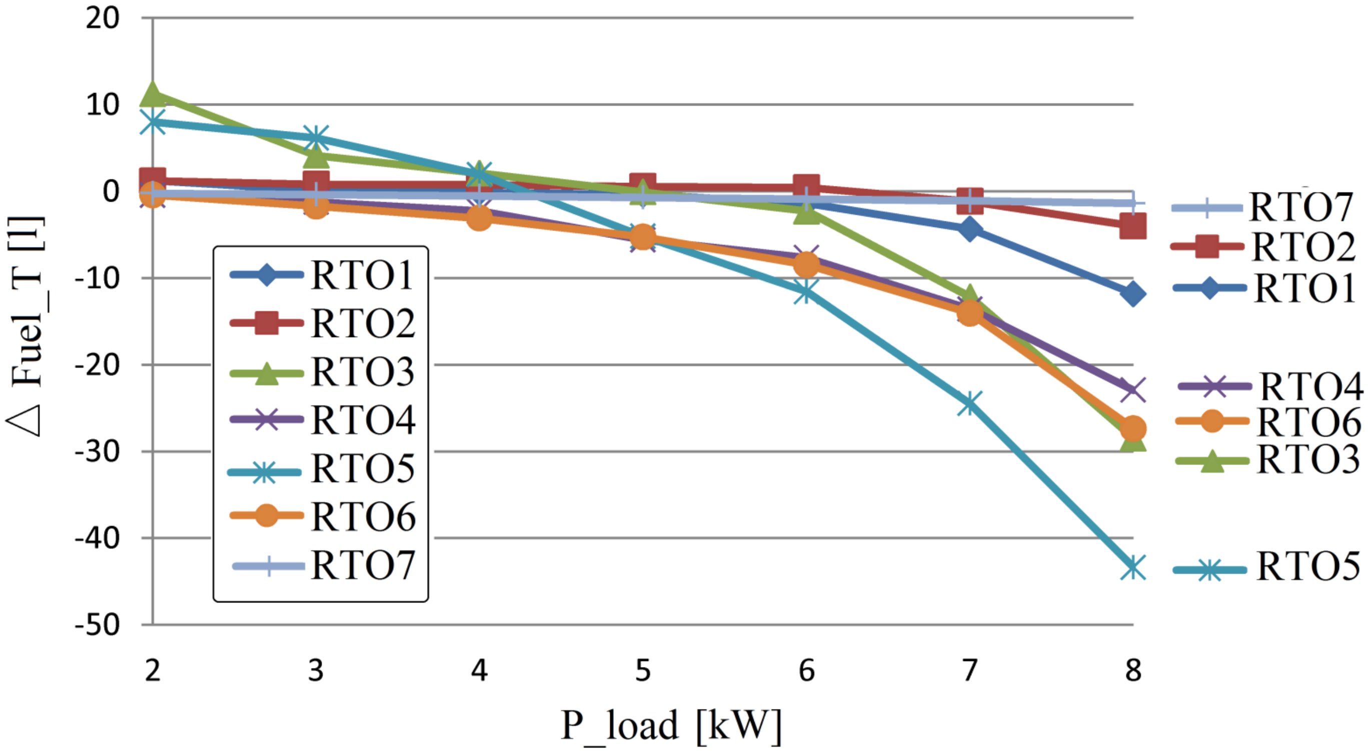
$P_{FCnet} \cong P_{FC} - P_{cm}$
$\eta_{sys} = P_{FCnet} / P_{FC}$
$Fuel_{eff} \cong P_{FCnet} / FuelFr$
$Fuel_T = \int FuelFr(t)dt$

$$FuelFr = \frac{60000 \cdot R \cdot (273+\theta) \cdot N_C \cdot I_{ref(H2)}}{2F \cdot (101325 \cdot P_{f(H2)}) \cdot (U_{f(H2)}/100) \cdot (x_{H2}/100)}$$

$$AirFr = \frac{60000 \cdot R \cdot (273+\theta) \cdot N_C \cdot \cdot I_{ref(O2)}}{4F \cdot (101325 \cdot P_{f(O2)}) \cdot (U_{f(O2)}/100) \cdot (y_{O2}/100)}$$

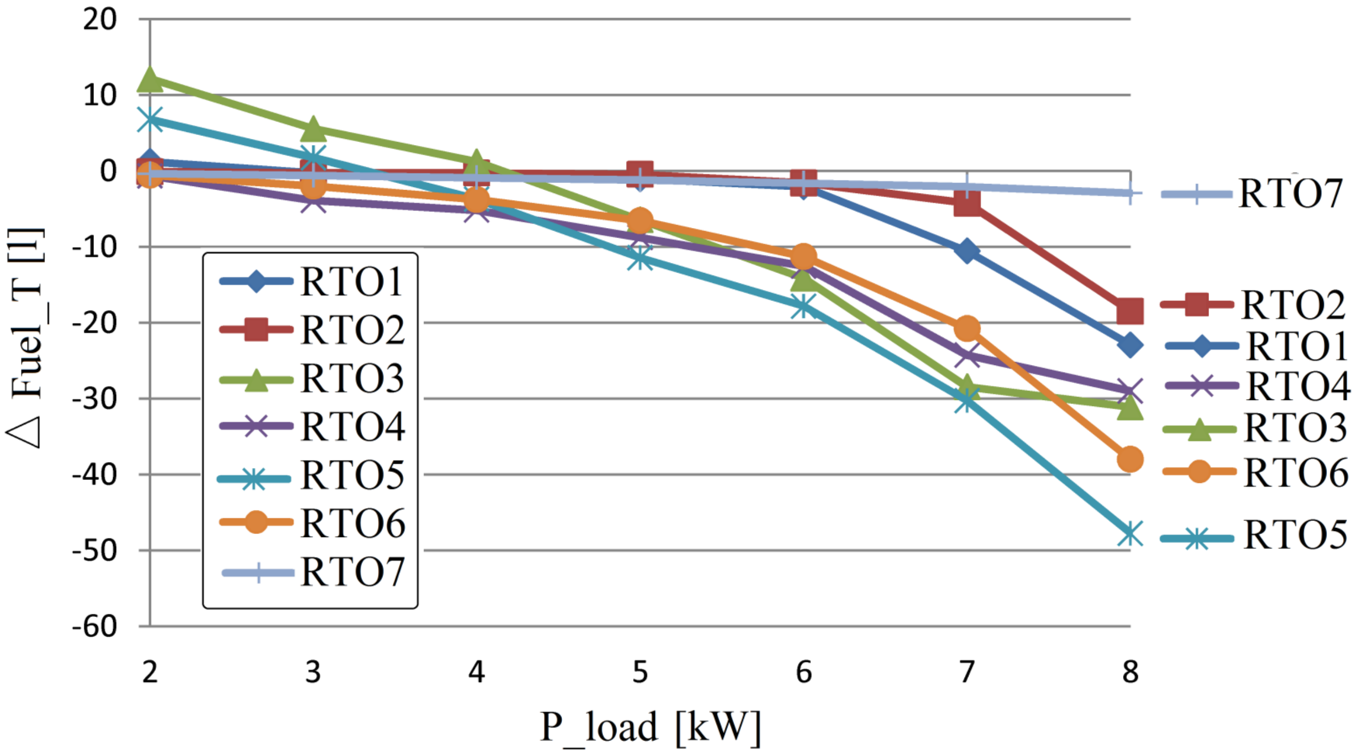
where:
R = 8.3145 J/(mol K);
F = 96485 As/mol;
N_C is the number of cells in series (65 cells);
θ is the operating temperature (65° Celsius);
$U_{f(H2)}$, $U_{f(O2)}$ are the nominal utilization of hydrogen (99.56%) and oxygen (59.3%);
$P_{f(H2)}$, $P_{f(O2)}$ are the pressure of the fuel (1.5 bar) and air (1 bar);
x_{H2}, y_{O2} are the composition of fuel (99.95%) and oxidant (21%);
$I_{ref(H2)}$, $I_{ref(O2)}$ are the reference currents.

3. Load-following based EMS for FCV



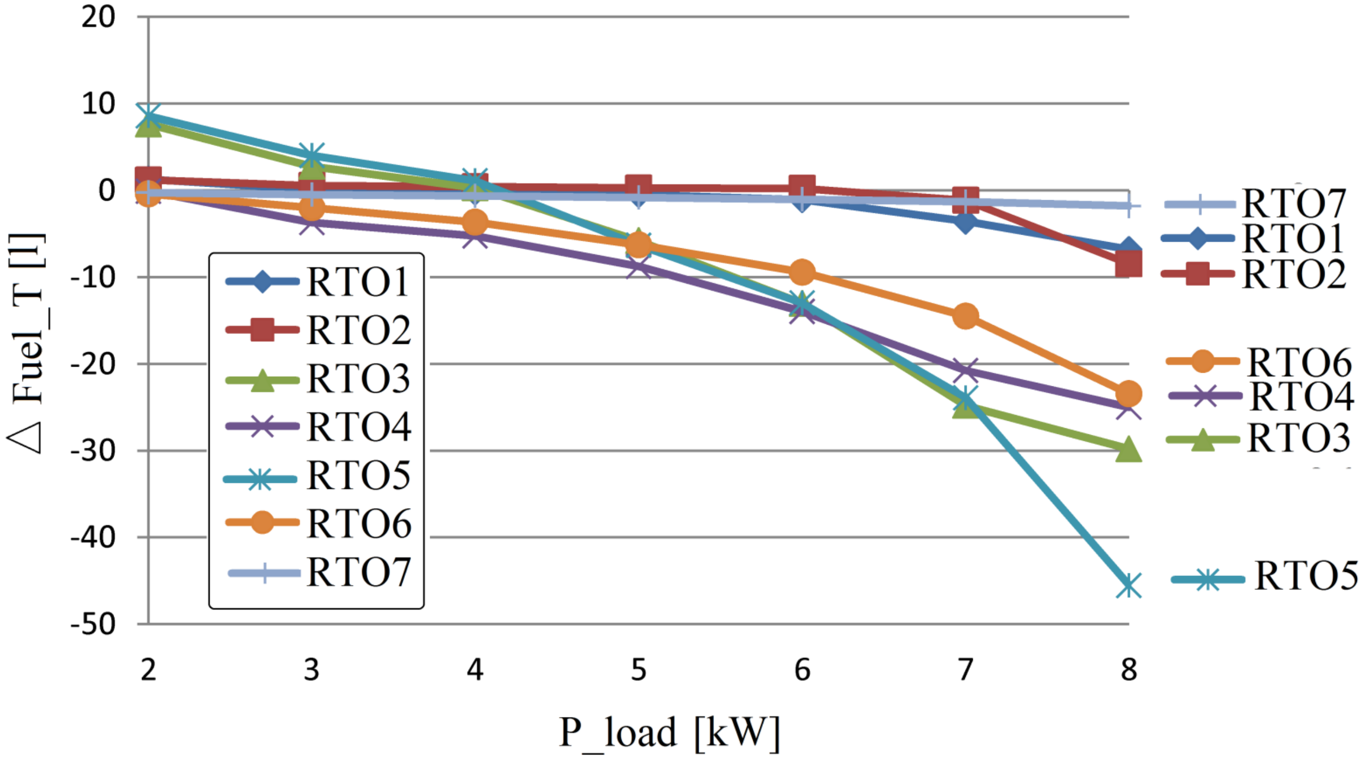
Fuel economy for all RTO strategies in case A (k_{net}=0.5, k_{fuel}=0

3. Load-following based EMS for FCV



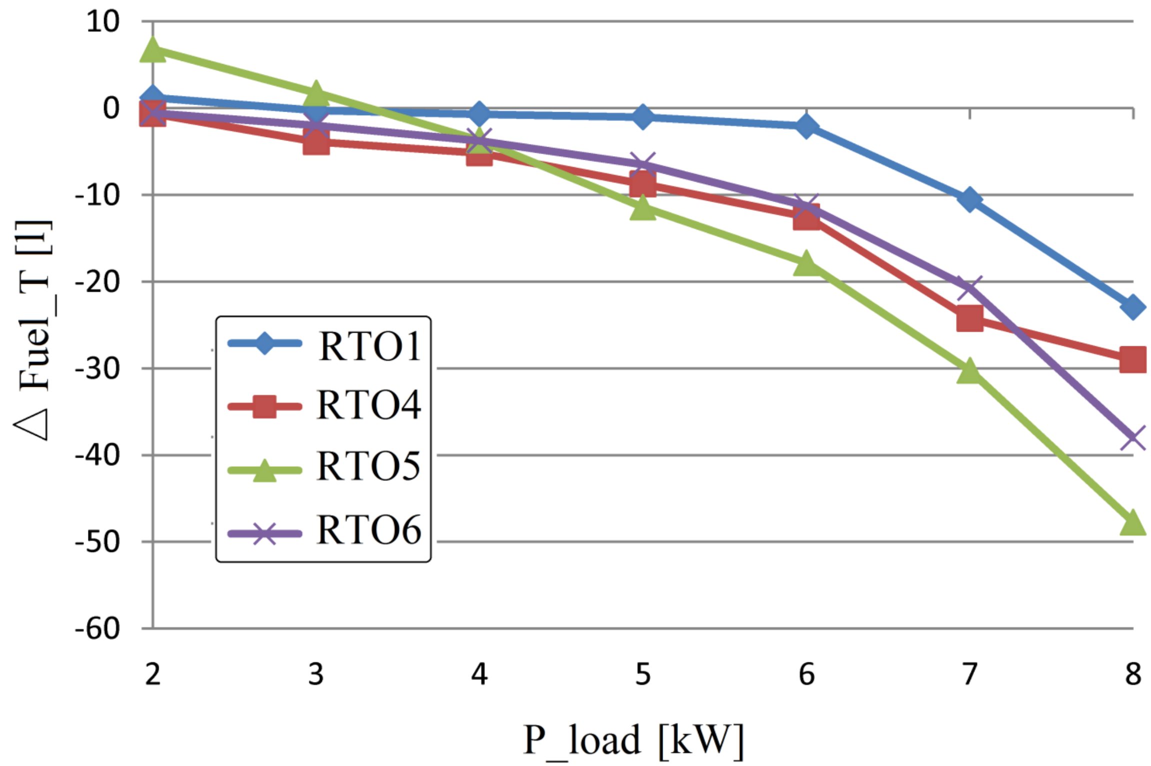
Fuel economy for all RTO strategies in case B (k_{net}=0.5, k_{fuel}=25).

3. Load-following based EMS for FCV



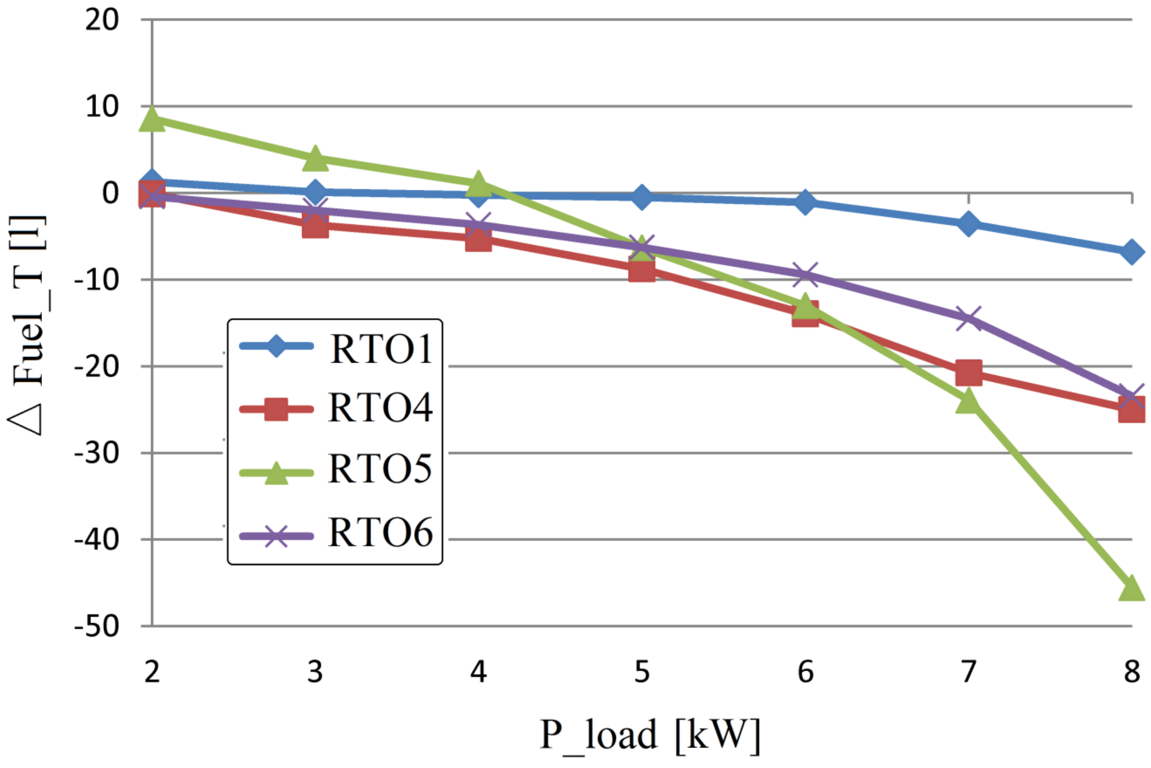
Fuel economy for all RTO strategies in case C (k_{net}=0.5, k_{fuel}=50).

3. Load-following based EMS for FCV



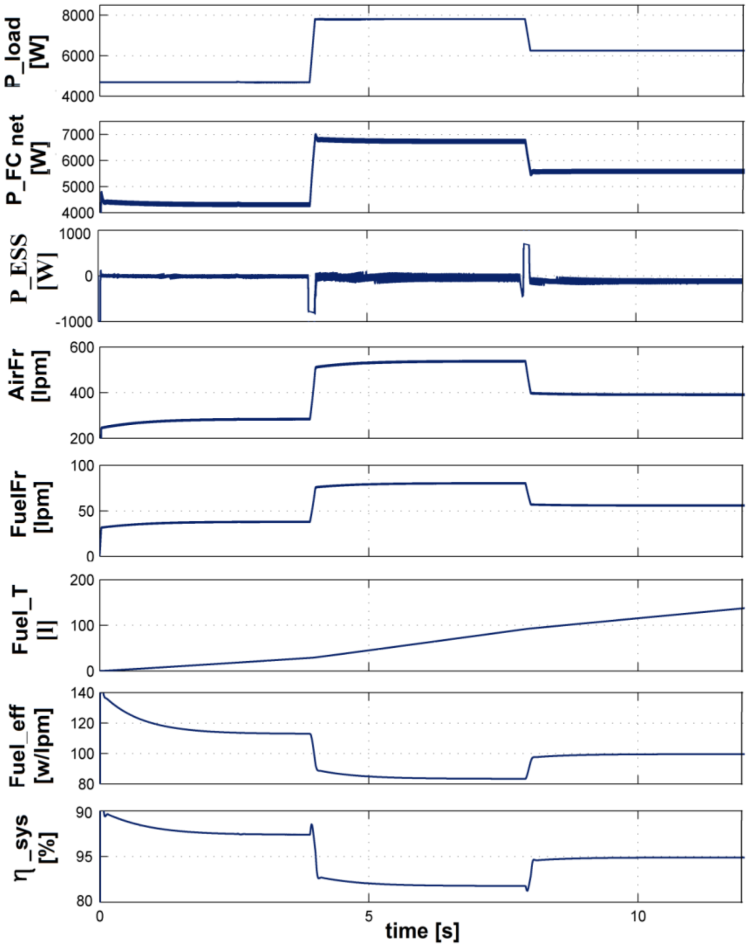
Fuel economy for selected RTO strategies in case B (k_{net}=0.5, k_{fuel}=25).

3. Load-following based EMS for FCV

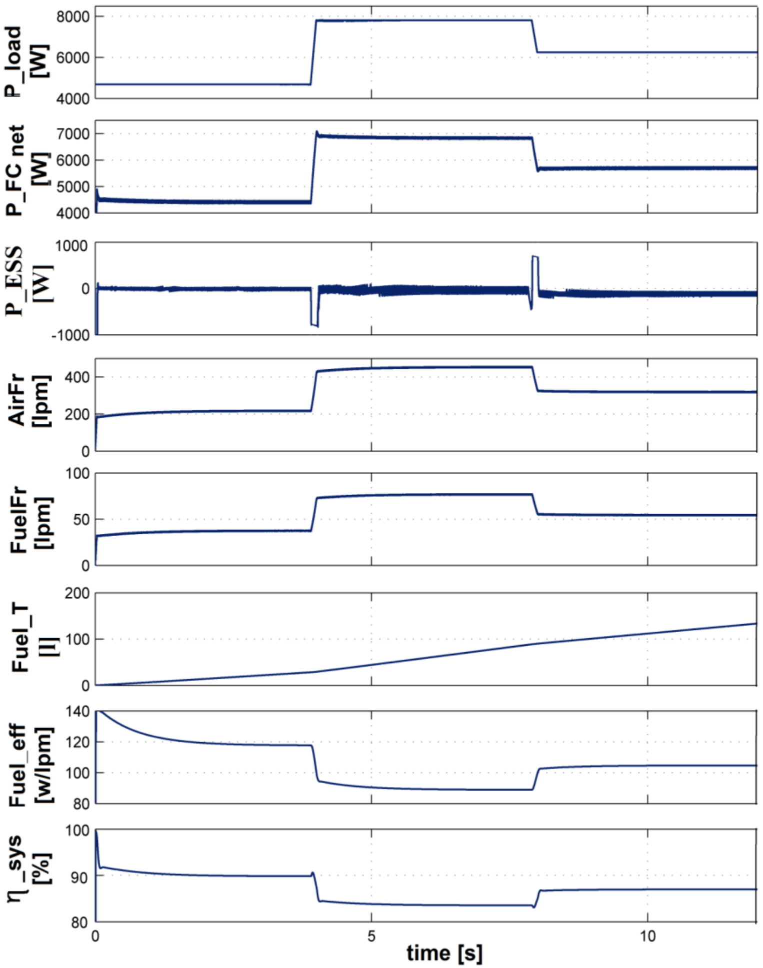


Fuel economy for selected RTO strategies in case C (k_{net}=0.5, k_{fuel}=50).

3. Load-following based EMS for FCV



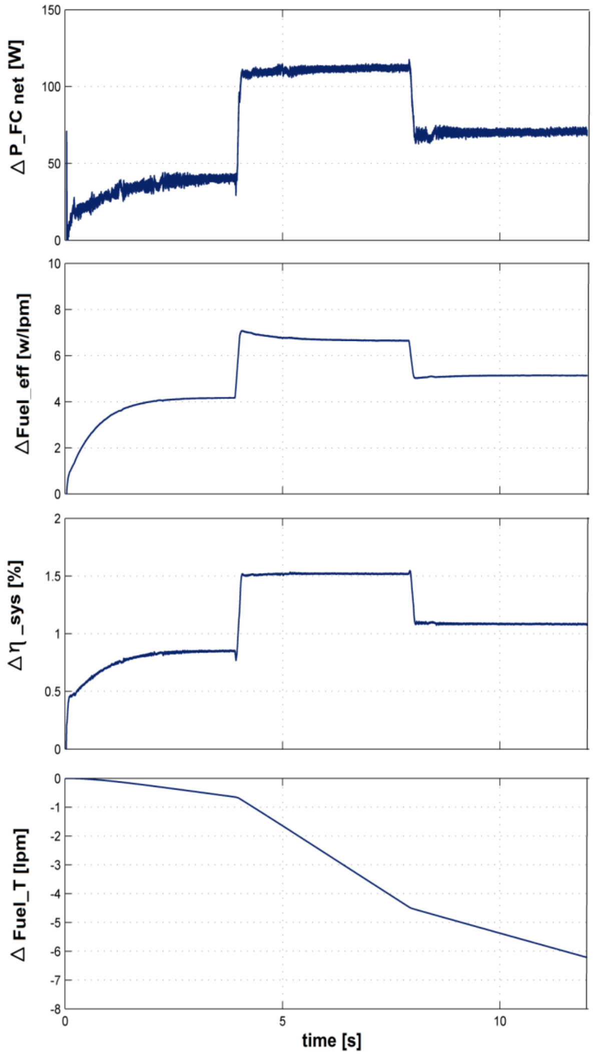
RTO1 strategy k_{fuel}=25



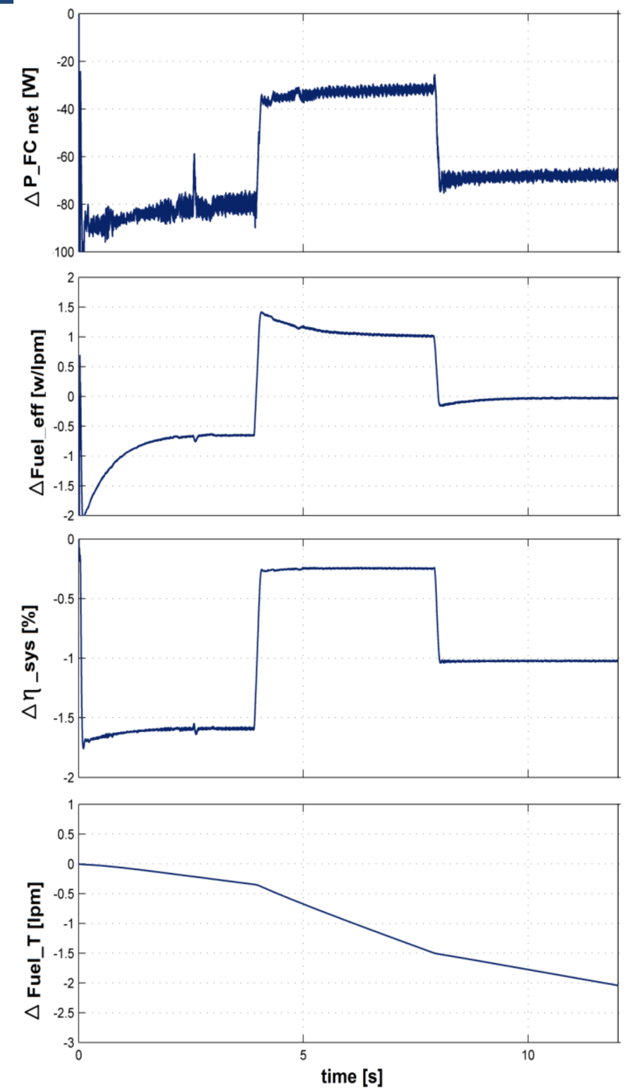
RTO2 strategy k_{fuel}=25

The behavior of the FC HPS under 6.25 kW LC

3. Load-following based EMS for FCV



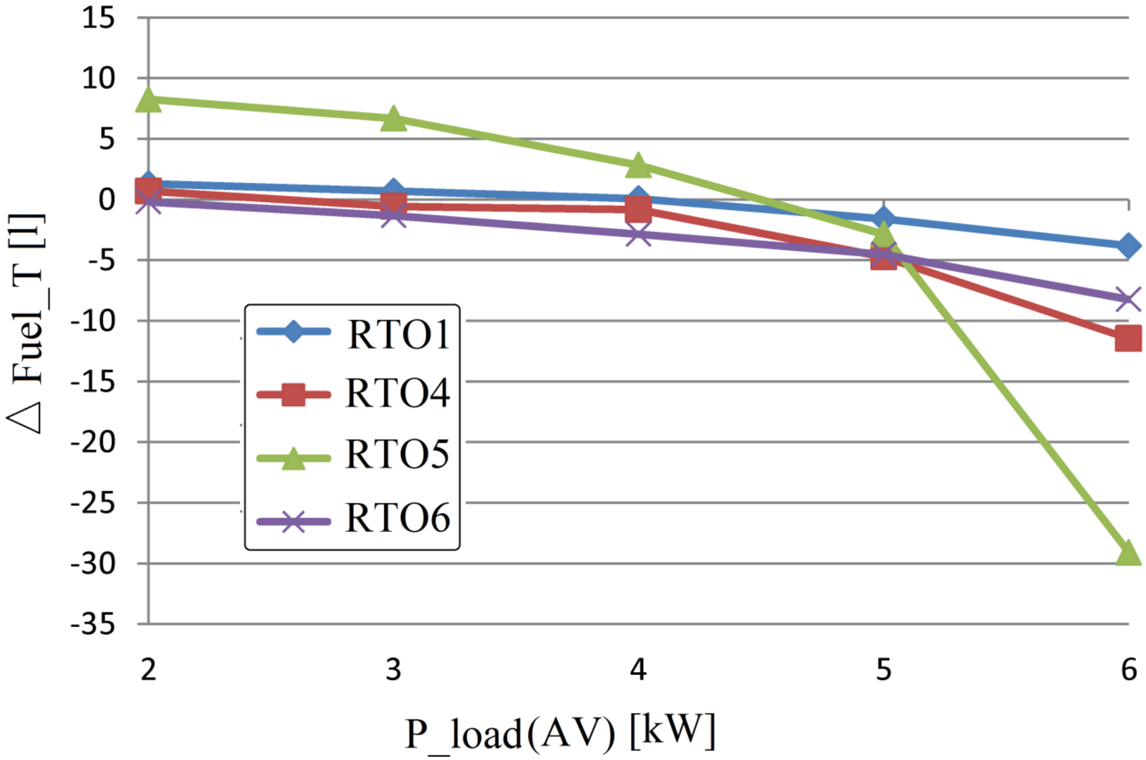
RTO1 strategy with k_{fuel}=25



RTO2 strategy with k_{fuel}=25

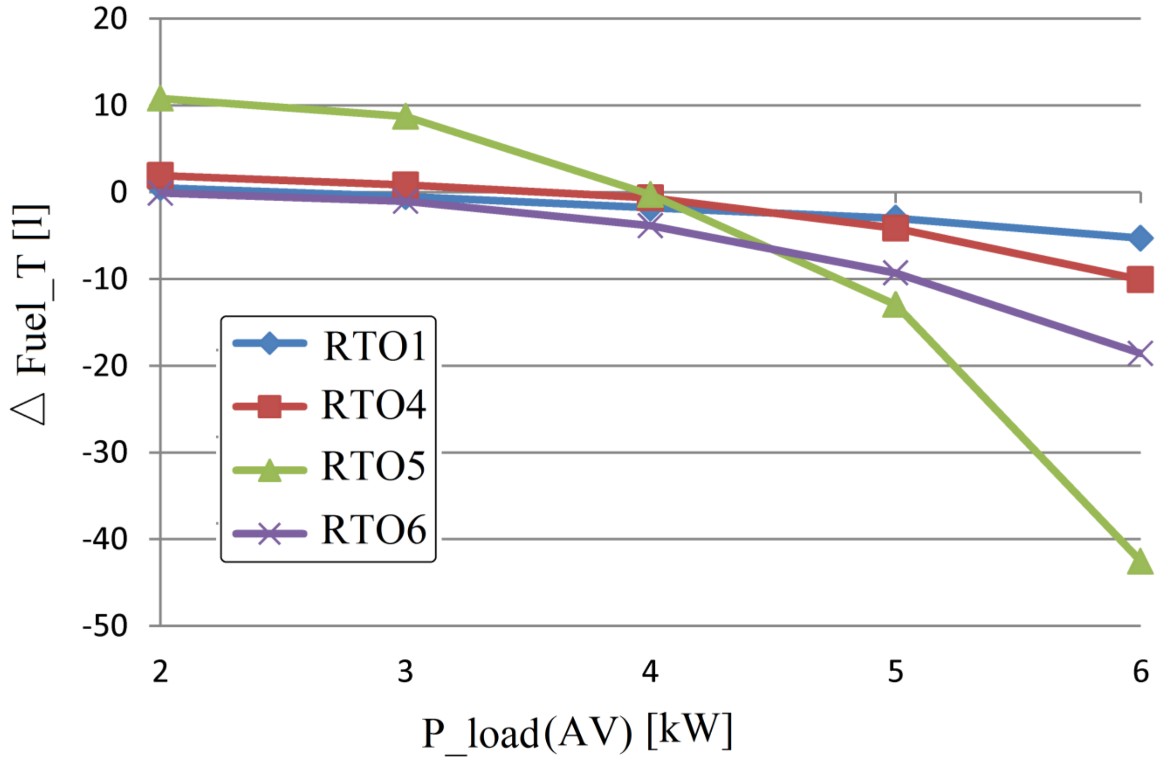
The behavior of the performance indicators for the FC HPS under 6.25 kW LC

3. Load-following based EMS for FCV



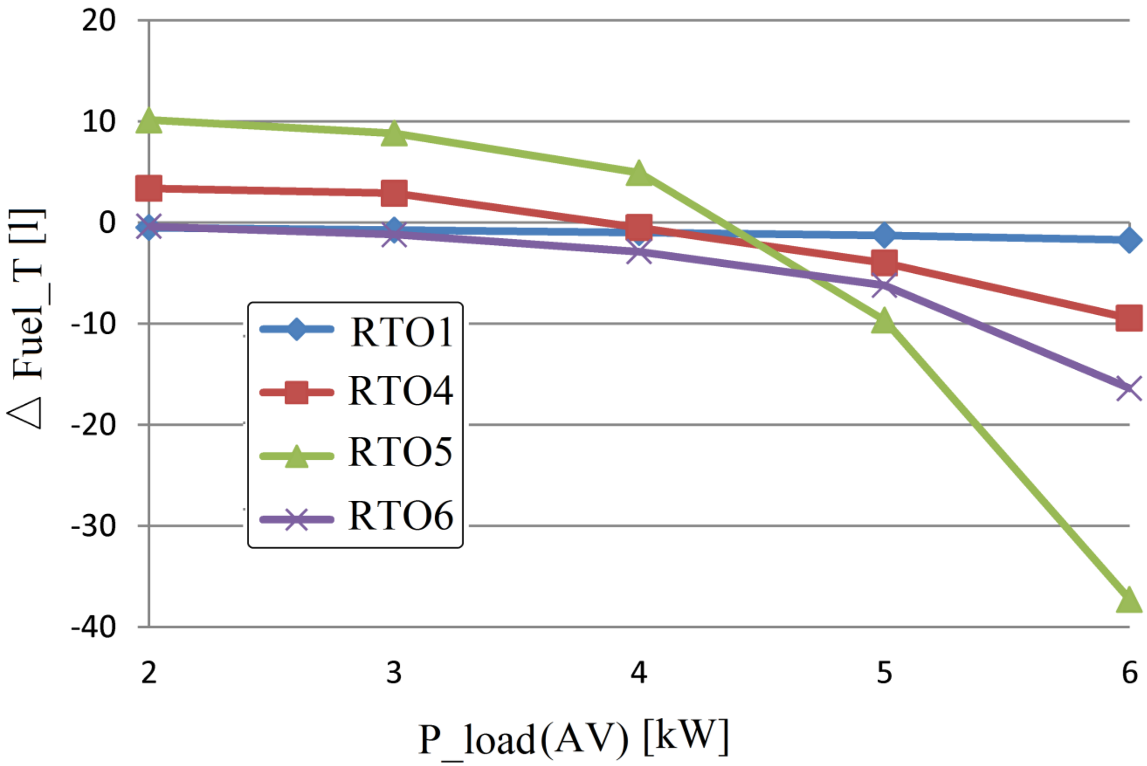
Fuel economy under variable load demand for selected RTO strategies in case A (k_{net}=0.5, k_{fuel}=0).

3. Load-following based EMS for FCV



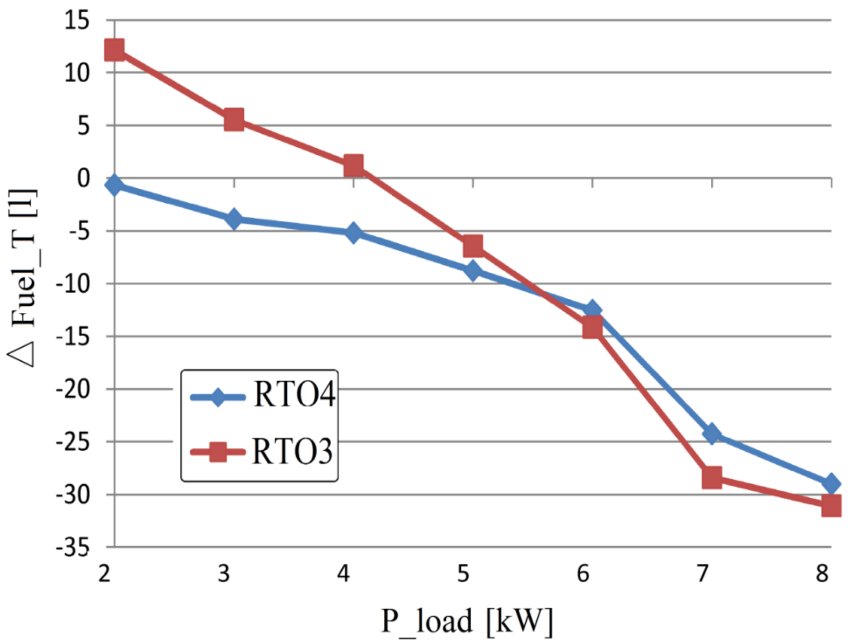
Fuel economy under variable load demand for selected RTO strategies in case B (k_{net}=0.5, k_{fuel}=25).

3. Load-following based EMS for FCV

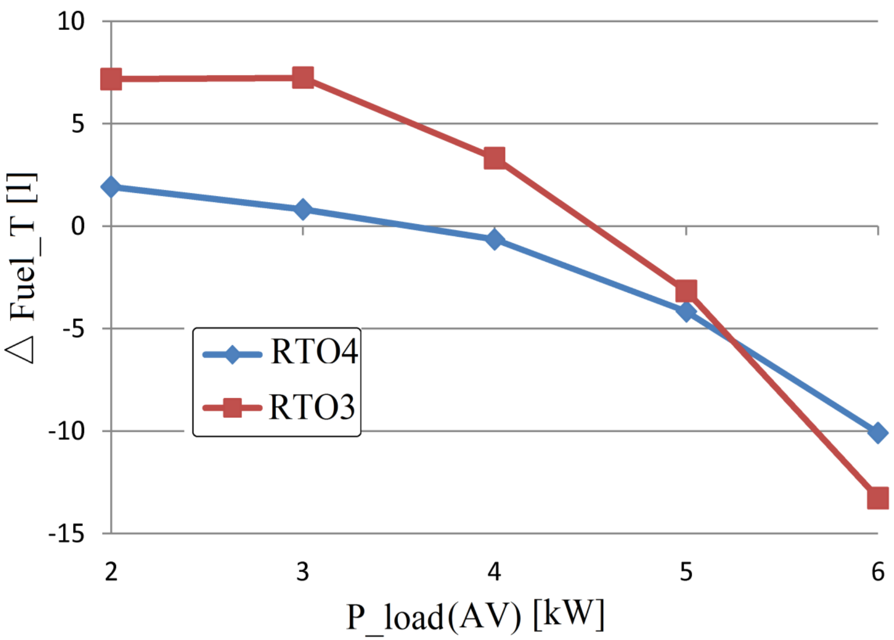


Fuel economy under variable load demand for selected RTO strategies in case C (k_{net}=0.5, k_{fuel}=50).

3. Load-following based EMS for FCV



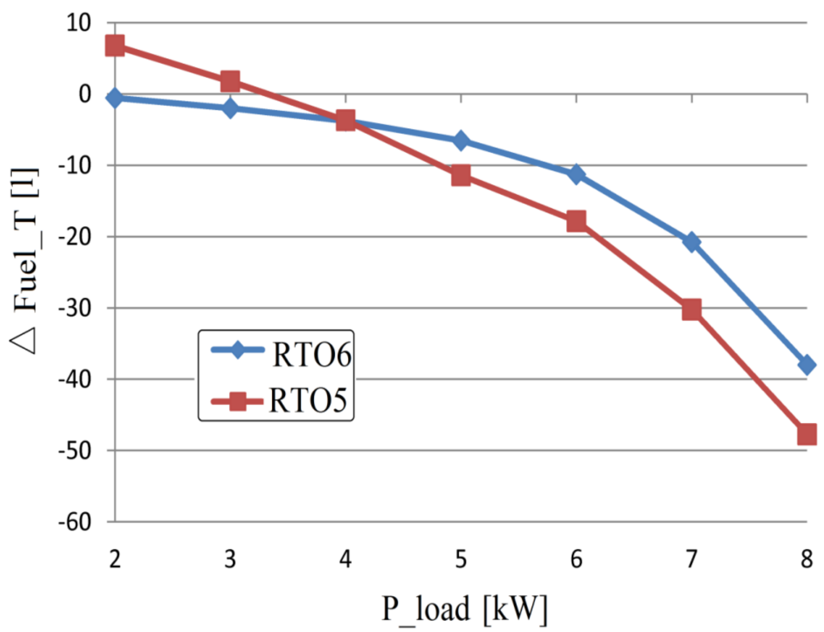
Constant load demand



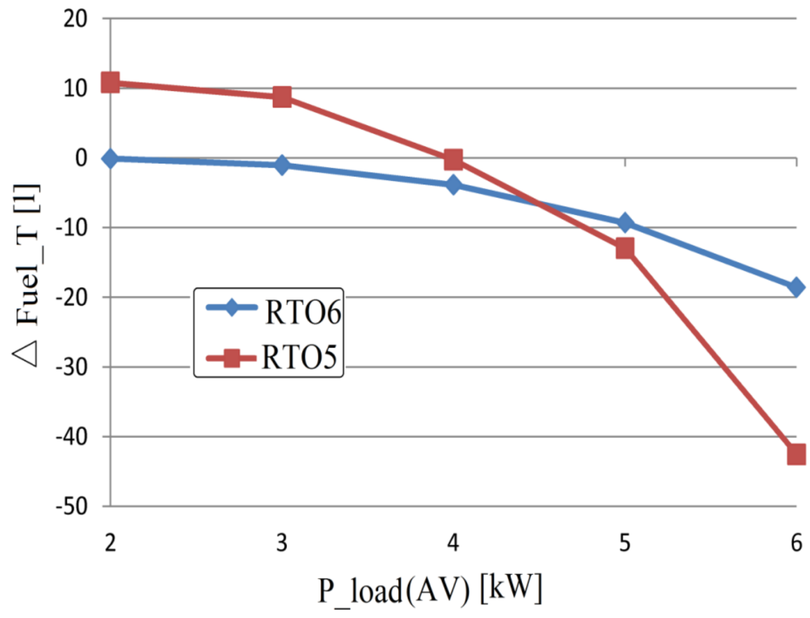
Variable load demand

Fuel economy for strategies RTO4 and RTO3 with k_{fuel} = 25

3. Load-following based EMS for FCV



Constant load demand



Variable load demand

Fuel economy for strategies RTO6 and RTO5 with k_{fuel} = 25

3. Load-following based EMS for FCV

- The performance in fuel economy and even the order of the selected RTO strategies (RTO1, RTO4, RTO5, and RTO6) remain the same in all cases analyzed for the FC HPS (under variable and constant load demand);
- the fuel economy increases if $k_{fuel} \neq 0$ and best fuel economy is obtained for k_{fuel} around value of 25 for the FC HPS under variable load demand;
- The rules of the RTO switching strategy for best fuel economy of 6kW FC HPS could be defined as follows: (i) set the weighting coefficient k_{fuel} to optimum value (around of 25); (ii) if the load demand is lower than 5 kW then the recommended strategy must be chosen from class C3 (the RTO4 strategy or the RTO6 strategy); (iii) if the load demand is higher than 5 kW then the recommended strategy must be from class C2 (the RTO3 strategy or the RTO5 strategy).
- The objective was to probe how optimization function through choosing the weighting coefficients k_{net} and k_{fuel} could be a crucial help when planning the fuel consumption of a FC vehicle under unknown route;
- The fuel economy can be maximized using the RTO4 strategy and RTO5 strategy (or RTO6 strategy and RTO5 strategy) for the FC vehicle which runs on a smooth route and, respectively, the FC vehicle ramps a hill;
- It is worth to mention that the strategies RTOk, $k=1 \div 4$ use only one GES controller to maximize the fuel economy, so may be simple to implement the RTO switching strategy using the RTO4 strategy for $P_{load}<5$ kW and RTO3 strategy for $P_{load}>5$ kW

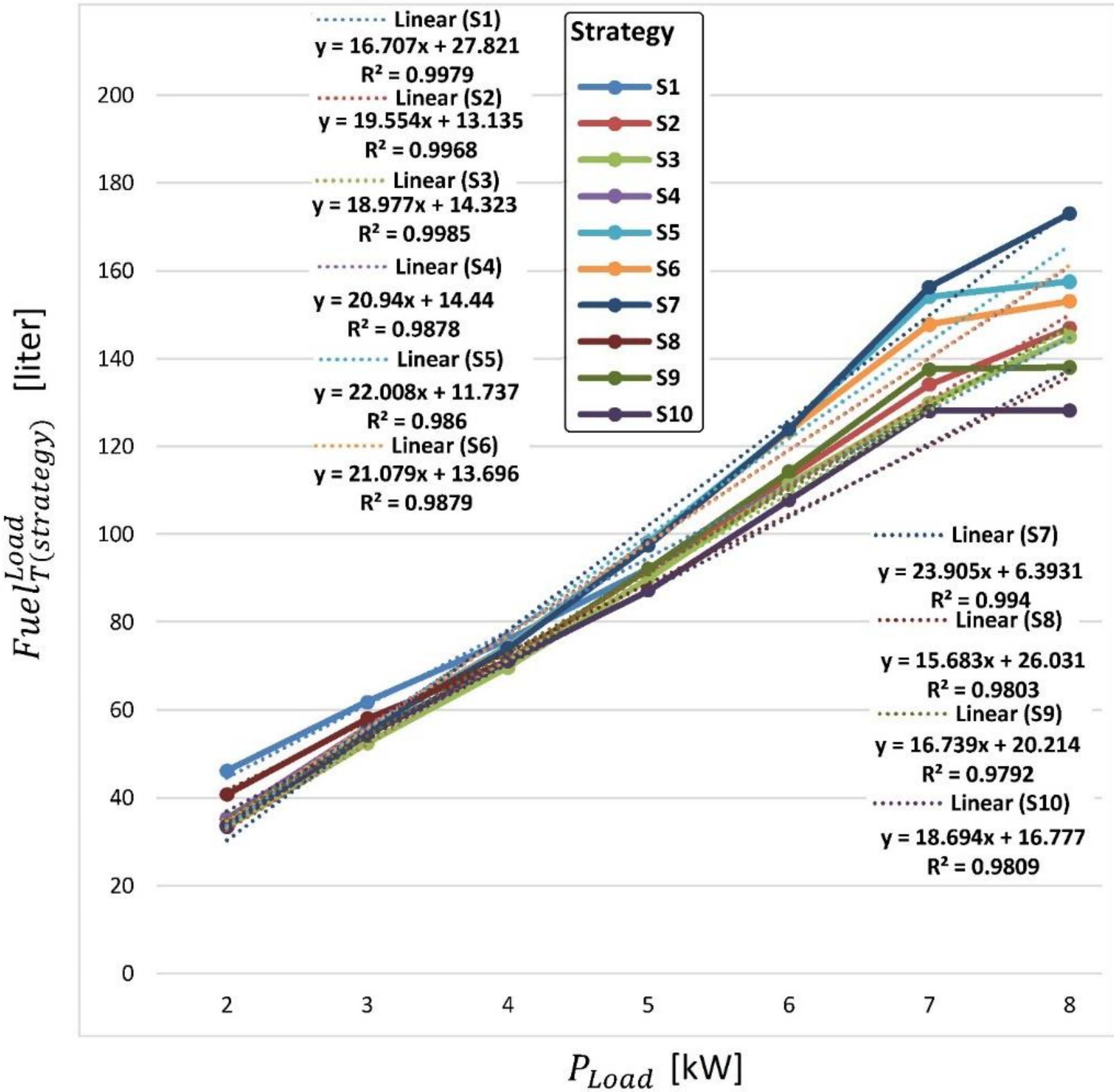
4. Advanced EMS for FCV

Strategy / Reference	S1	S2	S3	S4	S5	S6
$I_{ref(Air)}$	$I_{ref(PTC)}$	I_{FC}	$\begin{cases} I_{FC},\ if\ P_{DCreq} \leq P_{ref} \\ I_{ref(PTC)},\ if\ P_{DCreq} > P_{ref} \end{cases}$	I_{FC}	$I_{FC} + I_{ref(GES)}$	$\begin{cases} I_{FC} + I_{ref(GES1)},\ if\ P_{DCreq} \leq P_{ref} \\ I_{FC},\ if\ P_{DCreq} > P_{ref} \end{cases}$
$I_{ref(Fuel)}$	I_{FC}	$I_{ref(PTC)}$	$\begin{cases} I_{ref(PTC)},\ if\ P_{DCreq} \leq P_{ref} \\ I_{FC},\ if\ P_{DCreq} > P_{ref} \end{cases}$	$I_{FC} + I_{ref(GES)}$	I_{FC}	$\begin{cases} I_{FC},\ if\ P_{DCreq} \leq P_{ref} \\ I_{FC} + I_{ref(GES2)},\ if\ P_{DCreq} > P_{ref} \end{cases}$
$I_{ref(Boost)}$	$I_{ref(GES)}$	$I_{ref(GES)}$	$I_{ref(GES)}$	$I_{ref(PTC)}$	$I_{ref(PTC)}$	$I_{ref(PTC)}$

Strategy / Reference	S7	S8	S9	S10	sFF
$I_{ref(Air)}$	$I_{FC} + I_{ref(GES1)}$	$I_{ref(PTC)}$	$I_{FC} + I_{ref(GES2)}$	$\begin{cases} I_{FC} + I_{ref(GES2)},\ if\ P_{DCreq} \leq P_{ref} \\ I_{ref(PTC)},\ if\ P_{DCreq} > P_{ref} \end{cases}$	I_{FC}
$I_{ref(Fuel)}$	$I_{FC} + I_{ref(GES2)}$	$I_{FC} + I_{ref(GES2)}$	$I_{ref(PTC)}$	$\begin{cases} I_{ref(PTC)},\ if\ P_{DCreq} \leq P_{ref} \\ I_{FC} + I_{ref(GES2)},\ if\ P_{DCreq} > P_{ref} \end{cases}$	I_{FC}
$I_{ref(Boost)}$	$I_{ref(PTC)}$	$I_{ref(GES1)}$	$I_{ref(GES1)}$	$I_{ref(GES1)}$	$I_{ref(PTC)}$

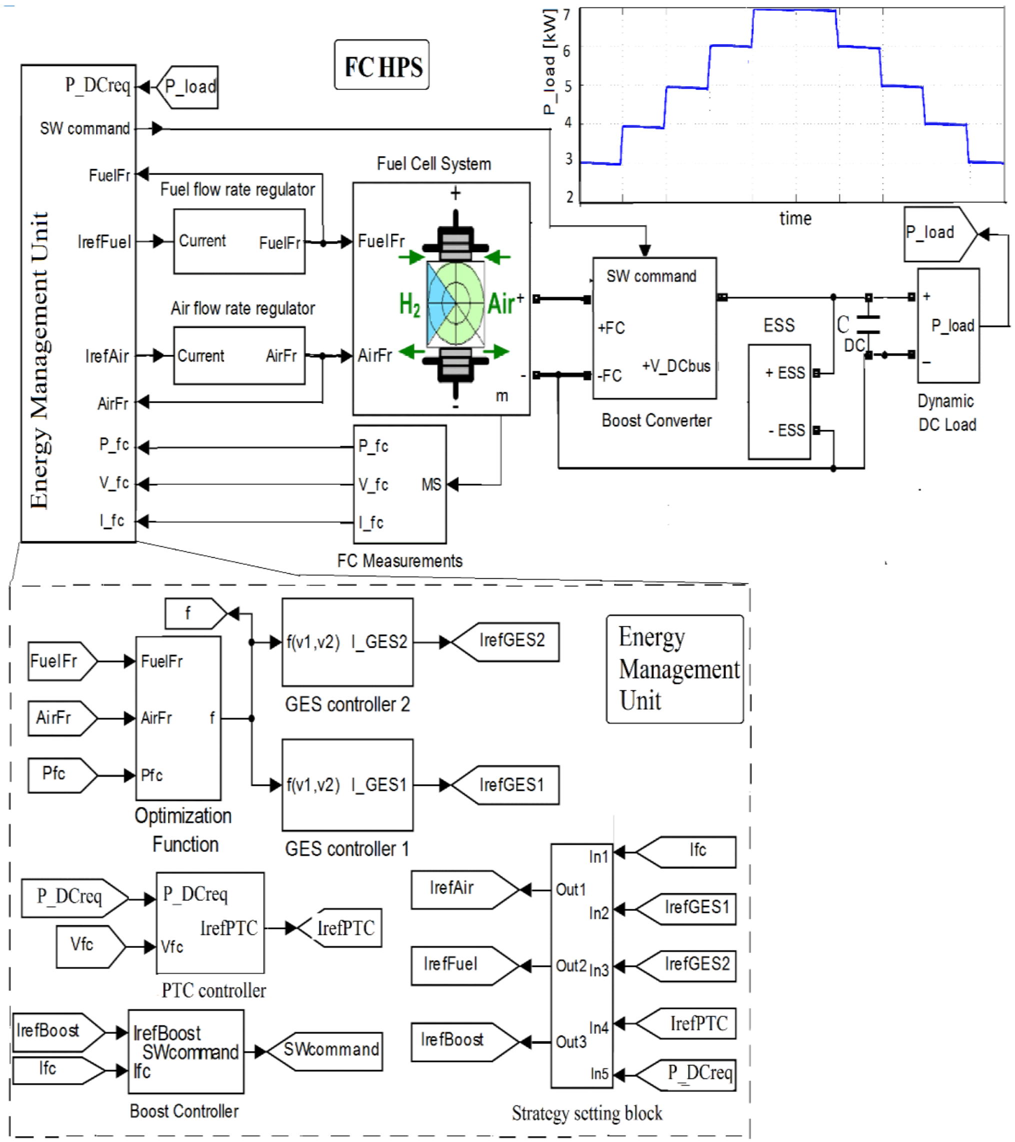
	$Fuel_{T(strategy)}^{Load}$ [liters]										
Strategy / P_{Load} $[kW]$	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	sFF
2	46.16	33.376	33.376	35.24	33.93	33.93	33.668	40.8	33.46	33.46	34.02
3	61.848	52.424	52.424	56.05	56.06	56.06	55.7	58.06	54.3	54.3	56.3
4	76.08	69.704	69.704	74.17	74.63	74.17	74	71.16	71.12	71.12	74.88
5	92.16	89.84	89.84	97.57	98.14	97.57	97.4	87.18	92.08	87.18	98.6
6	111.44	113.04	111.44	123.5	124	123.5	123.98	107.76	114.3	107.76	125.58
7	129.92	134.08	129.92	147.78	154.1	147.78	156.26	128.1	137.58	128.1	158.34
8	144.92	147	144.92	153.08	157.52	153.08	173.08	128.28	138.02	128.28	176

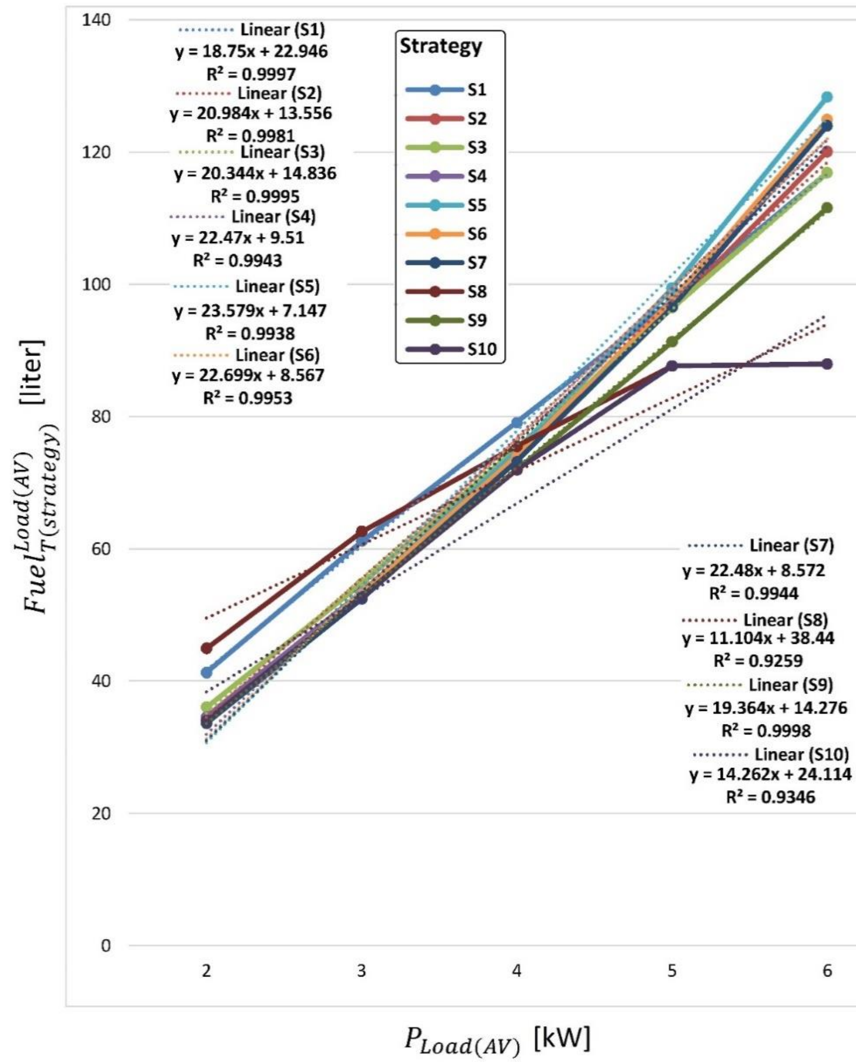
4. Advanced EMS for FCV



The total fuel consumption for the strategies S1-S10 under constant load

4. Advanced EMS for FCV

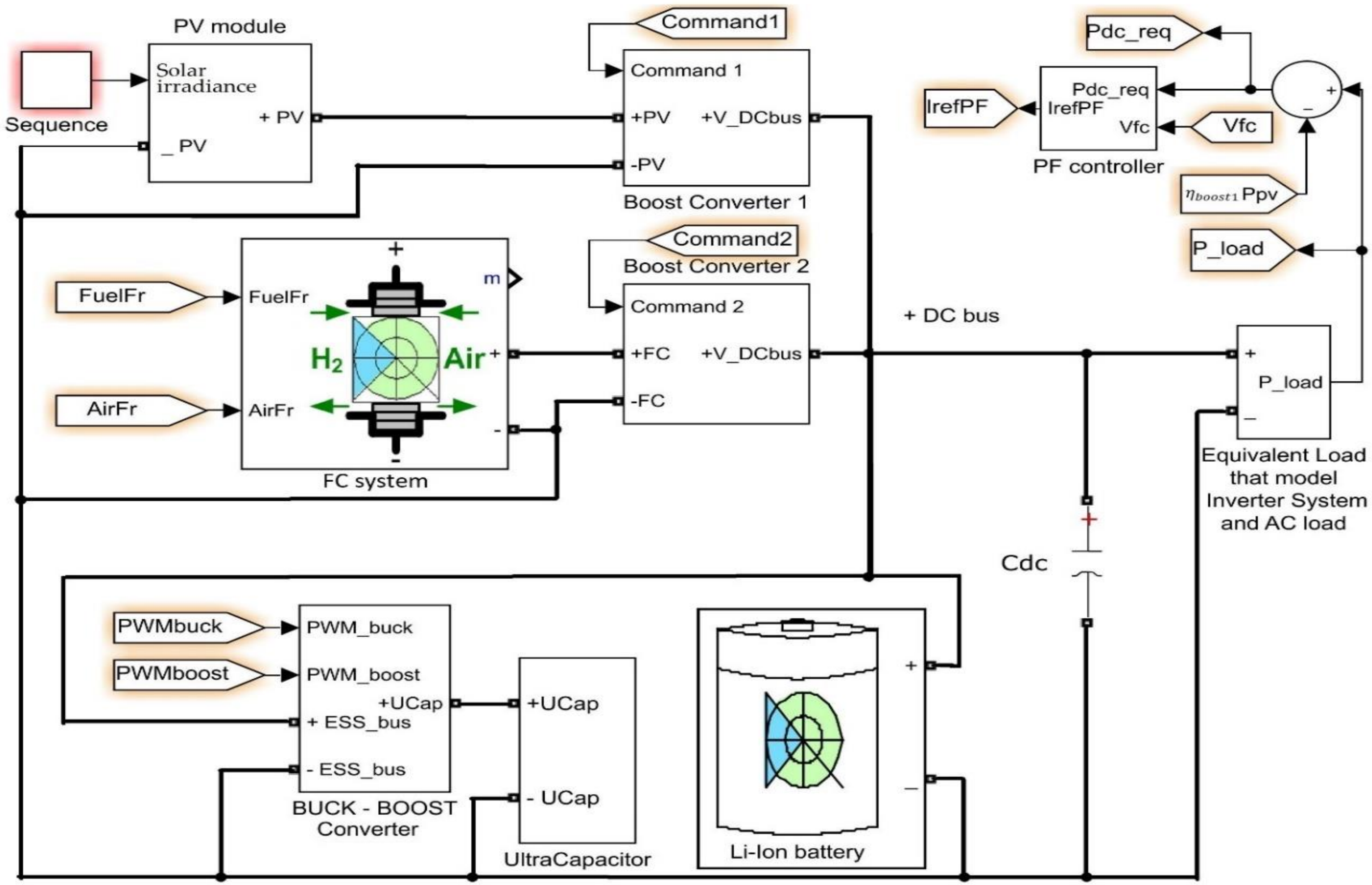




$\%Fuel_{T(S1)}$	$\%Fuel_{T(S2)}$	$\%Fuel_{T(S3)}$	$\%Fuel_{T(S4)}$	$\%Fuel_{T(S5)}$	$\%Fuel_{T(S6)}$	$\%Fuel_{T(S7)}$	$\%Fuel_{T(S8)}$	$\%Fuel_{T(S9)}$	$\%Fuel_{T(S10)}$
6.60	7.53	12.60	2.83	2.48	3.94	4.36	6.63	4.36	13.72

4. Advanced EMS for FCV

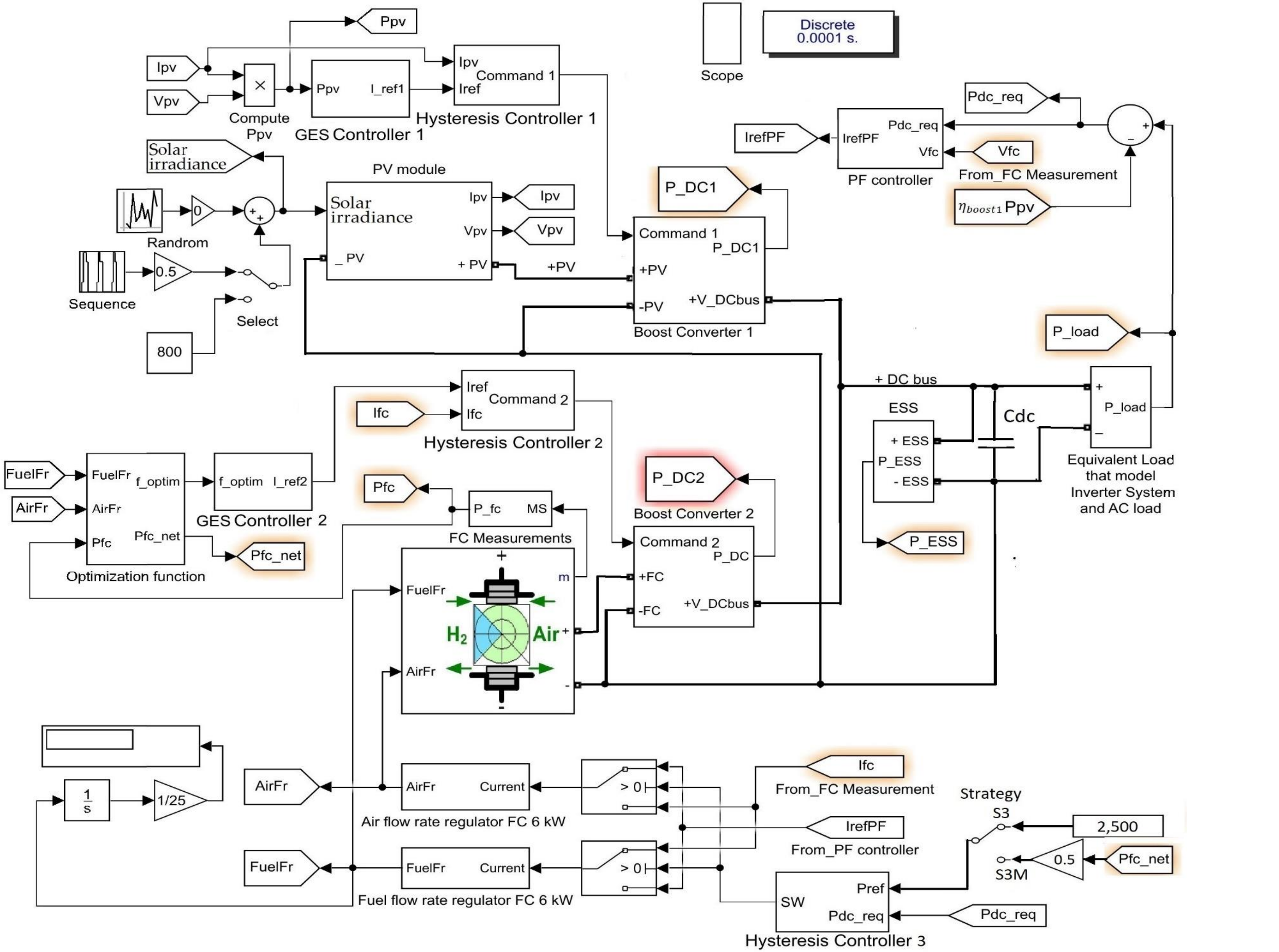
PV/FC/ESS hybrid power system for FCV



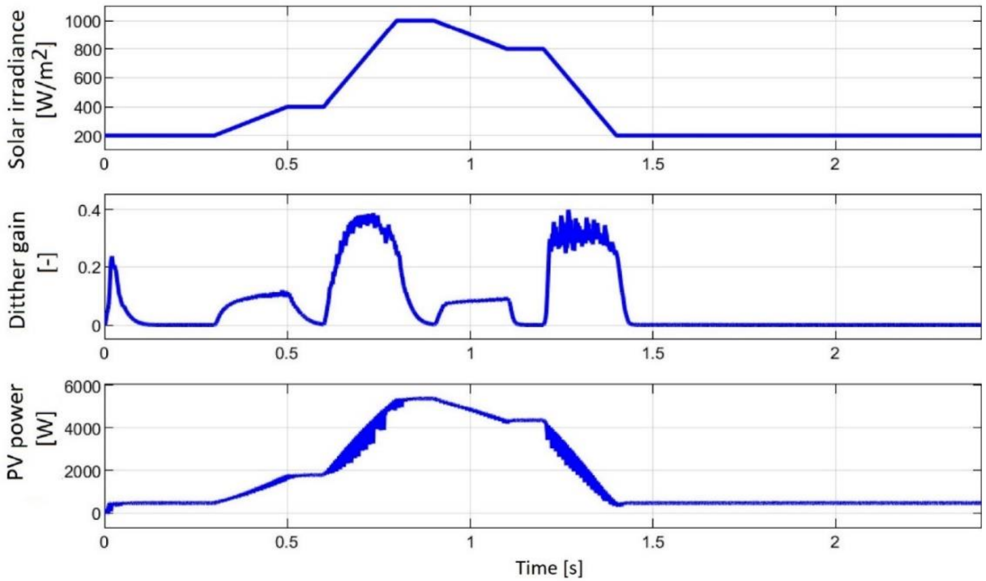
$$0 \cong \eta_{boost1} \cdot p_{PV} + \eta_{boost2} \cdot p_{FCnet} + p_{Batt} - p_{Load}$$

$$p_{FCnet} \cong \frac{\eta_{boost1} \cdot p_{PV} - p_{Load}}{\eta_{boost2}} = \frac{p_{DCreq}}{\eta_{boost2}} \qquad I_{ref(PF)} = \frac{\eta_{boost1} \cdot p_{PV(LPF)} - p_{Load(LPF)}}{\eta_{boost2} \cdot V_{FC(LPF)}}$$

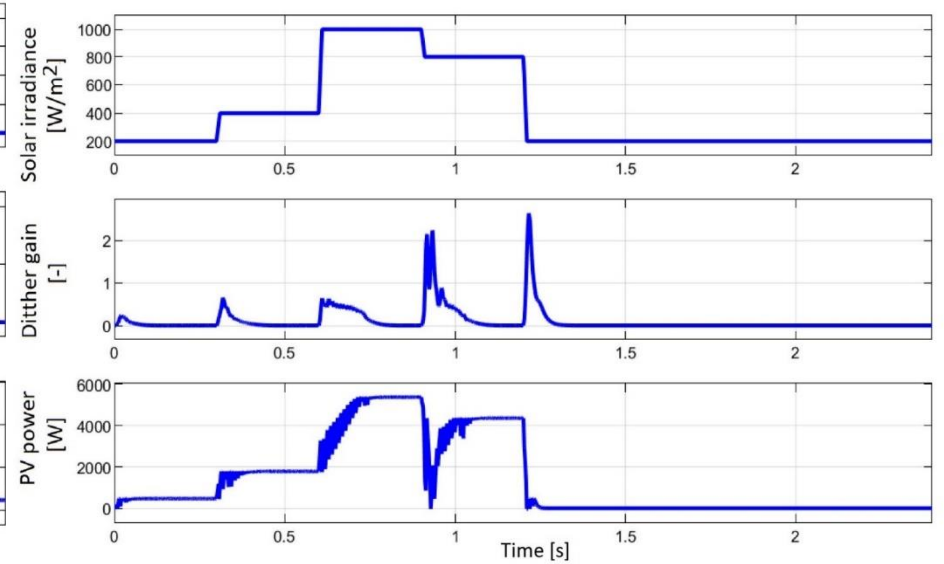
4. Advanced EMS for FCV



4. Advanced EMS for FCV

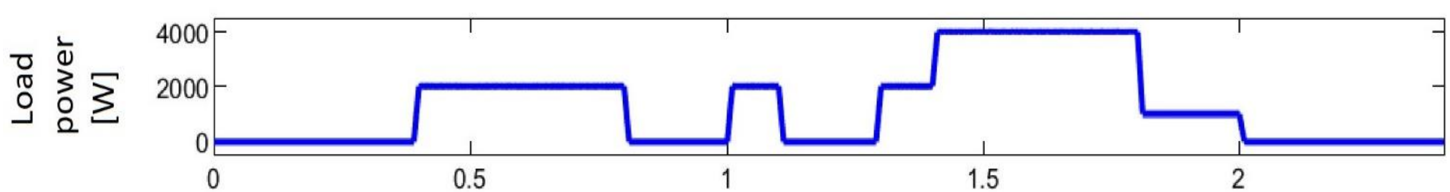


SIP1-Variable solar irradiance profile with slow slopes

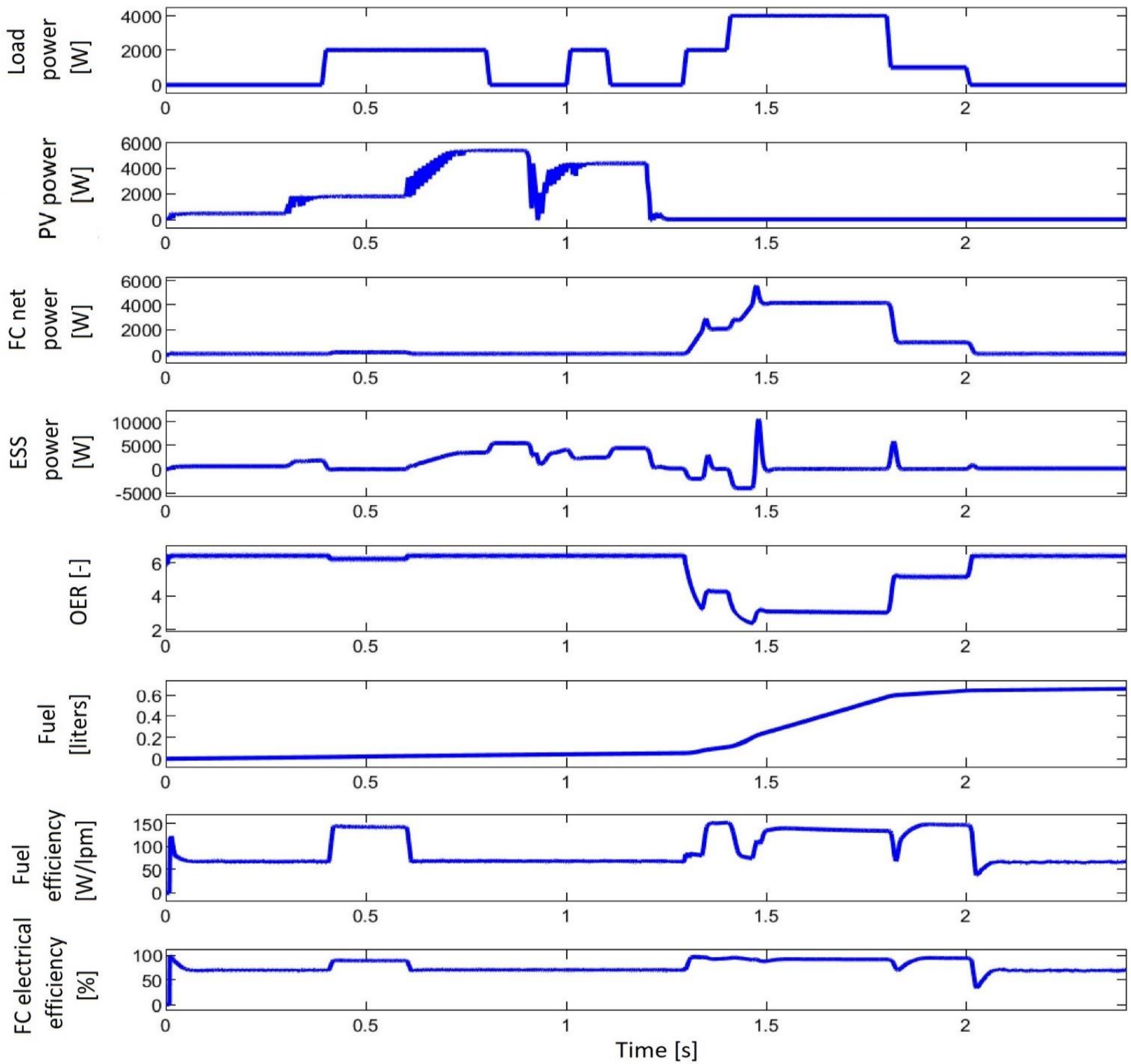


SIP1-Variable solar irradiance profile with high slopes

Scenario	SC1	SC2	SC3	SC4	SC5	SC6	SC7
Solar irradiance profile (SIP)	SIP1	SIP2	0.5 · SIP2	0.5 · SIP2	0.5 · SIP2	0.5 · SIP2	SIP2
Load demand profile (LDP)	LDP shown in next Figure	LDP	LDP	1.5 · LDP	2.0 · LDP	Constant load of 6 kW	2.0 · LDP



4. Advanced EMS for FCV



4. Advanced EMS for FCV

- The performance of the S3M strategy compared to the sFF and S3 strategies is demonstrated by the fuel economy obtained in different operating scenarios of the PV / FC / ESS hybrid power system;
- The percentage decrease in fuel consumption for the S3M strategy depends on the level of FC power generated (which is set by the profiles of the solar irradiance and load demand, considering the power flow balance on the DC bus and the proposed PF control), being in range 4.82 – 20.71 % and 1.64 – 3.34 % compared to strategies sFF and S3 respectively, under the scenarios considered in this study;

Total fuel consumption

	Scenario					
Strategy	**SC1**	**SC2**	**SC3**	**SC4**	**SC5**	**SC6**
sFF0	13.593	16.62	18.696	31.56	36.669	105.75
S3	13.227	15.225	17.4	25.675	31.225	102.325
S3M	12.785	14.825	17.05	25.025	30.325	100.65

Percentage decrease in fuel consumption

	Scenario					
Strategy	**SC1**	**SC2**	**SC3**	**SC4**	**SC5**	**SC6**
$\%Fuel_{(sFF-S3M)/sFF}$	5.94	10.80	8.80	20.71	17.30	4.82
$\%Fuel_{(S3-S3M)/S3}$	3.34	2.63	2.01	2.53	2.88	1.64

3. Conclusion

- The advantage of using an EMS based on LFW-control for a FC stack (used as a backup energy source in a hybrid power source for FCVs) is highlighted by the operation of the battery in charging mode, which leads to increased life by avoiding frequent charge-discharge cycles;

- All strategies based on LFW control operate the battery stack in charge-sustained mode with advantages related to its size and lifespan;

- The fuel optimization function and the innovative techniques for switching input references for fuel regulators ensure better fuel economy for these strategies compared to basic strategies based on LFW control;

- If the power reference used to switches the fueling references depends on the level of FC power generated, then the fuel economy increase for these modified strategies (S3M, S6M or S10M) compared to the switching strategies (S3, S6 or S10);

- The EMS based on LFW-control can be used for variable load cycle without or with support from another variable energy source (see the results for S3M strategy). Thus, the EMS based on power-following control may be easily adapted for a renewable-based hybrid power system using a FC stack as backup energy source.

Issues and challenges for FCV adoption

Infrastructure for H_2 stations

High cost of H_2 production

FC + B + UC control configuration is more complex to achieve

Low power density of the batteries

Low flexibility in controlling the power flow (FC + B topology)

Ways to improve energy management strategies for FCV

The latest reviews in field of FCVs' energy management strategy reveals that there are still some issues to be solved and others that must to be improved.

First, the performances of all EMSs are dependent by driving cycle. Therefore, the intelligent-based EMS that will include a driving cycle recognition or driving cycle prediction could be a viable solution to improve the FCV performance. Anyway, these recognition or prediction technologies will increase computation time and the intelligent-based EMSs will be difficult to be implemented as the real-time algorithms.
So, the EMS based on load-following technique could be an feasible alternative, making the ESS operation to be independent of the driving cycle.

Second, multi-objective EMSs (which integrate into a optimization function the fuel economy, the FC energy efficiency, the safety of FCV and comfort (drivability)) remain challenges for high-performance FCVs. Most of proposed EMSs only consider fuel economy of HEV, the FC energy efficiency or both, and few EMSs take into account the last two performance mentioned before as penalty terms in the optimization function.

Third, the compromise between system complexity, level of computation needed and optimization performance of EMSs continue to be an open issue.

Finally, every EMS has its own advantages and disadvantages. Thus, a standard to make an accurate and convincing assessment of EMS will be helpful in designing an appropriate EMS for FCV with specific performance objectives.

Thank you for your attention

Please send your questions

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