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Renewable/Fuel Cell Hybrid Power System Operation Using Two Search Controllers of the Optimal Power Needed on the DC Bus

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Abstract: In this paper, the optimal and safe operation of a hybrid power system based on a fuel cell system and renewable energy sources is analyzed. The needed DC power resulting from the power flow balance on the DC bus is ensured by the FC system via the air regulator or the fuel regulator controlled by the power-tracking control reference or both regulators using a switched mode of the above-mentioned reference. The optimal operation of a fuel cell system is ensured by a search for the maximum of multicriteria-based optimization functions focused on fuel economy under perturbation, such as variable renewable energy and dynamic load on the DC bus. Two search controllers based on the global extremum seeking scheme are involved in this search via the remaining fueling regulator and the boost DC–DC converter. Thus, the fuel economy strategies based on the control of the air regulator and the fuel regulator, respectively, on the control of both fueling regulators are analyzed in this study. The fuel savings compared to fuel consumed using the static feed-forward control are 6.63%, 4.36% and 13.72%, respectively, under dynamic load but without renewable power. With renewable power, the needed fuel cell power on the DC bus is lower, so the fuel cell system operates more efficiently. These percentages are increased to 7.28%, 4.94% and 14.97%.

Keywords: proton-exchange membrane fuel cell; fuel-saving; optimization; safe and healthy strategy; electrical energy efficiency

1. Introduction

With the rapid increase in electricity consumption and the depletion of fossil fuel reserves, additional demands have emerged in national electricity generation networks. To eliminate this disadvantage, the use of alternative energy sources that are sustainable and environmentally friendly is considered [1]. Currently, the most important sources of renewable energy are based on energy captured from the sun, wind and water, considered to be the most promising renewable energy technologies. However, the energy produced from renewable energy sources (RES) has an intermittent nature largely due to climatic conditions, and therefore, it is not a continuous source of electricity [2,3]. Nevertheless, if an extra surplus of electricity appears, to avoid any problems in managing this intermittent energy, it can be consumed by an electrolyzer to produce hydrogen, which can be further converted into electricity through a fuel cell when there is a need for surplus energy or renewable
energy is no longer available [4]. The proton exchange membrane fuel cell (PEMFC) can be used to manage the electrical load curve of the final consumers, offering in this way a proper option of balancing the frequency of the AC grid [5,6].

PEMFCs are devices that convert the chemical energy of hydrogen directly into electricity. This type of conversion is similar to the phenomenon that occurs in electrochemical batteries. The difference is that PEMFC is permanently supplied from the outside with fuels (hydrogen and oxygen) to generate electricity without interruption [7]. Normally, PEMFC is not capable of reversing the electrochemical process, as their basic function being to generate electrical power. There are special fuel cells that allow reversible operation. However, these are an exception [8,9]. The PEMFC transient response is strongly affected by the rate of the electrochemical reaction, especially from the cathode. Therefore, PEMFC is not the most appropriate choice in a stand-alone configuration, as it is not able to provide the power needed for fast load power transitions [10].

During applications on a real vehicle, the PEMFC stack is exposed mainly to four dynamic conditions, which have a significant impact on the durability and efficiency of the fuel cells: sudden load change (reactant starvation phenomenon and poor water management lead to the membrane drying and consequently to the loss of power of the PEMFC) [11–13], start–stop cycles [14–16] (lead to corrosion of the carbon support leading to platinum loss, irreversible damage), idle cycle [17–19] (the voltage at the cell level is in the range of 0.9 V and open-circuit voltage and may cause membrane dehydration and performance loss) and high power [19,20] (PEMFC efficiency is low, below 0.6 V voltage the components of the stack are rapidly degraded). The performance of PEMFCs used in the automotive sector is strongly dependent on their lifetime, with an impact on their commercialization. If the commercial requirement was established at 5000 h, in practice, it can only reach 2500–3000 h for automotive applications [21]. During automotive operation, the stoichiometry, temperature, humidity and voltage are strongly influenced by the electric current. Consequently, the Nafion membrane is subjected to the cyclic stress resulting from the repeated swelling and shrinkage of the membrane due to water sorption and desorption. For these reasons, the local pinholes can develop, which accelerates the rapid degradation of the membrane. The appearance of pinholes leads to an increase in the crossover of the reactants, and implicitly, the electrical contacts between MEA, GDL and bipolar plates are affected. Consequently, this leads to decreased open-circuit voltage (OCV), higher ohmic losses and, therefore, to a decreased fuel cell performance [22–24].

In addition, PEMFC degradation has been further investigated in many experimental works by finding novel solutions of platinum catalyst hybridization with other metals/nonmetals, taking into account certain drastic conditions for accelerated PEMFC degradation [25–30]. The results so far indicate that the decrease in performance during the frequent start–stop cycles was very severe [31]. Therefore, it is important to pay greater attention to developing system strategies to improve the sustainability of PEMFC, especially in start/stop cycles [32,33].

The ESS power needs to sustain the load for almost 2 s in order to increase the FC power from 10% to 90% and moreover to prevent the decrease in the FC lifetime [34]. Therefore, the PEMFC stack is hybridized with other power sources to suppress transient load regimes. Hybrid power systems (HPS) have a much better dynamic response while also contributing to the increased lifetime of PEMFC. Generally, PEMFC systems are used as a primary energy source, and peak power demand is usually provided from auxiliary energy storage sources (ESS). By coupling a high-energy-density source (PEMFC) and a high-power density source (an ultracapacitor (UC) is used in this study), the performance of hybrid power sources can be optimized [35].

Fuel cell technology is still very expensive; therefore, new solutions are being sought to reduce costs and, in particular, different control algorithms to increase PEMFC performance, taking into account the four dynamic operating conditions. Optimal control of the oxygen excess ratio (OER) must be implemented to avoid starvation based on the current produced by the stack. A reference value of the OER ratio is calculated through different control methods. In [36], a fuzzy control scheme successfully calculates airflow for different stack currents and temperatures. In [37], an adaptive
controller is used to adjust the air temperature at the cathode inlet to avoid dehydration and flooding while preventing starvation. Repeatedly starting and stopping a fuel cell during a driving cycle is a crucial operating sequence for MEA aging and which shortens the lifetime of the PEMFC. Eliminating this disadvantage can be solved quickly if the open-circuit voltage (OCV) of the PEMFC stack is brought to zero volts after the stack stops working. This is done using a shunt \[38,39\] or through limited voltage control \[19,40–42\]. In order to have the maximum FC efficiency and implicitly a low fuel consumption, the maximum efficiency point (MEP) on the efficiency curve of the PEMFC stack must be followed (usually, the current density is around 0.4 A/cm\(^2\)). When the fuel cell must operate at maximum power, the maximum power point (MPP) on the power curve must be followed (usually, the current density is around 1 A/cm\(^2\)). MPP and MEP are usually sought by implementing a tracker that controls the hydrogen and air regulator so that the efficiency or power of the PEMFC is maximized. Different approaches are used to control MPPT/MPET, which can be divided into perturb and observe algorithms \[43–45\], fuzzy logic control \[46–48\], sliding mode control \[49–51\], and extremum seeking control \[52–55\].

Rechargeable batteries (batteries) allow the conversion of both electrochemical energy into electricity and also electricity into electrochemical energy. The storage capacity and power at the battery terminals is dependent on their type. Depending on the application, the correct type of batteries will be chosen \[56\]. UCs are devices that store electricity in the form of an electric field. The operation of a UC versus a conventional capacitor differs by the transfer of ions into the dielectric material, which leads to a higher value of the specific capacitance. Even so, the energy density of a UC is much lower than for a battery; however, the power density of the UC is significantly higher \[57\]. By combining batteries, UCs and PEMFCs, an HPS with improved power flexibility can be achieved \[35,58\]. UCs can reduce transient regimes due to low impedance \[53,59\].

The interconnection topologies of hybrid power sources (HPS) and energy management strategies (EMS) are closely related to the specificity of the application. Meeting the energy consumption profile is a key objective that must be respected. For example, automotive applications have a random load profile due to accelerations/decelerations, where the speed of change of current and power is extremely high and sudden \[60\]. For example, the current consumed by the engine of a vehicle, in the acceleration phase, can reach up to 100 A/s \[61\]. In these specific applications, mainly, the current is limited by the reaction rate of the PEMFC; therefore, the transient response of the PEMFC is limited to such power demands \[62\]. Therefore, for automotive applications, UCs offer higher power density than batteries and are therefore usually preferred. Currently, the academic and industrial research focuses in particular on applications in the stationary and automotive fields, delimiting the aspects related to hydrogen storage \[63\]. The requirement to meet the power demand in stationary applications is not as pressing as in the automotive field. The interconnection topologies of HPS and EMS are designed to reduce costs, dimensions and hydrogen consumption. Academic and industrial research is currently focused on innovative algorithms and topologies to meet all conflicting requirements. Passive hybrid topologies are not justified to be implemented in high power applications due to their poor performance in terms of the lifecycle and reduced fuel consumption \[64\]. Therefore, only active hybrid topologies will be analyzed below. In the literature, several hybrid architectures are proposed. The innovative solutions of interconnection topologies are divided into three main classes: multilevel \[65\], common bus \[55\] and multi-input topologies \[66\]. Existing solutions differ mainly in the flexibility of design, complexity and cost reduction. Batteries and UCs are typically used as active storage elements \[67\].

In this paper, three fuel economy strategies based on the control of the air regulator and the fuel regulator, respectively, on the control of both fueling regulators were analyzed from the point of view of consumed hydrogen by an FC HPS without and with power from renewable energy sources (RES). The static feed-forward (sFF) control is used as a benchmark strategy under the same dynamic profiles of the load demand and renewable power (see Figure 1). All the strategies used in this work are safe, healthy and efficient strategies. The safety is given by the oxygen excess ratio (OER). The healthy is for the battery, which operates in sustained charging mode by using power-tracking control (PTC).
for the FC system. The efficiency of RES FC HPS is measured using performance indicators, such as the electrical energy efficiency and hydrogen consumption of the FC system. The optimization loops use two global extremum seeking (GES) schemes operating at different frequencies to maximize the multimodal optimization function that combines the performance indicators.

2. Materials and Methods

2.1. The Test Conditions

To fairly compare the sFF strategy with fuel economy strategies based on the control of the air regulator and the fuel regulator, respectively on the control of both fueling regulators (which will be called below as Air-PTC-2GES, Fuel-PTC-2GES and Air/Fuel-PTC-2GES), the same operating conditions must be used for RES FC HPS. Thus, the dynamic profiles of the load demand and renewable power are presented in Figure 1.

The load profile ($P_{\text{Load}}$) is of the scale type, with levels of 1 kW, up and down, changed every 2 s, as it is shown in the first plot of Figure 1. The renewable energy profile ($P_{\text{RES}}$) with an average value of about 2.2 kW is based on a variable profile that is spread by adding a random power with a peak of 1 kW (see the second plot of Figure 1).

2.2. The Architecture of the Hybrid Power System

The main blocks of the RES FC HPS and its energy management unit (EMU) are shown in Figure 2. A hybrid power source (HPS), fed by renewable energy sources (RESs) and fuel cell (FC) sources, with an energy storage systems (ESS—batteries and ultracapacitors stacks), equivalent load (AC and DC loads), DC–DC boost converter for FC, bidirectional buck–boost converter for battery and EMU (containing two GES controllers, the GES controller 1 and the GES controller 2, which are referred to below as GES1 and GES2) is developed. A 6 kW FC system with the slope limits of 100 A s$^{-1}$ for the fuel regulators and 0.2 s time constant was employed as a backup energy source. The battery/ultracapacitor
A hybrid power source (HPS), fed by renewable energy sources (RESs) and fuel cell (FC) sources, with an energy storage systems (ESS—batteries and ultracapacitors stacks), equivalent load (AC and DC loads), DC–DC boost converter for FC, bidirectional buck–boost converter for battery and EMU (containing two GES controllers, the GES controller 1 and the GES controller 2, which are referred to below as GES1 and GES2) is developed. A 6 kW FC system with the slope limits of 100 A s$^{-1}$ for the fuel regulators and 0.2 s time constant was employed as a backup energy source. The battery/ultracapacitor hybrid ESS operates as an auxiliary source for supplying the power deficit considering the dynamic power balance strategy. The power flow balance is sustained by 100 Ah battery/100 F ultracapacitors energy storage system (ESS) using a semi-active ESS topology having the battery on 200 V DC bus and the ultracapacitors via a bidirectional DC–DC buck–boost converter.

### 2.3. Design of the Power-Tracking Control (PTC)

The power flow balance on the DC bus is given by (1):

$$C_{DC}\frac{du_{DC}}{dt} = p_{DC} + p_{RES} + p_{ESS} - p_{Load}$$

where $C_{DC}$ is the 10,000 µF capacitor that filters the DC voltage $u_{DC}$, $p_{DC}$ = $\eta_{boost}p_{FCnet}$ is the power generated by the FC system on the DC bus, $p_{FCnet}$ is the FC net power, $\eta_{boost}$ is the efficiency of the DC–DC boost converter, $p_{RES}$ is RES power, $p_{ESS}$ is ESS power exchanged to compensate the power flow balance (1) and $p_{Load}$ is load demand.

If $p_{DC} = \eta_{boost}p_{FCnet} = p_{DCreq} = p_{Load} - p_{RES}$, then, considering the mean value of (1), will result (2):

$$P_{ESS(MV)} \approx 0 \Rightarrow P_{Batt(MV)} \approx 0$$

where subscript MV represents the mean value of the power during a load cycle. Thus, the battery will be operated in charge-sustained mode, which increases its lifetime and reduces the maintenance...
costs [68,69]. The ultracapacitors will dynamically sustain the power flow balance (1) through control of the bidirectional DC–DC buck-boost converter based on the DC voltage regulation loop.

Thus, considering MV of (1) and (2), FC net power requested on the DC bus is given by (3):

$$P_{\text{FCnet}} = P_{\text{DCref}(\text{MV})}/\eta_{\text{boost}} = (P_{\text{Load}(\text{MV})} - P_{\text{RES}(\text{MV})})/\eta_{\text{boost}}$$

(3)

The FC power that is generated on the DC bus is the FC net power ($P_{\text{FCnet}}$):

$$V_{\text{fc}}I_{\text{fc}} = P_{\text{FCnet}} \equiv P_{\text{FC}} - P_{\text{cm}},$$

(4)

where $P_{\text{FC}}$ and $P_{\text{cm}}$ are the FC stack power and the power losses of the air compressor, and $V_{\text{fc}}$ and $I_{\text{fc}}$ are the voltage and the current of the FC stack.

The compressor power losses can be modeled by (5) in series with a 2nd order dynamic system having 100 Hz natural frequency and 0.7 damping ratio [70,71]:

$$P_{\text{cm}} = I_{\text{cm}}V_{\text{cm}} = (a_2 \cdot \text{AirFr}^2 + a_1 \cdot \text{AirFr} + a_0)(b_1I_{\text{fc}} + b_0)$$

(5)

where $a_0 = 0.6$, $a_1 = 0.04$, $a_2 = -0.00003231$, $b_0 = 0.9987$ and $b_1 = 46.02$.

Considering (3) and (4), the power-tracking control (PTC) will be implemented using the $I_{\text{ref(PTC)}}$ reference given by (6):

$$I_{\text{ref(PTC)}} = (P_{\text{Load}(\text{MV})} - P_{\text{RES}(\text{MV})})/(V_{\text{fc}(\text{MV})}/\eta_{\text{boost}}) \equiv I_{\text{FC}}$$

(6)

### 2.4. The Fuel Economy Strategies

The fuel economy strategy is based on the optimization function (9) and the global extremum seeking (GES) controller that search and track in real time the optimum of (7):

$$f(x, \text{AirFr, FuelFr, P_{Load, P_{RES}}}) = 0.5 \cdot P_{\text{FCnet}} + k_{\text{fuel}} \cdot \text{Fuel_{eff}}$$

(7)

where $\text{Fuel_{eff}} \equiv P_{\text{FCnet}} / \text{FuelFr}$ measures the fuel consumption efficiency, $x$ represents the vector of FC state variables [52,55,72–75], and GES variables are the airflow rate ($\text{AirFr}$) and the fuel flow rate ($\text{FuelFr}$) given by (8) and (9) [72,76]:

The fueling flow rates for fuel ($\text{FuelFr}$) and air ($\text{AirFr}$) are as follows:

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

(8)

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

(9)

and $N_C, \theta, F_{\text{f(O2)}}, U_{f(O2)}, F_{\text{f(H2)}}, U_{f(H2)}$, and $x_{H2}, y_{O2}$ are default parameters [73,77].

It is worth mentioning that $k_{\text{fuel}}$ can be set at zero to maximize $P_{\text{FCnet}}$ [43] or at 25 [lpm/W] (the optimal value of this parameter was obtained by a sensitivity analysis) to reduce the hydrogen consumption, total fuel consumption defined by $\text{Fuel} = \int \text{FuelFr}(t) \, dt$ [78,79]. The last setting is used in this study.

Two GES controllers will generate the references $I_{\text{ref(GES1)}}$ and $I_{\text{ref(GES2)}}$ by tracking the maximum of the optimization function (7) under disturbances, such as load and renewable power, with the profiles shown in Figure 1. PTC-2GES based fuel economy strategies called Air-PTC-2GES, Fuel-PTC-2GES and Air/Fuel-PTC-2GES can be implemented through the strategy settings block as it is presented in
Figure 3, which will select the input references $I_{\text{ref}}(\text{PTC}), I_{\text{ref}}(\text{GES}1)$ and $I_{\text{ref}}(\text{GES}2)$ to the output references $I_{\text{ref}}(\text{Boost}), I_{\text{ref}}(\text{Air})$ or $I_{\text{ref}}(\text{Fuel})$ as determined by (10a), (10b) and (10c), respectively:

\begin{align*}
I_{\text{ref}}(\text{Fuel}) &= I_{\text{FC}} + I_{\text{ref}}(\text{GES}2), & I_{\text{ref}}(\text{Air}) &= I_{\text{ref}}(\text{PTC}), I_{\text{ref}}(\text{boost}) &= I_{\text{ref}}(\text{GES}1) \\
(10a) \\
I_{\text{ref}}(\text{Air}) &= I_{\text{FC}} + I_{\text{ref}}(\text{GES}2), & I_{\text{ref}}(\text{Fuel}) &= I_{\text{ref}}(\text{PTC}), I_{\text{ref}}(\text{boost}) &= I_{\text{ref}}(\text{GES}1) \\
(10b) \\
I_{\text{ref}}(\text{Fuel}) &= \begin{cases} 
I_{\text{ref}}(\text{PTC}), & \text{if } P_{\text{DCreq}} \leq P_{\text{ref}} \\
I_{\text{FC}} + I_{\text{ref}}(\text{GES}2), & \text{if } P_{\text{DCreq}} > P_{\text{ref}}
\end{cases} \\
(10c)
\end{align*}
threshold $P_{ref}$. In the strategies Air-PTC-2GES and Fuel-PTC-2GES, $I_{ref(PTC)}$ reference is the input of the air regulator or the fuel regulator, respectively.

If $P_{DCreq} = P_{Load} - P_{RES} < 0$, then $P_{RES} - P_{Load} > 0$, so an electrolyzed can be supplied with this excess power to produce hydrogen.

The diagram of RES FC HPS using the strategies Air-PTC-2GES, Fuel-PTC-2GES and Air/Fuel-PTC-2GES is shown in Figure 3. Parameter $k_{RES}$ sets the operation of HPS without and with renewable power (for example, $k_{RES} = 0$ $\Rightarrow$ $P_{RES} = 0$).

The operation of the RES FC HPS using the aforementioned strategies is compared with the static feed-forward (sFF) strategy using the setting given by (11) [74]:

$$I_{ref(Fuel)} = I_{FC}, I_{ref(Air)} = I_{FC}, I_{ref(boost)} = I_{ref(PTC)}$$

(11)

2.5. The Global Extremum Seeking (GES) Controller

Both GES controllers have the scheme shown in Figure 4. The signal processing relationships 12a–f are determined by the blocks presented in Figure 4:

$$y = f(AirFr, FuelFr) = 0.5P_{FChet} + k_{fuel}\cdot Fuel_{eff}, y_N = k_{Ny}y$$

(12a)

$$y_f = -\omega_1y_f + \omega_2y_N, y_{HPF} = y_N - y_f, y_{BPF} = -\omega_1y_{BPF} + \omega_2y_{HPF}$$

(12b)

$$\omega_1 = b_1\omega_t, \omega_2 = b_2\omega_t, s_d = \sin(\omega t), \omega = 2\pi f_d, \omega_{\text{HPF}} = 50 \text{ Hz} \text{ and } \omega_{\text{BPF}} = 100 \text{ Hz}$$

(12c)

$$y_{DM} = y_{BPF}\cdot s_d\cdot y_{\text{Gradient}} = y_{DM}\cdot p_1 = k_1y_{\text{Gradient}}$$

(12d)

$$y_{M} = \frac{1}{T_d}\int y_{BPF}dt, p_2 = k_2y_{M}\cdot s_d$$

(12e)

$$I_{ref(GES)} = k_{Ny}(p_1 + p_2)$$

(12f)

**Figure 4. GES controller.**

The design and analysis of GHG control are detailed in the references [43,76–78]. In this paper, is made only a brief presentation of the variables and parameters used. The input of the GES controller, which is the optimization function $f$, is normalized using $k_{Ny} = 1/1000$. The first harmonic of the $y_N$ signal is demodulated with different sinusoidal dithers, $s_{d1} = \sin(\omega_1 t)$ and $s_{d2} = \sin(\omega_2 t)$, and integrated to obtain the search gradient ($y_{\text{Gradient}}$), where $\omega = 2\pi f_d$ and $f_d = 50$ Hz and $f_d = 100$ Hz for the controllers GES1 and GES2, respectively. The $y_{M}$ signal, which modulates the dithers, is an approximation of the first harmonic of the $y_N$ signal (which is obtained using a band-pass filter and a mean value (MV) block to further smooth the signal). The cut-off frequencies of the band-pass filter are $\omega_1 = b_1\omega_t$ and $\omega_2 = b_2\omega_t$, where $\beta_1 = 1.5$ and $\beta_2 = 0.1$. The search and location signals ($p_1$ and $p_2$) are tuned using $k_1$ and $k_2$ to speed up tracking of the optimum. In this study, $k_1 = 1$ and $k_2 = 2$ for both GES controllers. The signals $p_1$ and $p_2$ are summed and normalized using $k_{Ny} = 20$. The limits of the
saturation block are defined specifically for an FC system. Note the very good tracking accuracy of 99.9% [73] and negligible ripple of FC power during stationary regimes [72].

2.6. The Performance and Health Indicators

The oxygen excess ratio (OER) given by (13) is a health indicator of the safe functioning of the FC system [79]:

\[
OER = \frac{c_3 I_{FC}^3 + c_2 I_{FC}^2 + c_1 I_{FC} + c_0}{d_1 I_{FC} + d_0}
\] (13)

where:

\[c_0 = 402.6, \quad c_1 = 8.476 \times 10^{-5} [1/A], \quad c_2 = -0.81252 [1/A^2], \quad c_3 = 0.02673 [1/A^3], \quad d_0 = 0.997 \quad \text{and} \quad d_1 = 61.38.
\]

OER can be controlled [70,79], but in this paper, OER is only monitored to see if the analyzed strategies are safe and healthy for the FC system.

The performance indicators usually used for the FC system are the total fuel consumption \( (Fuel_T) \), the fuel consumption efficiency \( (\text{Fuel}_{\text{eff}} = P_{FC_{\text{net}}} / Fuel_Fr) \) and the electrical efficiency of the FC system \( (\eta_{sys} = P_{FC_{\text{net}}} / P_{FC}) \).  

3. Results

The hydrogen consumption is measured in liters [l] and computed using (14):

\[
Fuel_T = \int_0^t Fuel_Fr(\tau) d\tau
\] (14)

If the hydrogen consumption is measured in liters per minute [lpm], then a gain of 1/3 (=20 s/60 s) is necessary to be used because the load cycle used has 20 s, not one minute (see the Gain Fuel_T and Fuel_T display in Figure 4).

Furthermore, note the use in the simulation of 100 A/s slope for the fueling regulators of 6 kW FC system, time constants of 0.2 s and 20 s for FC system and 100 Ah battery, respectively, and hysteresis of 0.1 A and 1 V of the controllers used for the boost DC–DC converter and the buck–boost DC–DC bidirectional converter.

The performance of the analyzed strategies, Air/Fuel-PTC-2GES, Air-PTC-2GES and Fuel-PTC-2GES, will be highlighted compared to the reference standard strategy based on SFF control for HPS with and without the support of renewable energy.

3.1. Hydrogen Consumption

3.1.1. Behavior of FC HPS Operating without Power from Renewable Energy Sources \( (k_{RES} = 0) \)

The operation of the FC HPS using the strategies sFF, Air-PTC-2GES, Fuel-PTC-2GES and Air/Fuel-PTC-2GES is presented in Figures 5–8, respectively, considering the load demand shown in the first plot of Figure 1.

The reference elements from the study (FC HPS operation) are presented schematically in Figures 5–8, in the form of plots (waveforms). The last three plots present the performance indicators \( (Fuel_T, \text{Fuel}_{\text{eff}} = P_{FC_{\text{net}}} / Fuel_Fr \) and \( \eta_{sys} = P_{FC_{\text{net}}} / P_{FC}) \), but for variable loads, hydrogen consumption is the only indicator that can give us a measure of performance. It can be easily seen that the hydrogen consumption (represented in Figure 5) changes partially, in the sense of improvement that depends on the control strategies used (see Figures 6–8). Therefore, the application of the proposed strategies can be beneficial in all cases.
Figure 5. FC HPS operation using the static feed-forward (sFF) strategy.

Figure 6. FC HPS operation using the Air-PTC-2GES strategy.
Figure 7. FC HPS operation using the Fuel-PTC-2GES strategy.

Figure 8. FC HPS operation using the Air/Fuel-PTC-2GES strategy.
Hydrogen consumption for all strategies is registered in Table 1. The hydrogen economy, compared to the sFF benchmark, is presented in Table 2 using (15) and $k_{RES} = 0$:

$$\%\text{Fuel}_{T(Air-Fuel-PTC-2GES)}^{RES} = 100 \cdot \frac{\text{Fuel}_{T(sFF)}^{k,RES} - \text{Fuel}_{T(Air-Fuel-PTC-2GES)}^{k,RES}}{\text{Fuel}_{T(sFF)}^{k,RES}}$$  \hspace{2cm} (15a)$$

$$\%\text{Fuel}_{T(Fuel-Fuel-PTC-2GES)}^{RES} = 100 \cdot \frac{\text{Fuel}_{T(sFF)}^{k,RES} - \text{Fuel}_{T(Fuel-PTC-2GES)}^{k,RES}}{\text{Fuel}_{T(sFF)}^{k,RES}}$$  \hspace{2cm} (15b)$$

$$\%\text{Fuel}_{T(Air/Fuel-PTC-2GES)}^{RES} = 100 \cdot \frac{\text{Fuel}_{T(sFF)}^{k,RES} - \text{Fuel}_{T(Air/Fuel-PTC-2GES)}^{k,RES}}{\text{Fuel}_{T(sFF)}^{k,RES}}$$  \hspace{2cm} (15c)$$

### Table 1. Hydrogen consumption of the analyzed strategies and sFF benchmark for $k_{RES} = 0$.  

| $\text{Fuel}_{T(sFF)}$ | $\text{Fuel}_{T(Air-PTC-2GES)}$ | $\text{Fuel}_{T(Fuel-PTC-2GES)}$ | $\text{Fuel}_{T(Air/Fuel-PTC-2GES)}$ |
|------------------------|-------------------------------|-------------------------------|-------------------------------|
| [liters]               | [liters]                      | [liters]                      | [liters]                      |
| 286.5                  | 267.5                         | 274.0                         | 247.2                         |

### Table 2. Hydrogen economy of the analyzed strategies compared to the sFF benchmark.  

| $\%\text{Fuel}_{T(Air-PTC-2GES)}^{RES}$ | $\%\text{Fuel}_{T(Fuel-PTC-2GES)}^{RES}$ | $\%\text{Fuel}_{T(Air/Fuel-PTC-2GES)}^{RES}$ |
|--------------------------------------|----------------------------------------|----------------------------------------|
| [%]                                 | [%]                                    | [%]                                    |
| 6.63                                 | 4.36                                   | 13.72                                  |

Variation of ESS power is around zero (see plot 3 in all Figures 5–8), confirming the operation of the battery in charge-sustaining mode.

The shape of the load demand is followed by both the AirFr and FuelFr in sFF strategy, by AirFr and FuelFr in the strategies Air-PTC-2GES and Fuel-PTC-2GES, respectively, and by FuelFr and then by AirFr in Air/Fuel-PTC-2GES strategy (see plots 4 and 5 in Figures 5–8, respectively).

Hydrogen consumption using the same strategies will be evaluated in the next section for FC HPS operating with power from renewable energy sources.

### 3.1.2. Behavior of FC HPS Operating with Power from Renewable Energy Sources ($k_{RES} \neq 0$)

The operation of the RES FC HPS using the strategies sFF, Air-PTC-2GES, Fuel-PTC-2GES and Air/Fuel-PTC-2GES is presented in Figures 9–12, respectively, considering the RES power shown in the second plot of Figures 1 and 9–12 as well).

The plots of Figures 9–12 represent the same waveforms as those in Figures 5–8, except for adding the waveform of RES power in the 2nd plot. Hence, the new structure of the plots is as follows: 1st plot and 2nd plot present the load demand and renewable power; 3rd plot—OER; 4th plot—ESS power; 5th and 6th plots—AirFr and FuelFr; 7th plot—FuelFr; 8th plot and 9th plot present the aforementioned performance indicators, Fuel$_{eff}$ and $\eta_{sys}$.

The fuel consumption under the analyzed strategies and sFF benchmark is registered in Table 3 for $k_{RES} = 1$ ($P_{RES}$ is shown in Figure 1). The fuel economy of these strategies compared to the sFF benchmark is presented in Table 4 using (15).

If $P_{RES} > P_{Load}$, then, the excess of power ($P_{RES} - P_{Load} > 0$) can be used to produce hydrogen using an electrolyzer. In addition, the FC system must operate in standby mode (with FC power about 100 W) to avoid the start/stop mode of operation. The values of Fuel$_{eff}$ and $\eta_{sys}$ are lower during FC standby mode (see the last two plots).
Figure 9. RES FC HPS operation using the sFF strategy.

Figure 10. RES FC HPS operation using the Air-PTC-2GES strategy.
Figure 11. RES FC HPS operation using the Fuel-PTC-2GES strategy.

Figure 12. RES FC HPS operation using the Air/Fuel-PTC-2GES strategy.
### Table 3. Fuel consumption of the analyzed strategies and sFF benchmark for $k_{RES} = 1$

| Fuel$_{RES}$$_{T_{(sFF)}}$ | Fuel$_{RES}$$_{T_{(Air\text{-}PTC\text{-}2GES)}}$ | Fuel$_{RES}$$_{T_{(Fuel\text{-}PTC\text{-}2GES)}}$ | Fuel$_{RES}$$_{T_{(Air\text{/}Fuel\text{-}PTC\text{-}2GES)}}$ |
|-----------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| [liters]                    | [liters]                                        | [liters]                                        | [liters]                                        |
| 123.6                       | 114.6                                          | 117.5                                          | 105.1                                          |

### Table 4. Fuel economy of the analyzed strategies compared to the sFF benchmark.

| %Fuel$_{RES}$$_{T_{(Air\text{-}PTC\text{-}2GES)}}$ | %Fuel$_{RES}$$_{T_{(Fuel\text{-}PTC\text{-}2GES)}}$ | %Fuel$_{RES}$$_{T_{(Air\text{/}Fuel\text{-}PTC\text{-}2GES)}}$ |
|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| [%]                                             | [%]                                             | [%]                                             |
| 7.28                                            | 4.94                                            | 14.97                                           |

### 3.2. FC Net Power and Electrical Efficiency

#### 3.2.1. FC HPS

The range of variation of FC electrical efficiency, $\eta_{sys} = P_{FC_{net}} / P_{FC}$, is from 84% to 93% (see plot 8 in Figures 5–8). The FC electrical efficiency decreases with the increase of the power density due to the high flow rates of the reactants. In practice, the flow rates of reactants with which FC is fed at the inlet are not fully consumed [75]. Figure 13 shows the fuel cell net power values taking into account the auxiliary power consumption of the BoP for all three control strategies compared to the sFF benchmark. It is observed that for lower load values, the FC system provides more power when the fuel/air regulators are controlled by the Air-PTC-2GES strategy and, while the loading power increases, the FC power decreases suddenly. This is explained by the fact that when the FC operates at low loads, it needs more airflow to increase the humidity of the membrane. Then, as the power load increases, the FC itself produces an increasing amount of water, which causes flooding in the canals and, therefore, a low efficiency. Increased values of the FC net power are obtained by the Air/Fuel-PTC-2GES strategy, especially for high loads. Although the value of $k_{fuel}$ was set to 25 in the optimization function (7) to minimize fuel consumption, in Figure 13, it can be seen that the FC net power is higher than the value controlled by the sFF strategy. The Air/Fuel-PTC-2GES strategy uses a power threshold (5.5 kW) through which the Air-PTC-2GES and Fuel-PTC-2GES strategies are switched, benefiting from their advantages. Thus, for high load, the air regulator is regulated by the PTC controller, which controls the OER value below 2.5, from where the low energy consumption of the air compressor and an adequate membrane humidity level for high currents are obtained.

#### 3.2.2. RES FC HPS

The variation of the FC net power supplied on the DC bus of RES FC HPS (see Figure 14) is from 100 W to 6 kW, corresponding to the standby and nominal operating modes. Lower values of FC electrical efficiency, $\eta_{sys} = P_{FC_{net}} / P_{FC}$, appear for RES FC HPS during the standby operating mode (see plot 9 in Figures 9–13). During applications of an FC-HPS combined with RES, the FC system is exposed to many issues caused by rapid power transitions, which have a negative impact on the durability and efficiency of the FC system. One of the issues is the sudden change of load correlated with the intermittent power of RES, which can lead to the starvation phenomenon of reactants and poor water management inside the FC system, which leads to drying/flooding of the membranes and, consequently, to low efficiency. Another issue is the avoidance of the start–stop cycles of the FC system (where irreversible damage occurs due to the loss of platinum) and of the FC operation without load (which causes dehydration of the membrane). All these issues are successfully avoided by the Air/Fuel-PTC-2GES strategy, which limits the current produced by the FC system to 100 A/s for the avoidance of the starvation phenomena; controls the OER rapport between 2.3 and 7 to adjust the optimal amount of water inside the FC (even if in certain situations this is done to the detriment of...
efficiency, especially at low loads) and sets the minimum operating the voltage threshold of the FC to avoid OCV and the excess power is converted into hydrogen by electrolysis.

Figure 13. FC net power supplied on the DC bus of FC HPS.

Figure 14. FC net power supplied on the DC bus of RES FC HPS.
3.3. Oxygen Excess Ratio

3.3.1. FC HPS

The OER variation is monitored for all strategies and shown in Figure 15.

![Figure 15. Oxygen excess ratio for FC HPS.](image)

Note that the OER range is within the safe limits of FC operation, from about 2.3 to 3.6 for any load demand profile [36,75,76]. The excess oxygen ratio (OER) is expressed as the ratio between the oxygen flow consumed in the electrochemical reaction of the stack and the oxygen flow generated by the air compressor at the cathodic input of the stack [69]. The reference value must be OER ≥ 2 to prevent oxygen starvation [75]. An OER excess leads to an increase in the partial pressure of oxygen, and thus the power performance is improved; however, after the optimal values of pressure and hydration level are reached, further increases of OER cause an increase in the power consumption consumed by the air compressor degrading the electrical efficiency of the system. At lower power densities of the stack, there is a possibility of a flooding effect, with the water formed inside possibly blocking the oxygen flow channels and leading to sudden drops in voltage. This critical problem can be overcome if OER is higher than 2, which is visible in Figure 15. At high power densities of the stack, the flooding effect is overcome through the significant increase of the stack temperature [80]. Figure 15 shows that the oxygen excess ratio follows the load profile in Figure 1. The proposed Air/Fuel-PTC-2GES strategy is the most optimal because the stack responds to changes in levels as flat as possible. For example, Figure 13 shows that at the 6000–7000 W power level, the proposed Air/Fuel-PTC-2GES strategy controls the FC power much easier than the SFF strategy, hence an increase in operational safety, while simultaneously showing a higher net FC power, especially downhill, therefore an increase in electrical efficiency can be obtained.
3.3.2. RES FC HPS

OER range is still within the safe limits of FC operation, from 2.3 to less than 7 for any load demand and renewable power profiles (see Figure 16). The upper value is higher because FC net power supplied on the DC bus starts from about 100 W and 3900 W for RES FC HPS (see Figure 14) and FC HPS (see Figure 13), respectively. Analyzing the data from plot 9 (electrical efficiency) in Figures 9–12, it is observed that the Air/Fuel PTC-2GS strategy ensures the highest electrical efficiency. This strategy provides a fast response for regulating reactant gas flows during fast power transitions. Insufficient oxidant supply of the PEMFC and obstruction of the gas channels due to flooding with liquid water are the main causes of cell voltage reversal [57]. During the experiments, the cell voltage reversal can be detected by monitoring the voltages on each cell and by setting an alarm threshold for the monitored voltage so that the algorithm can adjust the operating parameters to avoid reversing the cell voltage.

To avoid the repeated PEMFC on/off cycles at low power, known as cycles that have a significant impact on damaging the Pt catalyst and on the protection of the battery from overcharging, the PTC controller adjusts the PEMFC so that it should operate at low power (around 100 W). In this situation, the Air/Fuel PTC-2GS strategy is able to ensure a higher OER, which will increase the humidity of the membrane. In the situation where PEMFC operates at high powers, water production ensures the optimum degree of humidification of the electrochemical reaction, and Air/Fuel PTC-2GS strategy ensures a lower OER, having the advantage that the energy consumed by the air compressor is reduced. This behavior described above is visible in Figure 16.

![Figure 16. Oxygen excess ratio for RES FC HPS.](image)

4. Discussion

The discussion of the results presented in the section above is briefly shown below. The hydrogen consumption for the strategies sFF, Air-PTC-2GES, Fuel-PTC-2GES and Air/Fuel-PTC-2GES is shown in Table 5.
Table 5. Hydrogen consumption for FC HPS with and without RES power.

| Parameter [unit] | Strategy            | sFF Benchmark | Air-PTC-2GES | Fuel-PTC-2GES | Air/Fuel-PTC-2GES |
|------------------|---------------------|---------------|--------------|---------------|-------------------|
| $\text{Fuel}_T(\text{strategy})$ [liters] | 286.5              | 267.5         | 274          | 247.2         |
| $\text{Fuel}_T(\text{strategy})$ [liters] | 123.6              | 114.6         | 117.5        | 105.1         |
| $\text{Fuel}_T(\text{strategy}) - \text{Fuel}_T(\text{strategy})$ [liters] | 162.9              | 152.9         | 156.5        | 142.1         |
| $\frac{\text{Fuel}_T(\text{strategy})}{\text{Fuel}_T(\text{strategy})}$ [-] | 43.14              | 42.84         | 42.88        | 42.52         |

The Minimum hydrogen consumption is obtained using Air/Fuel-PTC-2GES for FC HPS with and without RES power. Table 5 shows that all three proposed strategies exceed the performance of the sFF strategy in terms of minimizing hydrogen consumption. The reason is that the sFF strategy controls the current using a control Load-Following loop, so it regulates the hydrogen flow in relation to the load demand. Compared to the sFF strategy, the strategies proposed in this paper use two search controllers based on the GES scheme, one to regulate the fuel and another to control the fuel cell converter. In addition, compared to the research conducted in [81], where the aim was to maximize the net power of the fuel cell, here both controllers use a mixt optimization function ($f (\text{AirFr}, \text{FuelFr}) = k_{\text{net}} P_{\text{FCnet}} + k_{\text{fuel}} \text{Fuel}_{\text{eff}}$) to minimize fuel consumption, where the coefficient $k_{\text{net}}$ is optimized in the reference [52]. The fuel economy obtained for all three strategies is higher than the 7.8% and 6.8% reported in the references [33,82].

The hydrogen economy compared to the sFF benchmark is computed using (15) and summarized in Table 6 for FC HPS with and without RES power.

Table 6. Hydrogen economy for FC HPS with and without RES power.

| Parameter [unit] | Strategy            | Air-PTC-2GES | Fuel-PTC-2GES | Air/Fuel-PTC-2GES |
|------------------|---------------------|--------------|--------------|-------------------|
| $\%\text{Fuel}_T(\text{strategy})$ [% ] | 6.63               | 4.36         | 13.72        |
| $\%\text{Fuel}_T(\text{strategy})$ [% ] | 7.28               | 4.94         | 14.97        |
| $\frac{\%\text{Fuel}_T(\text{strategy})}{\%\text{Fuel}_T(\text{strategy})}$ [-] | 1.10              | 1.13         | 1.09          |
| $\%\text{Fuel}_T(\text{strategy}) - \%\text{Fuel}_T(\text{strategy})$ [% ] | 0.65               | 0.57         | 1.25          |

The percentages $\%\text{Fuel}_T(\text{strategy})$ and $\%\text{Fuel}_T(\text{strategy})$ for Air/Fuel-PTC-2GES strategy are about double and triple compared to the strategies Air-PTC-2GES, Fuel-PTC-2GES. However, it is worth mentioning that their ratio, $\frac{\%\text{Fuel}_T(\text{strategy})}{\%\text{Fuel}_T(\text{strategy})}$, is about 1.1 and their difference, $\%\text{Fuel}_T(\text{strategy}) - \%\text{Fuel}_T(\text{strategy})$, is 1.25%, 0.65% and 0.57% for strategies Air/Fuel-PTC-2GES, Air-PTC-2GES and Fuel-PTC-2GES, respectively. This showed for all strategies that the hydrogen economy for RES FC HPS compared to FC HPS is almost the same due to about 2.2 kW RES power supplying the DC bus with about 44% ($=2.2 \text{ kW}/5 \text{ kW}$) from 5 KV MV of the load cycle considered in Figure 1. Note that the ratio $\frac{\%\text{Fuel}_T(\text{strategy})}{\%\text{Fuel}_T(\text{strategy})}$ mentioned in the last row of Table 5 is about 43%, being close to the 44% mentioned above. However, the highest increase in the percentage difference is also obtained for Air/Fuel-PTC-2GES strategy.

Another objective of the control strategy is to control the oxygen excess ratio because the OER value has a great influence on the performance of the fuel cell. The reference value of this ratio corresponding to each strategy was OER ≥ 2. It is also known that the air compressor is a high energy-consuming device in a fuel cell system so that to increase the electrical efficiency of the whole system, the power consumption of the compressor had to be optimized. It has been shown that the
proposed strategy for Air/Fuel-PTC-2GES strategy is the most optimal, even if at low fuel cell powers, a higher OER value was obtained; however, this is recommended to avoid membrane dehydration in spite of the disadvantage of BoP consumption. Otherwise, over the entire power range of the load, the control strategy ensures optimal control of the OER value, avoiding oxygen starvation and reducing energy consumption. The simulation results verify the effectiveness of the proposed controller.

During the start/stop cycles, as well as during the long-term operation of the FCS (at the OCV value), especially for RES FC HPS, the catalyst layer at the cathode is significantly affected by the carbon corrosion. In the FC HPS version, this phenomenon does not happen (because no repetitive cycles or OCV occurs). The FCS follows the load profile, and the results are presented in Figure 13. It is easy to see that the net power of FCS for all three strategies is high enough to avoid the operation of FCS at OCV. In order to minimize the detaching of the carbon support or the agglomeration of platinum metal particles from the catalyst, in the RES FC HPS variant, the electrochemical reaction to/from the active sites of the catalyst must be improved, for example, by increasing of the membrane humidity, which can be obtained especially by using more airflow. The Air/Fuel-PTC-2GES strategy for the RES variant avoids the repetitive cycles and OCV if a minimum power of minimum 100 W is established; in this case, the excess power can be transformed into hydrogen by using an electrolyzer. (Figure 14). The Air/Fuel-PTC-2GES strategy (shown in Figure 16) can avoid membrane dehydration by adjusting the OER to high values to the detriment of the electrical efficiency of the system.

The battery stack is used in the short term as a power buffer. Thus, the capacity and size of the battery are low compared to other hybrid power sources [6,35]. The battery stack operates in the charge-sustaining mode for RES FC HPS and FC HPS, controlled by the FC system’s power-tracking control (PTC). In this way, the battery stack is protected from deep discharges or frequent charge–discharge cycles at large and dynamic variations in charging demand. All PTC-2GES algorithms are designed to track the load throughout the operating cycle, where the state-of-charge (SoC) of the battery is almost constant, so the lifetime of the batteries is certainly increased. RES FC HPS mode is more unpredictable due to the RES power variation so that a surplus of power is converted into hydrogen gas by a water electrolyzer, avoiding overcharging the battery.

5. Conclusions

In this paper, the optimal and safe operation of the RES FC HPS was analyzed. An extended and systematic analysis of the strategies sFF, Air-PTC-2GES, Fuel-PTC-2GES and Air/Fuel-PTC-2GES is performed in this paper. The strategies were analyzed from the point of view of consumed hydrogen by an FC HPS without and with power from renewable energy sources (RES). The static feed-forward (sFF) control was used as a benchmark strategy under the same dynamic profiles of the load demand and renewable power. The optimization loops use two global extremum seeking (GES) schemes operating at different frequencies to maximize the multimodal optimization function that combines the performance indicators. The analysis of the proposed strategies indicated that the best performance was obtained for the Air/Fuel-PTC-2GES strategy due to the switched mode used for the air and fuel regulators of the FC system, which maximize the fuel economy through the efficient functioning of the FC system under the strategy Air-PTC-2GES or Fuel-PTC-2GES depending on the power requested on the DC bus to balance the power flow. The fuel savings compared to the fuel consumed using the static feed-forward (sFF) control was calculated. The main results of this study can be summed up as follows: 6.63%, 4.36% and 13.72%, respectively, under dynamic load but without RES power. With RES power, the needed FC power on the DC bus is lower, so the FC system operates more efficiently. These percentages were calculated at 7.28%, 4.94% and 14.97%. However, prior to its implementation, the performance of the Air/Fuel-PTC-2GES strategy must be further tested under various load cycles and renewable energy profiles.
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Nomenclature

Abbreviations:
- Air-PTC-2GES: Strategy based on the control of the air regulator
- Air/Fuel-PTC-2GES: Strategy based on the control of the air regulator and the fuel regulator
- AV: Average value
- EMS: Energy management strategy
- EMU: Energy management unit
- ES: Extremum seeking
- ESS: Energy storage system
- GES: Global extremum seeking
- Fuel-PTC-2GES: Strategy based on the control of the fuel regulator
- FC: Fuel cell
- FCHPS: Fuel cell hybrid power systems
- HPS: Hybrid power system
- LPM: Liter per minute
- LFW: Load-following
- MEA: Membrane electrode assembly
- MEP: Maximum efficiency point
- MPP: Maximum power point
- MV: Mean value
- PEMFC: Proton exchange membrane fuel cell
- PTC: Power-tracking control
- OCV: Open circuit voltage
- OER: Oxygen excess ratio
- RES: Renewable energy source
- RTO: Real-time optimization
- sFF: Static feed-forward
- SoC: State-of-charge
- SW: Switch
- UC: Ultracapacitor

Abbreviations:
- Air-PTC-2GES: Strategy based on the control of the air regulator
- Air/Fuel-PTC-2GES: Strategy based on the control of the air regulator and the fuel regulator
- AV: Average value
- EMS: Energy management strategy
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- ES: Extremum seeking
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- Fuel-PTC-2GES: Strategy based on the control of the fuel regulator
- FC: Fuel cell
- FCHPS: Fuel cell hybrid power systems
- HPS: Hybrid power system
- LPM: Liter per minute
LFW Load-following
MEA Membrane electrode assembly
MEP Maximum efficiency point
MPP Maximum power point
MV Mean value
PEMFC proton exchange membrane fuel cell
PTC Power-tracking control
OCV Open circuit voltage
OER Oxygen excess ratio
RES Renewable energy source
RTO Real-time optimization
sFF Static feed-forward
SoC State-of-charge
SW Switch
UC Ultracapacitor

Symbols:

AirFr Airflow rate
C_{DC} Capacitor DC
f_d Dither frequency
F Faraday constant
Fuel_{eff} Fuel consumption efficiency
Fuel_{Fr} Fuel flow rate
Fuel_T Total fuel consumption
k_{fuel} Weighting coefficient of the fuel consumption efficiency
k_{net} Weighting coefficient of the FC net power
k_{RES} Constant for RES
I_{cm} Air compressor current
I_{FC} FC stack current
I_{ref(Air)} Air flow reference
I_{ref(Boost)} Boost converter reference
I_{ref(Fuel)} Fuel flow reference
I_{ref(GES1)} GES 1 references
I_{ref(GES2)} GES 2 references
I_{ref(PTC)} PTC references
N_c Number of cells in series
P_{f(H_2)} Pressure of the fuel
P_{f(O_2)} Pressure of the air
P_{DCreq} Power requested on the DC bus
P_{FC} FC stack power
P_{DC} Power on the DC bus
P_{Load} Variable load power
R Universal gas constant
\nu_1, \nu_2 Variable for the reactant flow rate optimum
V_{cm} Air compressor voltage
V_{FC} FC stack voltage
u_{DC} DC bus voltage
U_{f(H_2)} Nominal utilization of hydrogen
U_{f(O_2)} Nominal utilization of oxygen
y_{BE} First harmonic of the FC power
y_{BF} Composition of oxidant
x_{H_2} Composition of fuel
\Theta Operating temperature
\eta_{sys} FC electrical efficiency
\eta_{boost} FC boost converter efficiency
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