# Performance analysis of fuel cells by modelling

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## Summary

European Commission energy politics pleads to guarantee electrical energy supply and reduce emissions associated with the climatic change. This requires immediate performances to develop renewable energy sources, alternative fuels for transportation and the increase of the energy efficiency of systems.

In this context, two technologies are attracting to the public and private sectors: the hydrogen, clean energetic vector that can be produced from any primary energy source (mainly wind and photovoltaic energy) and the cell fuels, very efficient devices to convert energy.

This paper presents a revision of the different technologies of fuel cells susceptible of being used to generate electrical energy and cogeneration processes.

## Key words

Fuel cells, electrolyzer, reaction electrochemical, SOFC, modelling, hybrid technology.

## 1. Introduction

Fuel cells are devices capable of producing electricity by an electrochemical transformation of the potential energy of a specific fuel, without classical combustion. So its efficiency can be twice of a system that uses the Carnot cycle. The type of fuel used embraces from hydrogen until simple and derived hydrocarbons such as alcohols.

The use of pure fuels eliminates problems associated with contamination such as S, NO, V, etc. By other hand, hydrogen doesn't generate derived such as CO y CO2. Hydrocarbons do it, but because of the high efficiency of the fuel cells, for equivalent quantities of produced energy, the CO2 emissions can be reduced in half or less, with the corresponding environmental benefit.

Fuel cells technologies highlight for their high potential efficiency, low emissions, modular character, flexibility in the use of fuel and silent operation. Besides, they allow the use of residual heat, increasing notably the overall systems efficiency. Hydrogen production with a renewable source and the use of it in the fuel cells, promise a clean energy source than can be implemented in interconnected or isolated microgrids.

One of the main critics to the renewable energies is their discontinuous character. But this critic will lose completely sense at the moment of development of the hydrogen production technology, because this one will allow storage the other energies when it is convenient.

The use of this hydrogen to produce electricity by means of fuel cells becomes a secondary generation with the advantage that it is generated in the point and the moment needed, in a fixed or mobile installation.

In the future perspective, hybrid systems are contemplated among which it is necessary to highlight the integration of fuel cells with gas microturbines that allow increasing notably the system efficiency.

In the SOFC fuel cells, as the temperature of exhaust gases is around 900 °C, it seems convenient using this thermal energy and the difference of pressure to impel a gas turbine, placed later, to the electric, heating and refrigerating energy generation, avoiding the use of additional fuel. In Figure 1, it is shown a possible SOFC fuel cells connection with gas turbines, using a heat exchanger.

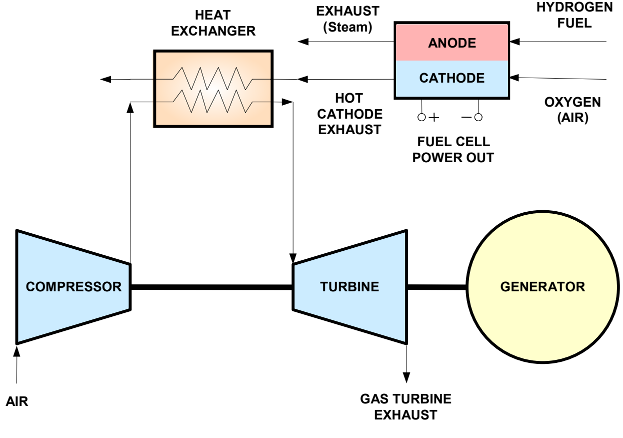


Fig. 1. Integration of fuel cells with gas turbines

## 2. Fuel Cells classification

Fuel cells can be classified based on two fundamental aspects:

- Operation temperature (low or high)
- Electrolyte material (substance used as a bridge to exchange ions between the anode and cathode)

Regarding the temperature four models (AFC, PEMFC, DMFC, PAFC) are considered of low temperature and two models (MCFC y SOFC) of high temperature.

### *A. Alkalines (AFC – Alkaline Fuel Cell)*

Electrolyte used is a solution of diluted potassium hydroxide. It uses as fuel pure hydrogen, with null concentration of CO or CO2, to avoid reducing notably the efficiency. They operate at atmospheric pressure and the electrodes are usually made of nickel and oxide of nickel, or carbon doped with platinum. The cells voltage is of the order of 0.8V and the current density is around 1500 A/m2. Their useful life is usually a year of operation.

### *B. Proton Exchange Membrane (PEMFC – Proton Exchange Membrane Fuel Cell)*

Electrolyte consists of a solid polymer layer usually Nafion (based on a polyethylene polymer). The anode or fuel electrode is Pt/C deposited on coal paper and the cathode or air electrode is also Pt/C. They can be feed with reformed fuel and with air.

Their operation temperature is low and when having the solid electrolyte they have a long useful life, around 50.000 hours. They can supply maximum energy after three minutes of operation. Every cell supplies around 0.7V of c.c. and current densities near to 900 mA/cm2. “Air bleed” technique allows that this kind of cells operates with hydrogen obtained from alcohols or carbonated fuels.

### *C. Direct Methanol (Direct Methanol Fuel Cell – DMFC)*

Direct Methanol fuel cells are a PEMFC variant. They use as fuel direct methanol instead of hydrogen; this fuel is obtained generally from natural gas or biomass. Their current density is low and they haven’t got a competitive development.

### *D. Phosphoric Acid (Phosphoric Acid Fuel Cell – PAFC)*

It uses phosphoric acid like electrolyte, container inside a silicon carbon matrix placed together with teflon. Catalysts are made of platinum and electrodes are made of porous carbon.

Thermal energy that can be obtained from this kind of cells is very similar to electric energy. Power density is around 0.18 W/cm2. Their time response is higher than PEMFC ones and they are used in fix installations with power range of 0.2 – 20 MW, being contemplated their use in cogeneration systems.

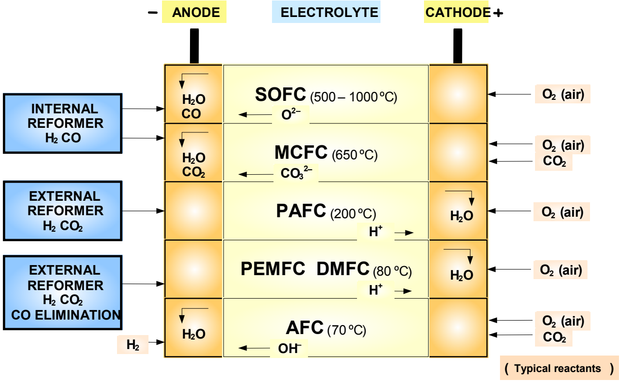


Fig. 2. Fuel Cells ranges

### *E. Molten Carbonate (Molten Carbonate Fuel Cell – MCFC)*

Electrolyte is a liquid solution of lithium carbonate or potassium carbonate, contained inside a porous and inert ceramic matrix, usually $LiAlO_2$. Acid consists of sintered nickel powder (porous) with some of chromium to avoid material agglomeration. Cathode consists of nickel oxide with some of lithium.

It can operate with hydrogen, carbon monoxide, natural gas, propane, etc. Its efficiency is around 60% and, if cogeneration is used, up to 90% (with gas turbine).

Comparing with other technologies, this cell is capable of operating with higher voltage than PAFC ones for the same current. When temperature falls about 30°C the voltage output is reduced 15% approximately.

### *F. Solid Oxide (Solid Oxide Fuel Cell – SOFC)*

Electrolyte is a solid ceramic material (zirconium) that operates with temperatures in the range of 750 – 1050 °C, to those which ceramic material presents an acceptable ionic conductivity. Besides, they allow internal reformer and cogeneration using the residual heat that is of great quality. By other hand, these high temperatures condition a higher starting time.

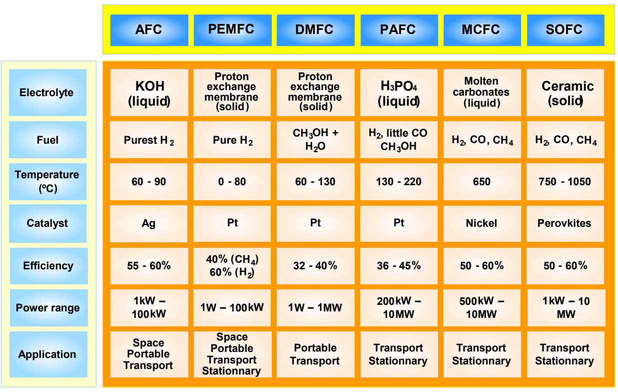
This technology is very sensible to the temperature variations; a reduction of 10% in temperature causes a 12% efficiency fall of the system. This is because resistance in the oxygen ions conductivity increases.

Anode is made of porous zirconium / nickel and cathode is a lantano manganate doped with magnesium. They reach voltages of 0.6V/cell and current densities near to 0.25 A/cm2. Their useful life is near to 30.000 hours.

## 3. Fuel Cells more relevant properties

In Table 1 the fuel cells characteristics that are being developed currently are presented. Polymeric and phosphoric acid cells are in a nearer stage of commercialization than the rest of the technological alternatives. This doesn’t mean that there is a clear winner, since the different technologies are oriented towards different sectors of the market.

TABLE 1. - Fuel cells characteristics



| | AFC | PEMFC | DMFC | PAFC | MCFC | SOFC |
|---|---|---|---|---|---|---|
| Electrolyte | KOH (liquid) | Proton exchange membrane (solid) | Proton exchange membrane (solid) | $H_3PO_4$ (liquid) | Molten carbonates (liquid) | Ceramic (solid) |
| Fuel | Purest $H_2$ | Pure $H_2$ | $CH_3OH$ + $H_2O$ | $H_2$, little CO<br>$CH_3OH$ | $H_2$, CO, $CH_4$ | $H_2$, CO, $CH_4$ |
| Temperature (ºC) | 60 - 90 | 0 - 80 | 60 - 130 | 130 - 220 | 650 | 750 - 1050 |
| Catalyst | Ag | Pt | Pt | Pt | Nickel | Perovkites |
| Efficiency | 55 - 60% | 40% ($CH_4$)<br>60% ($H_2$) | 32 - 40% | 36 - 45% | 50 - 60% | 50 - 60% |
| Power range | 1kW – 100kW | 1W – 100kW | 1W – 1MW | 200kW – 10MW | 500kW – 10MW | 1kW – 10 MW |
| Application | Space<br>Portable<br>Transport | Space<br>Portable<br>Transport<br>Stationnary | Portable<br>Transport | Transport<br>Stationnary | Transport<br>Stationnary | Transport<br>Stationnary |

## 4. Hydrogen production

Fuel cells need hydrogen to operate. Hydrogen can be obtained in several ways:

*Reformed of natural gas with vapour*; it is the catalytic endoergic conversion of light hydrocarbons (methane to gasoline) with vapour of water. The industrial chemical reaction is produced at 850 °C and pressures of 2.5 MPa (25 bar).

*Partial oxidation of hydrocarbons*; it is the heat-emitting conversion of weight hydrocarbons (residual fuel – oil of the petrol treatment) using oxygen and vapour.

*Partial oxidation of carbon*; the process is identical to the partial oxidation of weight hydrocarbons, with the difference that carbon is crushed with fine powder and it is mixed with water.

*Separation of carbon and hydrogen of hydrocarbons*; it is carried out by means of an arch of plasm process at temperatures around 1600 °C, obtaining pure carbon and hydrogen without producing significant emissions.

*Small size and partial oxidation reformer processes;* they are studied to be carried out over fuel cell modules of powers between 10 and 250 kW in mobile applications and small fix systems.

*Renewable energies*; in some cases the renewable energy source is not connected to the network (by reasons of distance or operation). So, it can interest, in these situations, producing locally hydrogen by means of electrolyzers, and then using or transporting it.

*Electrolysis*; the conventional water electrolysis has been used commercially for 90 years. In the eighties it was produced only in the range of 0.1 – 0.2% of the world hydrogen production, obtaining the hydraulic power stations electricity. Electrolyzers produce hydrogen by means of water electrolysis. The required energy can be obtained from renewable energies, in particular eolic, solar or oceanic one, than can be dedicated exclusively to the hydrogen production that it will arrive later to the consumption points. In Figure 2, the blocks diagram corresponding to the use of photovoltaic solar energy to produce hydrogen is shown

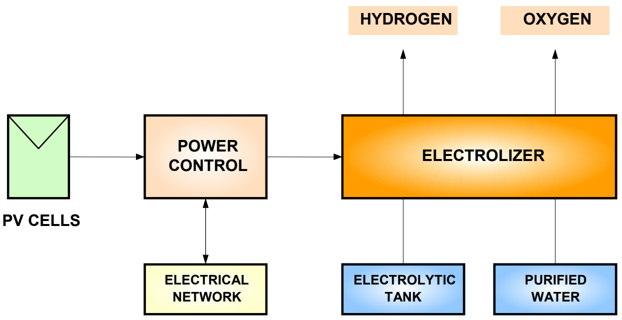


Fig. 3. Hydrogen production with solar energy [5]

## 5. SOFC System Modelling

Although second generation of fuel cells, such as MCFC or SOFC, is still at the development stage, these types of cells have a great potential to get high efficiencies. As consequence, we will discuss about SOFC system with the expectative that response time of other cell types would be similar.

Based on the parameters and the dynamic model proposed by [1], this model is shown in Figure 4. In this figure, Nernst equation, Ohm law, input flow element, reaction element, fuel utilisation factor, stoichiometric ratios, transfer functions, reaction speeds, time constants and others are modelled.

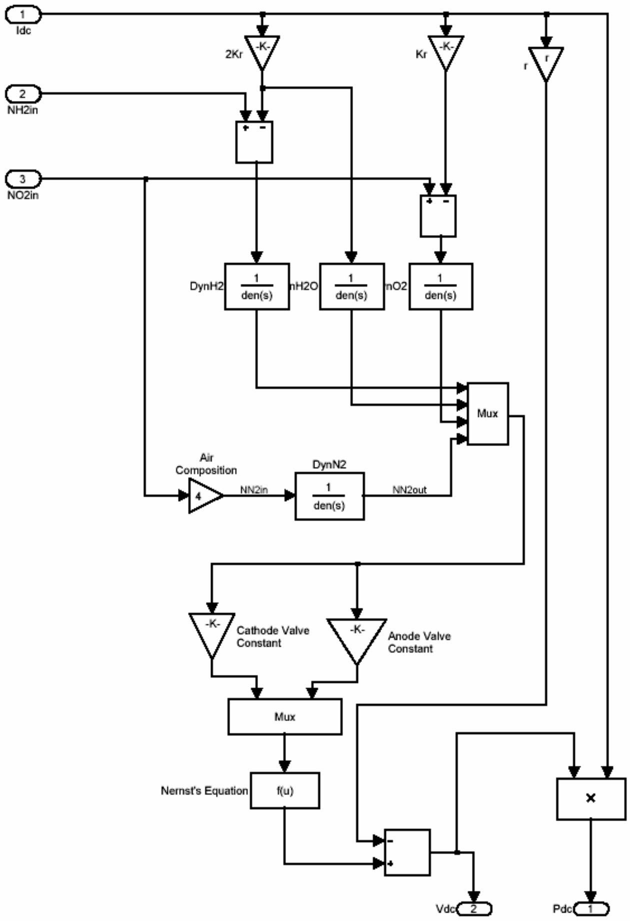


Fig. 4. SOFC System Modelling [1]

### *A) Limited Transient*

This simulation considers a current step input from 200A to 500A (Figure 5). The purpose of this analysis is revealing the effects of the $U_f$ estimator (fuel utilisation factor).

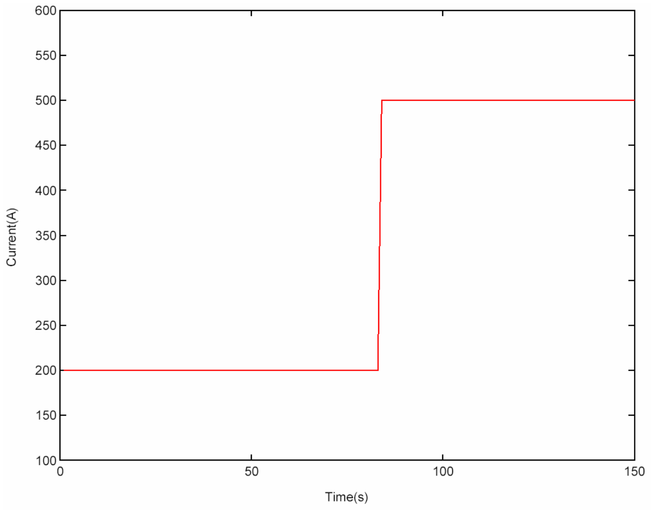


Fig. 5. DC Current Step Input

In Figure 6 we can see that although the desired current step input on the stack oscillates between 200A and 500A, some type of mechanism is limiting the rate of change of current at some stage. It can also be seen that an instantaneous transition from 200A until approximately 300A is allowed, but from that point to 500A, its evolution is slow and it reaches the desired current at t = 67.73s.

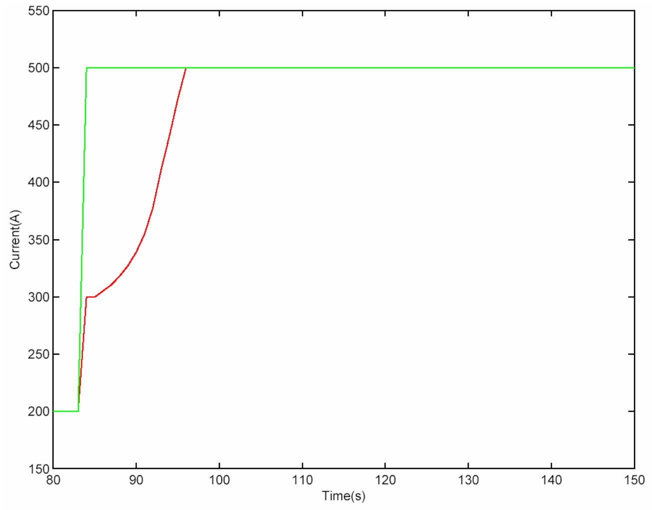


Fig. 6. Stack DC Current from 200A to 500A

Figures 7 and 8 show instantaneous voltage and power which appear starting from the first current transition. It can be seen a voltage variation from 269.18V to 261.67V and a power variation from 53.84 kW to 78.44 kW. From this moment onwards, current evolves slowly, and voltage and power too.

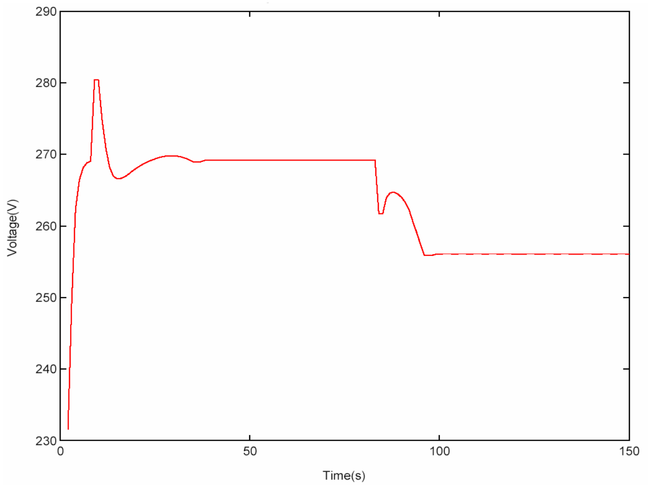


Fig. 7. Stack DC Voltage under a current step (200 to 500A)

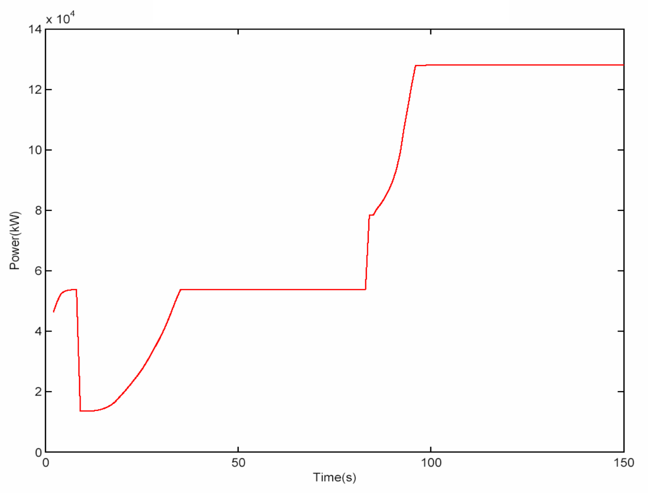


Fig. 8. Stack DC Power under a current step (200 to 500A)

In Figure 9 it can be seen that limits in the fuel utilisation have been the cause that limits current ratio. When an $U_f$ value is greater than 0.9, the value of current is limited in order to get fuel cell operates under acceptable operation limits. At t = 67.73 s, $U_f$ comes back to the established limits and fuel cell operation with unlimited current remain from this moment inside the allowed range.

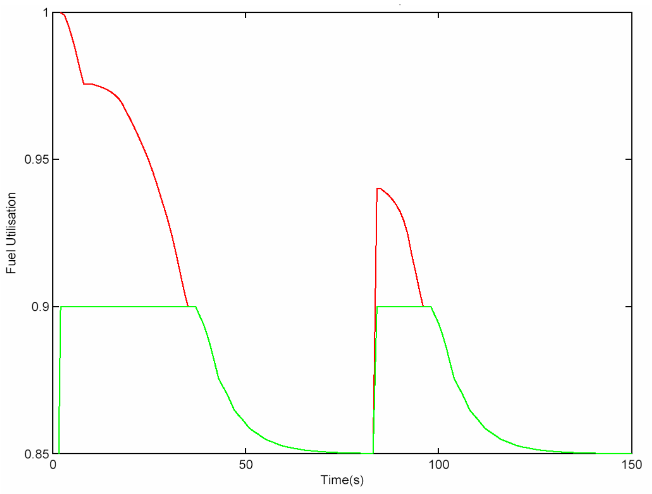


Fig. 9. Stack fuel utilisation under a current step

## 6. Conclusions

This paper presents the different models of fuel cells that are being developed at present time. The most outstanding characteristics of each of them, physical constitution, electrolytes, ranks of power, efficiency, etc. are presented.

We stated how cells SOFC and MCFC constitute a good alternative for generation of electrical energy in power stations; PAFC are suitable in the production of domestic electrical energy; finally PEMFC and DMFC can be applied in transport.

In any case, the more promising systems, PEMFC-DMFC and SOFC, have practically place setting an ample interval of applications.

On the other hand, a simulation study is made, by means of MATLAB/SIMULINK, of the behaviour of cells SOFC, contemplating its answer with a step input.

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