# The Use of Low Power Fuel Cells for Power Supply of Mobile or Stationary Electrical Apparatuses

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*Abstract* - **During the last few years, the growing energy demand in the telecommunication sector and more care for safety and reliability of energy production systems have driven the development of integrated systems, using innovative power production processes. The choice made by the Company FAAM focuses on the production of small and medium size appliances based on fuel cell technology. In these appliances, easy system management is combined with their safety, in terms of energy quality and the absence of risks for operators and user equipment. The choice was focused on fuel cells with 400 Watt power, fed with high purity hydrogen and air taken from the surrounding environment and introduced through a ventilator. For hydrogen storage, metal hydride reservoirs have been used, containing up to 400 liters of hydrogen in N.C., with a very wide allowance in relation to safety in handling and operation. The choice to manufacture small size power systems simplifies the issues related to the management of thermal flows and humidification of membranes and their use at a demonstration scale becomes immediately applicable. The use of fuel cells with these characteristics is not limited to the field of stationary applications, but it has a good market in the transport sector with the application of engine-driven bicycles (Camaleo bikes) and small size electric vehicles, therefore ensuring further reduction of production costs and a better success in alternative sectors.**

**The purpose of this article is to provide a detailed description of the technical specifications adopted as a base for system design and show the flexibility in using this system. A special focus is assigned to hydrogen storage technology in metal hydride reservoirs, and the techniques adopted to facilitate desorption during system operation.**

## I. INTRODUCTION

FAAM batteries–electric vehicles is a company based in the Marche region – Italy – and established in 1974. Production activities are carried out in the plant of Monterubbiano - electric accumulators Lead acid for start-up use, and in the plant of Monte S. Angelo (Foggia) - industrial and stationary accumulators, type Lead acid and Gel. Since 1999, a plant for production of electric vehicles is operating in Monterubbiano. The transfer of know-how of the battery sector, the knowledge of electric vehicle market and stationary appliances and, especially, continuous support to research from major customers (such as Telecom Italia, Ferrovie dello Stato, etc.) pushed the company to start research and development in the sector of fuel cells, PEMFC type. The choice of Proton Exchange Membrane technology is based on some positive characteristics identified in stationary and mobile applications. The first of these characteristics is low operating temperature, which involves the absence of pre-heating systems and enables achieving working conditions in very short time as compared with other fuel cell systems. Not less important is the characteristic based on the absence of corrosive liquid electrolyte, which increases the safety levels of the application and enables installations in different positions (horizontal and vertical). The use of tanks with metal hydrides increases this system safety characteristic, due to the fact that gas release pressure rates are lower than 3 bar and that hydrogen is not only present in the gaseous status, but it is present in the adsorbed status. One of the main positive characteristics of fuel cells is that in a wide use range, their efficiency does not depend on stack dimensions. This characteristic allows using modular systems mounted in series and/or in parallel to achieve desired voltage and electric power values. This modularity characteristic simplifies, especially in stationary applications, the management of water and dissipated energy, enabling at the same time the reduction of parasitic losses and recovery of part of generated heat.

## II. TYPES OF FUEL CELLS

*Cells with polymer membrane (PEMFC)*: the main characteristics of these cells are:

1. operating temperature 45-90°C
2. electrolyte under the solid polymer form (sulphonated polyfluorocarbon)
3. graphite or metal electrodes
4. reaction catalyst: Platinum

These cells appear as the main alternatives in mobile systems. The presence of a solid electrolyte provides these cells with an excellent resistance to gas crossover, which means low energy loss at low operating regimes. The low operating temperature implies that it is possible to quickly bring the cell in regime operating conditions, although – on the other hand – the temperature of exhaust gases at outlet does not enable cogeneration operations. These cells can operate at high current density, although in these conditions

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they may be affected by the limits originating from the need to humidify membranes and control temperatures. One of the main limits of these cells is the low tolerance to CO, actually lower than 10 ppm, which limits the types of usable hydrogen sources.

*Alkaline Cells (AFC)*: the main characteristics of these cells are:

1. operating temperature 50-200°C
2. liquid electrolyte (KOH solution)
3. Nickel or Raney metal electrodes
4. reaction catalyst: Platinum

This type of cells, historically developed for space applications, show fairly good reaction kinetics on oxygen electrode, but they are very sensitive to the presence of $CO_2$ and $H_2O$ in reactant gases; therefore, reformer systems cannot be used. Gas purification systems, because of their high management costs, currently justify their use for special applications only.

*Pphosphoric acid fuel cell (PAFC)*: they have the following characteristics:

1. operating temperature 200°C
2. liquid electrolyte absorbed ($H_3PO_4$ solution)
3. graphite electrodes
4. reaction catalyst: Platinum

These cells must remain above the temperature of 42°C to avoid the phosphoric acid solution freezes. From the construction viewpoint, they are very similar to PEMFC, although they have the advantage of faster reaction kinetics and higher tolerance to CO. Another advantage related to high operating temperature is that the residual heat may be used for cogeneration. As compared with other high temperature cells, the disadvantage is that they require purification of reactant gases to keep CO level lower than 0.5%.

*Molten carbonates fuel cell*: they have the following characteristics:

1. operating temperature 650°C
2. fused electrolyte (mix of alkaline metal carbonates)
3. stainless steel electrodes
4. reaction catalyst: Nickel

The main advantages of these cells are related to the fact that they can work at high temperatures: in fact, the catalyst used is Nickel, instead of the more expensive Platinum. Blocks are made of steel and the temperature of waste gas is so high that these gases can be used in cogeneration systems without any problems.
However, these cells need a long pre-heating period before they reach the required condition. CO may be used directly as fuel; therefore, its presence is not a problem for catalysts. One of the disadvantages is certainly related to high corrosiveness of the electrolyte.

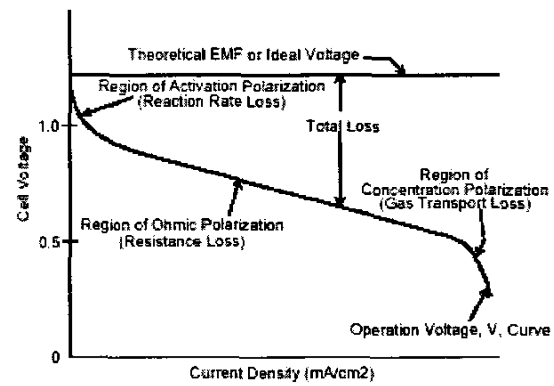
*Solid oxides fuel cell (SOFC)*: they have the following characteristics:

1. operating temperature 600-1000°C
2. solid electrolyte
3. ceramic electrodes

the absence of liquid parts in these cells is certainly an advantage, especially because this limits the effect of gas counter-flow and reduces the total strength of the system. On the other hand, the high operating temperature involves high differential dilatations and subsequent problems on seals and joints.

## III. Operation of Fuel Cells

The main difference between fuel cells and conventional batteries is related to their discharge profile:




While the discharge profile is substantially parallel with EMF lines for conventional batteries, for fuel cells the behaviors observed are very far from the ideal situation. Substantially, three areas may be identified, each showing differences from the ideal situation, determined by different chemical - physical situations:

1. An area of activation losses where a gradual accumulation of electric charges is observed on electrode surfaces, without power supply. This area is usually related to the energy barrier that needs to be passed to enable hydrogen and oxygen redox reaction. The higher catalyst content on electrodes the smaller this area . In the same region, voltage drop related to fuel crossover in the electrolyte is also observed. With a fairly good approximation, this area may be studied through the following relation:
$$V = E - A\ln\left(\frac{i + i_n}{i_0}\right)$$
where $i_n$ is current density caused by the crossover and $i_0$ is the activation current;
2. An area with ohmic losses, where Ohm laws may be applied to determine voltage drops;

3. An area with concentration losses, where gas transport through internal distribution channels is not sufficient to compensate consumption on electrodes. These losses are well described by the following equation:

$$V = E - B\ln\left(\frac{i_l + i}{i_l}\right)$$

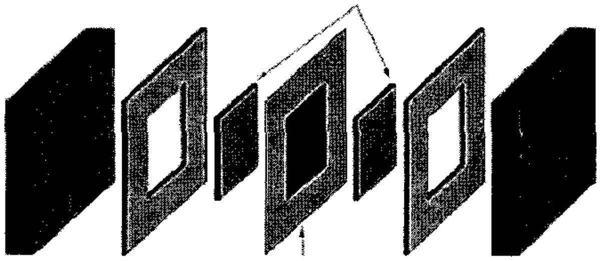
where $i_l$ is the limit current density.

From the analysis of the previous graph, it is possible to understand how the choice of regime operating conditions of fuel cells may depend on project choices and the type of application desired. The area with low current density has the advantage of working with higher energy efficiency, therefore, with lower gas consumption. However, the power supplied is very low as compared with the power that may be supplied; it means that the system is over-dimensioned in relation to the load applied. On the other hand, the area with high current density shows lower efficiency (higher gas consumption), higher power supplied and therefore – considering that smaller systems can be used with the same power supply – the stack cost is considerably lower. The flexibility of these systems – which is clear from this short information – is certainly one of the main characteristics allowing their use in any situations.

One of the common characteristics of all types of fuel cells is that they hardly stand power transients. For this reason, they are often used – especially in mobile applications, combined with energy accumulation systems and super-capacitors.

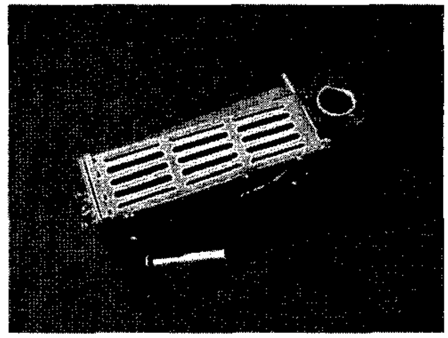
From the construction viewpoint, a stack of fuel cells (specifically of the PEFC type) consists of a series of gas distribution blocks alternated with MEA (Membrane Electrode Assembly) and seals. The stack voltage is achieved connecting in series a given number of blocks; after electric power has been selected, in relation to the type of load they have to support, and the system operating point, mostly in accordance with the system efficiency, the area of single cells is determined.

The following figure shows a PEMFC assembly diagram:




Graphite blocks play a double role of transferring reactant gas as homogeneously as possible on the surface of electrodes and conduct electric current flow. The role played by diffusion layers is to equalize gas concentration on the electrode surface. Finally, the membrane is made of a layer of sulphonated perfluorocarbon coated on both surfaces with a layer of finely dispersed carbon black and Platinum.

The following photo shows a 200 W stack operating at 24 V, provided with air inlet ventilator.



## IV. System Configuration

The system so far described is the basic configuration of the generator. As previously mentioned, these systems have a certain degree of inertia; therefore, they poorly adapt to sudden load variations. To compensate these transients, hybrid systems are being developed, consisting of fuel cells, accumulators and super-capacitors connected between each other in parallel or in series.

In the connection in series, managed by power electronic control, fuel cells work as power generators and recharge batteries (accumulation system). Therefore, they are dimensioned to supply less energy, achieving savings on weights and volumes occupied by accumulators, or they are dimensioned in accordance with the load to support, therefore achieving an extension of the system range and a reduction of total recharging time. This configuration is called Range Extender. To compensate any power peaks, banks of super-capacitors are increasingly frequently used. These apparatuses enable supplying power to users in very short time and, at the same time, help avoiding stress to batteries caused by quick charging and discharging actions, therefore increasing their life cycle.

On the other hand, in connections in parallel, fuel cell is the main power source, while batteries and/or super-capacitors only act in the compensation of transients and power peaks. In this configuration – considering that user operation depends on proper fuel cell operation – run parameters become a critical factor. For this reason, it is essential to operate the control on humidity of reagent gases, cell temperature, total voltage, treatment of residual water and dissipated heat. A further critical factor is hydrogen storage system, which shall ensure flows at the instantaneous rate and pressure required by the system and for which there are now two alternatives: pressurized tanks and metal hydride tanks.

## V. SYSTEM DESCRIPTION

Assuming the construction of a stationary system, it can be obtained in Range Extender configuration with a fuel cell charging the battery set.

Due to their modularity, the fuel cell system can be designed in such a way as to connect in series low power stacks to achieve the desired voltage. To achieve the required power, the series of cells can be connected in parallel between each other. The advantage obtained from this type of installation, as compared with direct design and construction of a stack with proper voltage and power is related to the fact that the management of water and generated heat flows are simplified, as well as the control of cell temperature. One of the desirable characteristics in managing fuel cells is the absence of humidifying systems for reactant gases, because this reduces costs, dimensions and complexity. In Buchi and Srinivasan, 1997, it is shown that the maximum power of a fuel cell is reduced by approximately 40% if an external humidifying system is not used, even in systems with low operating temperature (60°C). However, for low power cells this is the cost to pay. One of the best management systems for fuel cells without humidifying is to set the air flow in such a way as to obtain at outlet an exhaust with approximately 100% relative humidity, and such as to ensure a proper mass balance on the cell water. In general, this operation involves parasitic losses of less than 2% of the overall electric power. For low power cells used by FAAM, the humidifying factor was faced by conducting cells at low current density regimes. In facts, they are relatively low at these reaction speed regimes, and it is possible to obtain proper humidifying of the electrodes and membrane, simply using the water produced on the cathode side.

Other crucial components of the system are hydrogen accumulation tanks. FAAM has selected metal hydride tanks. The following table shows a comparison between the various and most common hydrogen storage systems:

| Method | Storage efficiency (% on $H_2$ mass) | $H_2$ mass (Kg) per liter |
|---|---|---|
| Compressed Gas | 0.7-3.0 | 0.015 |
| Metal hydrides | 1.2 | 0.028 |
| Water + Metal hydrides | 2.2 | 0.020 |
| Cryogenic Liquid | 14.2 | 0.040 |
| Reformed Methanol | 13.9 | 0.055 |

Source: Larminie-Dicks, 1999

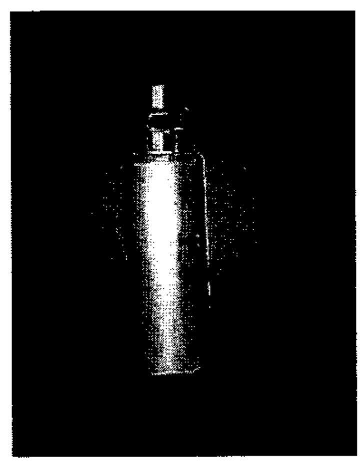
As compared with other accumulation systems, metal hydride tanks offer some advantages:

1. The most significant and clear advantage is low release pressure, which involves higher safety limits in handling and use. The maximum pressure achieved during release is 3 Bar. This point is very important, especially in mobile applications, where the safety factor is a critical factor.
2. Easy filling operations, for filling can be performed through a simple connection with a tank or an electrolyte production system, able to ensure a supply at a pressure of 8-12 Bar. Filling operations produce heat (approximately 30 KJ/mole); therefore, it is faster if performed in a thermostatic bath, able to keep temperature below 30°C.
3. Fairly good release speed rates, included in the range 7-30 SL/minute. The release speed is influenced by the tank temperature and therefore by the capacity to supply the 30 KJ/mole required by the system for hydrogen desorption. As described below, proper management of residual heat flow enables optimizing this aspect. The consequence of this characteristic on the project is that small tanks with high surface/volume ratio are preferable.
4. Recharging time of these tanks is very short and varies from 20 to 40 minutes, in relation to the fact that there is a cooling system or not.

The main disadvantage of these tanks is that their weight is high. However, this characteristic does not influence so much if the installation is stationary .

Furthermore, these tanks require gas with high purity level and especially CO free.

The following photo shows a tank containing 100 SL hydrogen (able to supply approximately 65 Wh power to a system with 48% efficiency) having dimensions: L = 140 mm; D = 50 mm.



## VI. MANAGEMENT OF HEAT FLOWS

According to the above descriptions, the efficiency of the cells + tanks system depends on the efficiency of energy recovery from the heat dissipated by the stack. This heat is released at low temperature; therefore, it may be conveniently used for tank heating only, while cogeneration possibilities are completely excluded.

For the purpose of properly dimensioning exchange surfaces, it is necessary to refer to the heat released by the cell, which may be first calculated through the following relation:

$$Q = P_e\left(\frac{1.25}{V_c} - 1\right)\text{Watts}$$

where Pe is electric power and Vc is the cell voltage.

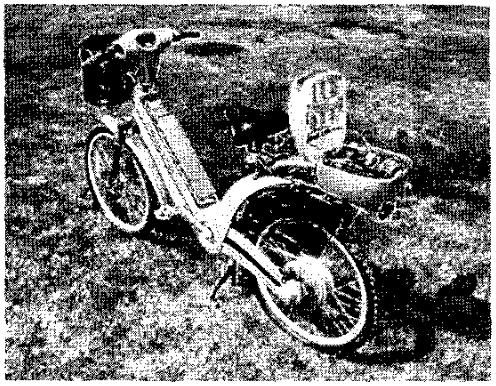
This heat is made available at the average temperature of 50°C. The other relation that should be taken into account is hydrogen consumption speed:

$$F_{H2}\left[\frac{mol}{s}\right] = 5.2\times10^{-6}\times\frac{P_e}{V_c}$$

The use of these equations also provides criteria for selecting hydrides, considering that the quantity of heat produced is necessarily higher than the heat required by tanks during discharging. Warm air flow at outlet to the fuel cell is conveyed to tanks for heating.

## VII. Conclusions

The use of small size fuel cells simplifies the applications of these innovative devices, especially when applications are of the stationary type. However, due to their use flexibility, these devices may be used with no major changes even in the sector of mobile applications, therefore expanding potential markets and reducing production costs. FAAM has started its first commercial application on an electric bicycle with assisted pedal strokes and is now developing the prototype of an off-the-shelf electric scooter with fuel cell supply. In all applications, cells follow the same design criteria, although they have different electric power.



The fuel cell has been positioned in the front part, while tanks and batteries are located in the rear box.

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