EFC2005-86219

**A FEASIBILITY STUDY OF AN AUXILIARY POWER UNIT BASED ON A PEM FUEL CELL FOR
ON-BOARD APPLICATIONS**

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ABSTRACT

PEM (Proton Exchange Membrane) fuel cells show characteristics of high power density, low operating temperature and fast start-up capability, which make them potentially suitable to replace conventional power sources (e.g. internal combustion engines) as Auxiliary Power Units (APU) for on-board applications.

This paper presents a methodology for a preliminary investigation on either sizing and operating management of the main components of an on-board power system composed by: i) PEM fuel cell, ii) hydrogen storage subsystem, iii) battery, iv) grid interface for the connection to an external electrical power source when available, and v) electrical appliances and auxiliaries installed on the vehicle.

A model able to reproduce the typical profiles of electric power requests of on-board appliances and auxiliaries has been implemented in a computer program. The proposed methodology helps also to define the sizing of the various system components and to identify the fuel cell operating sequence, on the basis of the above mentioned load profiles.

NOMENCLATURE

Acronyms

AC	Alternate Current
APU	Auxiliary Power Unit
DC	Direct Current
FC	Fuel Cell
PEM	Proton Exchange Membrane
SOC	battery State Of Charge

Symbols

$A_{i,j}$	logic variable for on/off state of load j at time interval i
B_i	battery SOC reduction at time interval i (kWh)
E_{Acc}	minimum required battery capacity (kWh)
E_{Tsh}	threshold of battery SOC reduction for FC startup (kWh)
i	index of time intervals
j	index of loads
M	number of time intervals
N	number of loads
P_j	rated power request of load j (kW)
P_{FCi}	FC power output at time interval i (kW)
P_{min}	minimum operating value of FC power output (kW)
P_0	rated (maximum) value of FC power output (kW)
$p_{i,j}$	utilization probability of load j at time interval i
R_i	total load energy request in time interval i (kWh)
T	time window (h)
T_{net}	duration of FC operation (h)
T_w	FC startup delay (min)
Δt	time interval duration (min)

1. INTRODUCTION

The energy dependence on oil of many industrialized countries and the rising barrel price are encouraging studies related to the development of a hydrogen economy. In this framework, the employment of Fuel Cells (FC) is considered as a viable strategy to generate electricity, in view of the possibility of producing hydrogen also from renewable energy sources.

Several benefits can be highlighted concerning FC systems. FC are characterized by high energy conversion efficiency values. Moreover, the system performances are not significantly affected by the FC size in a typical range from few kW up to about 200 kW, which allows for modular installation. FC employment leads also to local environmental benefits in comparison with systems based on combustion of fossil fuels.

In stationary applications, according to the distributed generation concept, FC systems may replace conventional technologies as emergency back-up units, energy sources integrating the electricity request of grid-connected customers or to supply grid-independent power systems [1].

In on-board applications, such as vehicles (trucks, campers, etc...) and also marine yachts or planes, FC have been proposed to be adopted both to supply electric traction drives and as auxiliary power unit (APU) of the electric loads, when generators moved by the traction engines are not operating and the external network is not available.

Low temperature fuel cells are well suited for both on-site stationary or on-board power units [2-6], due to their rather simple and safe operation. Low temperature levels allow fast start-ups and fast responses, suitable for load-following applications. The PEM (Proton Exchange Membrane) fuel cell technology, in particular, seems to be the most competitive solution for on-board applications, because of its very low operating temperature (60-90°C) and compactness.

This paper aims at presenting a methodology for a preliminary investigation on either sizing and operating management of the main components of an APU energy system for on-board application based on a PEM fuel cell.

Section 2 describes the considered energy system.

Section 3 presents the proposed methodology, implemented in a computer program, able to reproduce typical electric power request profiles and to define the most adequate sizing of the APU components and to identify the FC operating sequence.

Section 4 shows some of the results obtained for a typical configuration of a medium size motor yacht.

2. APU BASED ON A FC FOR ON-BOARD APPLICATIONS

As already mentioned, the energy system considered in this study is an APU based on a FC, devoted to the supply of several small electric appliances and auxiliaries installed in a vehicle.

As shown in Fig. 1, the system is composed by: i) PEM fuel cell, ii) hydrogen storage subsystem, iii) grid interface for the connection to an external power source, when available, iv) battery and v) on-board (AC and DC) loads. The external power source may be represented either by a generator moved by the traction engines, when operating, or by the external network, when available.

Fig. 1 – Main components and energy fluxes of the considered energy system

A simplified scheme of the electric system is shown in Fig. 2. The FC and the battery are connected to the main AC bus through power electronic interfaces. This solution would reduce the mutual interference between the two energy sources. The same AC bus is also fed by the external source when available. When the connection with such an external source is not available, the power electronic interface of the battery assumes the main role on the control of the electric power characteristics of the system.

Fig. 2 – Scheme of the electric system

3. METHODOLOGY

A computational procedure has been developed in order to define the size of the APU components and to decide the operating sequence of the FC, once the main characteristics of the appliances and auxiliaries to be supplied are defined. The developed

procedure (illustrated in Fig. 3) has been implemented in a numerical code, which simulates the random occurrence of the utilities request.

The procedure takes into account the possibility for the system to be fed by external source, as it usually happens when the system is connected to the external electric grid, or when traction engines are in operation and move an electric generator.

The proposed procedure is based on the assumption that the FC operation (i.e. full-load, part-load or disconnected) is decided on the basis of the battery State Of Charge (SOC); therefore, the FC operation is not based on a load-following strategy.

Thus, three different operating conditions of the APU are identified:

- connection with external source available: in this case the loads are expected to be fully fed by the external source, being the FC switched off and the battery in charge;
- external source not available and FC not operating: in this case the energy required by both DC and AC loads is provided by the battery;
- external source not available and FC switched on: in this case the loads are completely or partially fed by the energy provided by the FC, while the unbalances between load request and FC production are compensated by the battery. In case of high load peaks, which cannot be met by the available resources, the intervention of a specific protection device is required.

Fig. 3 - Flow chart of the proposed procedure

3.1 Computation of typical load profiles

The most convenient operating management of the FC depends on the load levels and profile during the considered time window. Therefore, the procedure generates several typical load profiles, by using the following input data:

- duration of the considered time window T (e.g. the study can be carried out only for few hours, on daily basis or for more than one day, depending on the considered scenario);
- number M of time intervals i in which time window T is divided;
- time intervals in which an external source is available (whose total duration is T_{net});
- list of N loads to be supplied;
- electric power rating (P_j , where $j = 1, \dots, N$) of the different loads of the system;
- expected time of operation of each appliance or electric auxiliary. This information is represented in terms of probability of utilization of load j at time i , $p_{i,j}$, and also, for certain types of loads that can be conveniently grouped (e.g. lighting devices), in terms of expected level of load j connected at time i .

On the basis of the above information, the expected energy request in the i -th period (R_i) is calculated as:

$$R_i = \sum_{j=1}^N P_j \cdot A_{i,j} \quad (1)$$

where $A_{i,j}$ are the binary variables (i.e. equal to 0 or 1) describing the actual on-off state of load j at time i . The $A_{i,j}$ value is a function of probability $p_{i,j}$. $A_{i,j}$ is obtained by generating a random number in the range from 0 to 1: if the random number is lower than the estimated probability $p_{i,j}$, then $A_{i,j}$ is set equal to 1 and vice-versa. Following this procedure, a single run of the code provides a typical load profile of R_i values for $i = 1, \dots, M$.

3.2 FC “on-off” operating sequence

Once a typical load profile is obtained, the developed procedure determines in which periods the FC should be put in operation and the convenient FC power output levels. The procedure imposes that the FC could start only when the battery state of charge reduction is above a defined threshold E_{Tsh} , as illustrated in Fig. 4. In particular, at time interval i , the FC start-up is allowed if:

$$B_{i-1} > E_{Tsh} \quad (2)$$

where B_{i-1} is the SOC reduction (with respect to the full charge condition) at time interval $i-1$. E_{Tsh} value is a function of the FC characteristics, i.e., it is equal to the energy provided by the FC operating at full load P_0 for a given period of time T_w , named in this work as startup delay. T_w is the time required to completely recharge the battery if the load request is zero and the FC is operating at the rated power level (P_0).

Fig. 4 – FC startup logic as a function of the battery stored energy level.

At each time interval i , the procedure estimates the level of energy reduction from full charge of the battery (B_i) as a function of the load energy request (R_i) and of the energy produced by the FC in the period ($P_{FCi} \cdot \Delta t$):

$$B_i = B_{i-1} + (R_i - P_{FCi} \cdot \Delta t) \quad (3)$$

In the following time interval, $i+1$, the most convenient FC production level $P_{FC(i+1)}$ is chosen as a function of the value of B_i as illustrated in Fig. 5: P_{FC} is set to be proportional to the energy reduction in the battery B_i only if the FC is operating between the maximum and minimum values (P_0 and P_{min} , respectively), as the FC efficiency would dramatically decrease for P_{FC} values external to the $P_{min} - P_0$ range (e.g. [2]).

Fig. 5 – FC power output as a function of battery SOC. The values of P_{FC} and B are normalized with respect to FC rated power P_0 .

The proposed procedure adopts the following condition to stop the FC:

$$B_{i-1} + R_i < P_{\min} \cdot \Delta t \quad (4)$$

At time interval i , the FC is stopped if the energy provided by the FC at production level $P_{\min}$ would exceed the battery energy reduction level taking, into account the expected load energy requirement.

Equations (2) and (4) define the simplified conditions for FC on-off decisions, while Fig. 5 illustrates the simple criterion assumed to choose a convenient power production level of the FC in each time interval. The above criteria are only adopted in the proposed procedure for a preliminary investigation on either sizing and operating management of the FC and battery. The actual automatic control system will take into account several other criteria based on field measurement and on the estimation of the state conditions of all the components.

3.3 Estimation of the required battery capacity

Given the load profile and the calculated FC power production, we estimate the minimum value of battery capacity E_{Acc} required to compensate, in each time interval i , the unbalance between the energy required by the loads and the FC production:

$$E_{Acc} = \max_i (B_i) \quad \forall i = 1 \dots M \quad (5)$$

Other quantities are also calculated by the above described procedure:

- total energy required by the loads during the considered time window ;
- maximum load peak;
- energy amount provided by the FC in the entire time window;
- number of FC startups;
- net energy amount provided by the battery in the entire time window.

Due to the probabilistic character of the load profiles, we obtain different results for each calculation. The calculations are therefore repeated several times (e.g. 1000) in order to obtain a group of “sample” values for each output. In order to achieve a practical information from a statistical point of view, the developed code calculates the average and the maximum values. On the one hand, the maximum value can be used for a first conservative estimate of the target quantity (e.g. battery size), in the framework of a preliminary design activity. On the other hand, for the case of interest, we have observed that the mean values may often represent a more economically viable option, by smoothing the effects of extreme operating conditions on the final result. In such a case, a proper protection system should be designed and implemented.

4. RESULTS OBTAINED FOR THE CASE OF A CRUISE MOTOR YACHT

The above described procedure and the developed code have been applied for the analysis of the design of an APU on-board of a 15 m length cruise motor yacht. The list of the appliances and electrical auxiliaries is shown in Table 1.

Table 1 – Appliances and electrical auxiliaries of the considered 15 m length cruise motor yacht.

DC loads	Power (W)	Utilization characteristics	Possible delay
cruise lights	600	night	No
internal lighting	528	night	No
navigation instruments	768	during cruise	No
GPS	144	during cruise	No
plugs	240	random	No
autoclave	768	random	No
refrigerators	336	cyclic operation (1 h per cycle)	Yes
bilge pump	384	30 min	No
sanitary water pump	1032	random	No
AC Utilities	Power (W)	Utilization characteristics	Possible delay
plugs	1500	random	No
air conditioning system	2000	cyclic operation (30 min per cycle)	Yes
kitchen hot plates	7500	4 plates	Yes
desalting set	2000	3-4 hour	Yes
anchor winch	1944	10 min	No

A typical one-day utilization scenario has been simulated. Figures 6 and 7 show the assumed probabilities of utilization of various appliances and electrical auxiliaries. For some appliances, namely refrigerators and air conditioning, a cyclic operation has been considered so that once switched on, they remain in operation for a predefined duration. The assumed probabilities of some loads (namely navigation instruments, GPS, cruise lights and anchor) are associated to the considered cruise scenario. For example, we present here some results obtained for a 9 hours APU utilization scenario (between 10 a.m. and 7 p.m.), while in the remaining time of the day the on-board load is assumed to be fed by the harbor power grid or by the generator moved by the traction engines.

Fig. 6 – Probability distributions of DC loads

Fig. 7 - Probability distributions of AC utilities

Figure 8 shows a load profile obtained by applying the described procedure and the relevant FC productions for the case of an APU equipped with a 1 kW FC and for the case of an APU equipped with a 5 kW FC. In both cases FC startup delay T_w has been assumed equal to 15 min.

Fig. 8 – Load profile and generated power production for the case of a 1kW FC and for the case of a 5 kW FC.

Figure 8 shows that the 1 kW FC should operate continuously at full load while the 5 kW FC is required to modulate its power output. This is a behavior that we have observed also for different load profiles.

The minimum FC size that would allow covering the total energy requested by the on-board load during the period of external source unavailability can be calculated with the following equation:

$$P_0 = \frac{\sum_i R_i \cdot \Delta t}{T - T_{net}} \quad (6)$$

For the case of Figure 8, the minimum FC size is equal to nearly 2 kW. In case of a smaller FC size, for example 1 kW, the battery (assumed to be fully charged when the external source becomes unavailable) provides the remaining amount of energy not produced by the FC.

Figure 8 shows also that the load power request and the FC power output do not match at every time interval, thus requiring the battery intervention. The net energy amount provided by the battery is shown in Fig. 9, for the same load profile of Fig. 8 and for the case of 1 kW FC, 2 kW FC and 5 kW FC. This energy amount increases when the battery contributes to feed the load, while it decreases in the periods in which the FC power output is greater than the load request and the resulting surplus is stored in the battery. According to Eq. (6), the maximum net energy amount of Fig. 9 indicates the minimum required value of the battery capacity, if a specific load management scheme is not implemented which would also block or delay the utilization of some loads.

Fig. 9 shows that the battery size for the APU equipped with a 1 kW FC is significantly (almost five times) larger than for the case of a 5 kW FC system. Similar results have been obtained also for different load profiles.

Fig. 9 – Net energy amount provided by the battery (for the case of 1 kW FC, 2 kW FC and 5 kW FC)

In order to assess the most suitable FC size and the required battery capacity, a sensitivity analysis has been carried out: the range of FC size P_0 from 1 to 5 kW has been investigated and the FC startup delay value (T_w) has been varied between 15 min and 90 min. For each considered value of P_0 and T_w a set of 1000 load profiles has been analyzed.

The calculated average values of required battery capacities are shown in Fig. 10. It can be observed that, for a given FC size, the lower T_w , the lower the required size of the battery. For low FC delays ($T_w=15$ min), the battery capacity decreases if the FC installed power increases, with a minimum of about 2 kWh for FC size up to 4-5 kW. For longer T_w , the minimum battery size is obtained for FC size of approximately 3 kW. It can be observed that the calculated average battery size is about 2 kWh for $T_w=30$ min and increases up to 4 kWh for $T_w=75$ min.

The calculated average number of FC startups occurring during the simulated day is provided in Fig. 11. These results show the effect of FC size and FC startup delay T_w . The smallest FC (1 kW) must be working during the whole operating period of the APU (only one startup), while for larger FCs the number of startups depends on the FC delay value. If T_w is low (15 min) a larger FC undergoes a higher number of startups (up to 3 for a FC of 5 kW). Moreover, according to the obtained results, the lower the FC delay the higher the number of FC startups.

Fig. 10 –Battery required capacity (mean value over 1000 different load profiles)

Fig. 11 – Number of FC startups (mean value over 1000 different load profiles)

The above results have been obtained without taking into account any limitation on the peaks of the load request. Nevertheless, because of the probabilistic characteristic of the load, the load profile can present very high peaks (up to 8-10 kW). In order to avoid a low utilization of the resources, a second group of simulations has been carried out introducing the possibility to delay and/or to shed the power requested by certain appliances (indicated in Table 1), if the total instantaneous load exceeds a given limit. In particular, if, in time interval i , the load exceeds the given threshold, two different load management strategies are implemented:

- desalting set and refrigerators are switched-off and their request of power is shifted to the first following time interval when the total load is below the given threshold;
- air conditioning and kitchen hot plates load requests are halved and the time of operation is doubled, so that the global energy required is kept constant.

A priority list in load management is established based on the appliance power request: the first load request shed or delayed is the largest one.

Figure 12 shows, for a typical load profile, the effects of the described load management strategy. The peak shedding strategy allows reducing the required battery capacity, as illustrated in Fig. 13 where the battery capacities are calculated by averaging over 1000 load profiles and assuming a peak shedding threshold equal to 4 kW. The reduced battery size requirement is more evident for the case of low T_w values and intermediate FC size. The maximum battery size reduction (namely 22 %) is obtained for the case of $T_w = 15$ min and $P_0 = 3$ kW.

Fig. 12 – Peak shaving effect of load delay and reduction

Fig. 13 – Peak shaving effect on battery size (threshold for load shedding equal to 4 kW)

Another aspect that has been considered is the amount of fuel consumption by the FC, which directly implies the size of the fuel tank that should be installed on-board in order to grant the required autonomy. We have assumed to employ hydrogen as a fuel and a FC stack efficiency equal to 45% [2]. The efficiency value of the power conditioning devices is preliminary assumed equal to 90 %.

The resulting average fuel consumptions for a one day utilization scenario and for different values of P_0 and T_w are shown in Fig. 14 . For the case of a 1 kW FC, the hydrogen consumption is lower than for all other considered FC sizes. Indeed, as already observed, even if the 1 kW FC operates continuously, the FC generated energy is lower than the total energy required by the loads. On the contrary, larger FCs are able to provide enough energy to cover the load energy request. The obtained results show that with a low FC startup delay (e.g. $T_w=15$ min), the FC hydrogen consumption is almost constant for FC sizes from 2 to 5 kW. If T_w is high (e.g. 60 min), the consumption of H_2 decreases for FC sizes from 2 to 5 kW, due to the fact that, as the T_w value rises, a larger quantity of energy is supplied by the battery before the FC startup.

Fig. 14 – FC hydrogen consumption and H₂ storage system weight (without load management)

The proposed methodology allows the assessment of the benefit due to the employment of a FC based APU system in terms of weight, a parameter of significant importance in on-board applications. The total weight of the battery, the H₂ storage system and the FC has been compared with the weight of a battery able to provide all the energy requested by the loads of the considered yacht during the considered time window.

Concerning the battery, two technologies have been considered: conventional lead-acid elements (with a mean weight of 30 kg per kWh of stored energy) and high-density Ni-Zn elements (20 kg/kWh). Figure 10 shows the weights of the batteries required to cover all the energy requests, with and without the presence of a FC.

The assumed weight of the hydrogen storage system is equal to 80 kg per kg of H₂ in case of a 220 bar steel tank, or 20 kg/kg of H₂ in case of a 350 bar composite material tank. The calculated values of the H₂ storage system weight are provided in Fig. 14.

The FC weight (including the cell, the auxiliaries and the power conditioning device) has been estimated to be around 20 kg/kW.

The reduction of the APU system mass due to the adoption of a FC with respect to the case of a simple battery is illustrated in Fig. 15, where the effect of P_0 is shown. In case of high density batteries and a composite materials H₂ storage system, the weight reduction is somewhat larger than for the case of the adoption of more conventional technologies. The results show that the adoption of an APU with a 3 kW FC, which requires the lowest battery size according to the results of Fig. 10, provides a benefit in terms of weight (reduction of nearly 50 – 60 %) in comparison with a simple battery unit.

Fig. 15 –FC based APU weight reduction with respect to a simple battery unit

6. CONCLUSIONS

The methodology developed in this study for a preliminary design of an APU equipped with a FC can be in principle employed to study various on-board applications. The results which have been shown here refer to the case of a yacht application, where a group of relatively small auxiliaries and appliances occasionally require energy with stochastic occurrence, when external energy sources (harbor power system or propulsion engine) are not available. As shown by the estimated typical load profiles referring to a one-day utilization scenario, a PEM fuel cell system is in principle suitable for the employment in this case, since the typical FC sizes are comparable with the on-board load requests.

In this study, it has been assumed that the FC does not operate according to a load following mode, so that, in order to cover the instantaneous load request, the FC operation must be integrated by a battery.

The proposed methodology helps to identify the most suitable sizes of the FC, battery and hydrogen storage system. The obtained results show that in order to limit the required battery size, the optimum FC size should be in the range of 2-3 kW. Small FCs are not able to cover all the energy request and thus oblige to install large batteries, while the adoption of large FCs will increase the number of FC startups (for low T_w values) or the battery size (for high T_w values).

The obtained results show also that, if an appropriate load management scheme (able to postpone and/or reduce the required power of some appliances at peak load periods) is implemented, the battery size can be significantly reduced.

ACKNOWLEDGMENTS

This paper presents some of the results obtained in the framework of a research project between YdroXel s.r.l. and CIMIS (Research Consortium among the Universities of Bologna, Perugia and Ferrara – Italy). Thanks are due to Prof. Carlo Alberto Nucci and Prof. Antonio Peretto for their useful comments on the manuscript.

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