A Methodology for Sizing Backup Fuel-Cell/Battery Hybrid Power Systems

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A Methodology for Sizing Backup Fuel-Cell/Battery Hybrid Power Systems

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***Abstract*—Hybridization of fuel cells and batteries combines the advantages of both power sources. This paper proposes the use of fuel-cell/battery hybrid power systems as backup power systems and develops a methodology for sizing both fuel cell and battery bank, according to a minimum lifecycle cost criterion, from any defined hourly load profile and any defined backup time. For this purpose, an existing power-system-sizing computer tool has been used, but its initial capabilities have been extended. The developed methodology allows decisions to be taken before any investment is made. As a practical application, the methodology is used for the sizing of a backup power system for a telecommunication system.**

***Index Terms*—Cost saving, decision capabilities, fuel-cell systems, hybrid system, simulation tool.**

I. Introduction

FUEL-CELL/BATTERY hybrid power systems combine the advantages of both power sources. This way, these power systems can be interesting for certain backup applications. This paper develops a methodology for sizing backup fuel-cell/battery hybrid power systems, according to a minimum lifecycle cost criterion, from any defined hourly load profile and any defined backup time. The developed methodology is based on an existing sizing tool for hybrid systems, but its initial capabilities have been extended in order to consider backup performance. This way, it is possible to make decisions before investment is made, which is much more important in such expensive systems. As a practical application, the methodology is used for the sizing of a backup power system for a telecommunication system.

The most commonly used technologies for backup power systems are lead–acid battery systems and engine–generator sets. These two alternatives do not clearly comply with some requisites of an ideal uninterruptible power supply (UPS): 1) good quality of electric service (total harmonic distortion, power factor, fast transient response, zero switching time from normal to backup mode and vice versa, etc.); 2) high power and energy density; 3) high reliability and efficiency; 4) low electromagnetic interference and acoustic noise; 5) electric isolation; 6) low maintenance; 7) low cost; and 8) low weight and small size [1]. The disadvantages of engine–generator sets are mainly high maintenance, fuel availability (both are very inconvenient in remote locations), high pollution, and noise. Nevertheless, they are suitable for long runtimes and are relatively highly reliable. On the other hand, batteries are low cost, but they are not suitable for long runtimes (due to low energy density). They are also nondurable and very sensitive to temperature and fluctuations in the power drawn. Thus, there is uncertainty in lifetime and capacity. Although most backup power systems use lead–acid battery systems and engine–generator sets, or a combination of both, customers are seeking out alternatives that provide high reliability and durability at a reasonable cost. Among these alternatives are fuel cells.

Fuel-cell-based systems are emerging as an important candidate to substitute technologies used in backup power systems [1]–[4], thanks to their high specific energy, high reliability, and no pollution. Specifically, proton-exchange-membrane (PEM) fuel cells are considered as among the best alternatives due to their low operating temperature and relatively fast response time [5]. Moreover, PEM fuel cells are compact and lightweight. In comparison to batteries, fuel cells provide longer continuous runtime (energy storage is decoupled from power source size, unlike batteries) and greater durability in hard outdoor environments under a greater range of temperature conditions. They require less maintenance than both generators and batteries because they have fewer moving parts. They can also be monitored remotely, reducing the actual maintenance time. In comparison to generators, fuel cells are quieter and can have no emissions.

Among the backup power system markets of most interest for PEM fuel cells are backup systems for telecommunication applications [6]–[12], specifically backup power systems for telecommunication systems connected to the electric grid but in remote locations, where interruptions are common [2]. Such telecommunication systems could require a power capability from 1 to 10 kW and an autonomy of 1–2 or 24 h [7].

However, there are not only advantages with fuel cells. They also have drawbacks that primarily include high capital cost, slow dynamics in starts and transients, and low power density. Consequently, fuel cells mandatorily need an auxiliary power source to overcome slow dynamic response and to supply the auxiliary devices in the start. A small battery bank can perform this function. In conclusion, each alternative might be better than the others, depending on the specific application. Fig. 1 suggests the best alternative for backup power systems based on the required power and energy [13]. It is deduced from Fig. 1

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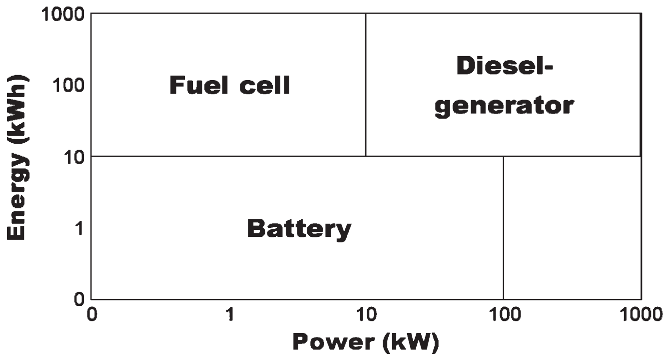

Fig. 1. Options for backup power systems.

that fuel cells can compete in applications when the required power is low and backup time is long. Note that, in spite of current high capital costs of fuel-cell power sources, lifecycle costs can be lower in these applications.

In order to overcome the drawbacks of fuel cells and batteries, a fuel-cell/battery hybrid power system can be considered. This system combines the advantages of both components, mainly the high power density of batteries and the high energy density of fuel cells [14]. In addition, hybridizing allows the size of both components and the energy efficiency to be optimized due to the degree of freedom in power sharing since neither would have to provide the full load. Supercapacitors are also suggested as an auxiliary power source added to a fuel-cell system [15]. These elements solve the limitation in the slow dynamics of fuel cells and have higher power density and lower maintenance than batteries, but they have much less energy density.

Certain load profiles and long runtimes can make the use of fuel-cell/battery hybrid power systems interesting for backup applications, but searching for an optimum size for both power sources is not a trivial matter. Most present works in the literature on sizing of hybrid power systems are applied to stand-alone power systems that incorporate renewable energy sources and to propelling systems for vehicles [16], [17]. In the first case, sizing focuses on obtaining systems with a minimum lifecycle cost and a minimum unmet load. The search for the minimum-cost stand-alone power system is vital because an oversized system may mean a high price. Since there is no direct relation between the component sizes and the total cost of the system, the methods found in the literature are mainly based on simulations of the power system behavior, which must supply a known profile load, with the period of study being one or several years and the simulation step being usually an hour. Some works base optimization on an iterative method where several power systems that are different in size are simulated and analyzed [18], [19]. In this sense, there are several software tools for sizing hybrid power systems. One of the most widespread sizing tools is HOMER [20], which is developed by the National Renewable Energy and is free access. This tool allows evaluation of the economic and technical feasibility of several technology options by carrying out long-term performance simulations based on hourly energy balances. Other methods apply optimization techniques for finding the minimum-cost power system [21]–[24].

This paper develops an easy methodology for sizing backup fuel-cell/battery hybrid power systems. This methodology allows selection of the size for the backup fuel-cell/battery hybrid power system, according to a minimum lifecycle cost criterion, from any defined hourly load profile and any defined backup time. The developed methodology uses the HOMER tool in some steps. However, it has been necessary to extend its initial capabilities in order to consider backup performance.

Section II describes the power system under study. In Section III, the developed methodology is explained. Then, in Section IV, the methodology is applied for a certain load profile, which is very common in telecommunication systems. Finally, the conclusions are shown in Section V.

II. Description of the Power System Under Study

The configuration of the backup power system under study is shown in Fig. 2 (framed in a box), where it is inserted in a whole UPS system. The backup power system consists of a fuel cell, its energy storage, a battery bank, and the power electronic devices. The fuel cell is connected to the dc bus by means of a dc–dc converter. It allows the fuel-cell output voltage to be regulated and the fuel-cell output power to be controlled [25]. The battery bank can be connected directly to the dc bus or by means of a dc/dc bidirectional converter (for charging and discharging batteries). The latter alternative gives more flexibility in selecting batteries because the constraint of the dc bus voltage is eliminated. However, the low-level control strategy is more difficult because converters are cascaded, and cascaded converters cause constant power instability and subharmonic production [26].

The international standard IEC 62040-3 classifies UPS systems as three main types, which are as follows: 1) passive standby; 2) line interactive; and 3) double conversion [27]. Only this last topology offers nearly absolutely UPS and compensates all power disturbances such as voltage fluctuations, frequency fluctuations, voltage transients, short interruptions, and long power outages. The double energy conversion (ac to dc and dc to ac) allows all aspects of power quality to be controlled, even though it allows the output frequency to be changed. However, low efficiency and theoretical low reliability in comparison with the other topologies are its drawbacks. In spite of this, it is the most common UPS topology over 10 kV · A [28].

The UPS topology in Fig. 2 is based on the double-conversion type, where the battery bank (the typical backup power system) is now replaced by a backup fuel-cell/battery hybrid power system. In addition, the UPS has several outputs, which are ac and dc types. An example of the need for these two outputs includes telecommunication facilities. The current convergence of telecommunication and information technology equipment can result in critical loads requiring both −48 VDC and 240 VAC [29].

The proposed double-conversion UPS has three operating modes (see Fig. 2): 1) normal mode—power from the mains is rectified to the dc bus and then distributed to ac and dc loads; 2) stored-energy mode—when the quality of the mains power goes outside a specified range, the loads are supplied by the backup fuel-cell/battery hybrid power system (note that the dc

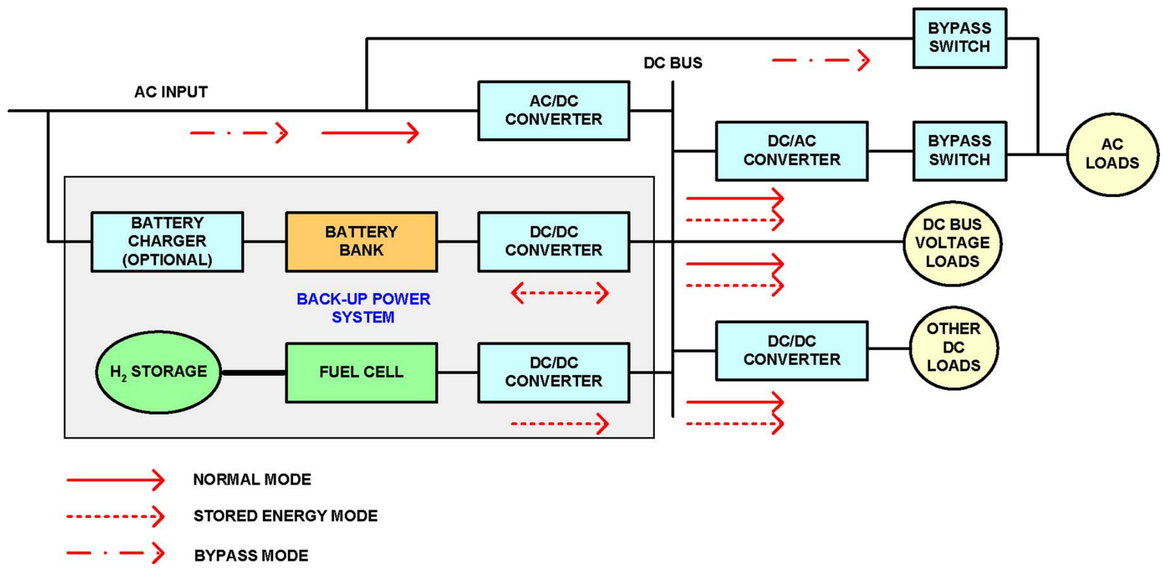

Fig. 2. UPS system configuration.

bus must have capacitors to provide stored energy during the transition to stored-energy mode); and 3) bypass mode—bypass switches allow the ac load to be supplied directly by the mains when the UPS fails. An additional battery-charging circuit is also included, which is supplied by the mains.

The developed methodology is only applied to sizing the fuel-cell system and the battery bank. Therefore, the methodology is independent of the chosen UPS topology.

In the studied backup power system, the battery bank mainly assists the fuel cell in the following four issues: 1) cold starting (supplying the control system and auxiliary devices in the fuel cell); 2) limitation of the fuel cell in fast load transients (due to slow dynamic response caused by mechanical transients in the hydrogen/oxygen delivery system); 3) supply of critical load while the fuel cell starts (from seconds to minutes, depending on the type of fuel cell); and 4) supply of critical load in high-power periods when fuel-cell power is not enough. However, depending on the defined energy management strategy, the battery bank could supply the load in other situations.

The load profile is input data that must be defined in order to carry out the sizing. The load profile will be based on hourly average power values, as done in other works on sizing of stand-alone power systems [18], [19], [21], [23], [30]. The intrahour load fluctuations may influence the energy requirements of the system, so the concept of *required operating reserve* is used to guarantee that the power system has enough energy capacity to support short-term fluctuations in the load.

The backup time (t_{backup}) is another parameter that must be set in the developed methodology. This value represents the maximum time that the backup power must supply the load during a power disturbance, which is out of UPS tolerance range. In order to simplify the writing, in this paper, these power disturbances are called *serious power disturbances*. The backup time will be set slightly higher than the estimated maximum length of *serious power disturbances*.

The hydrogen storage size will be set based on the following data: 1) It is assumed that the fuel cell is refueled annually, and 2) statistics about *serious power disturbances* are known. Section III-C describes the method for sizing the hydrogen storage.

III. Methodology

This section describes the methodology for sizing the backup hybrid power system. The developed methodology is based on long-term performance simulations in order to check the technical reliability and to calculate the lifecycle costs of the system. The simulation is carried out, making energy balance calculations for each hour.

The sizing will be tackled with the aim of obtaining a minimum-cost system according to any defined hourly load profile and any defined backup time. Several solutions can be evaluated. A solution is defined by both fuel-cell and battery-bank sizes and the energy management strategy. Note that selecting a good energy management strategy is essential in order to obtain a fine size of power sources because these two problems are coupled [16]. The technical reliability and lifecycle cost of each solution are obtained as a result of this evaluation.

The methodology is carried out according to the algorithm shown in Fig. 3.

Next, the steps of the developed algorithm are described in more detail.

A. Step 1: Selecting the Fuel-Cell Size

According to the load profile, the following considerations must be taken into account when selecting the range of fuel-cell rated powers, which is going to be tested.

1) To determine the minimum rated power, it can be established that it must be sufficiently larger than the maximum average backup load power in any interval of duration that is equal to the defined backup time. However, this constraint is conservative because it does not take into account the battery initial capacity. Therefore, lower powers could be tested.

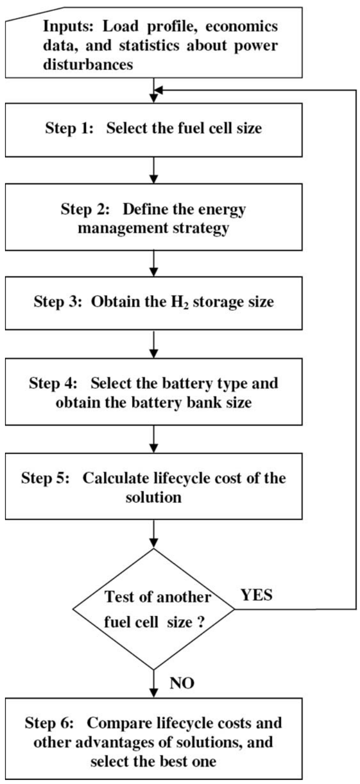

Fig. 3. Algorithm for sizing the backup fuel-cell/battery hybrid power system.

2) To establish the maximum rated power, the following two criteria must be taken into account: 1) rated powers that are greater than the load maximum value (calculated at the fuel-cell output) will not be tested, and 2) the minimum fuel-cell power (recommended by the manufacturer due to poor efficiency at low power levels) must be lower than the minimum backup load power. This constraint can be eliminated using more than one fuel cell operating in parallel.
3) The larger the fuel-cell size, the higher the fuel-cell capital cost and the less restrictive the battery requirements.

B. Step 2: Defining the Energy Management Strategy

Selecting a good energy management strategy is crucial in order to obtain a fine size of power sources. Since only two power sources exist, setting the fuel-cell power output means that the energy management strategy is defined. As mentioned in Section II, the backup time is a specification that must be set. Considering the defined value for this, it is necessary to find a time interval for the load profile that corresponds with the more restrictive requirements in energy and power demand. This is the time interval that must be studied, and obviously, it has to be as long as the backup time. Thus, it is possible to define several hourly power distributions that can be considered during that time interval. These energy management solutions are tackled with the aim of finding a system with the least size and cost.

Development of energy management strategy is one of the most important tasks in hybrid power systems. Generally, the goals pursued by the energy management strategy are as follows: 1) to satisfy the demanded power; 2) to maintain the reliability of components; and 3) to maximize the overall system efficiency. Many studies can be found in the literature, with a lot of them focusing on power systems for propelling vehicles. The more complex scenario happens when the demanded power is unpredictable, e.g., in vehicles. Many works propose to use rule-based or heuristic methods for the development of energy management strategy in fuel-cell-based systems [15], [25], [26], [31]. However, these strategies are usually far from being optimal. Other literature focuses on strategies on the basis of optimization theory [16], [32], [33]. The main drawback of these optimization strategies is their limitations for experimental applications because they are based on precise models.

For sizing purposes, only the steady-state performance is taken into account in the strategy. Since the load profile is supposed to be known, deterministic dynamic programming [32] or other dynamic optimization methods can be used to find the optimal solution. However, a different and easy solution, based on static optimization, for any defined hourly load profile and any defined backup time is proposed in this paper, but this does not lead to find the optimal solution. In any case, the proposed method is aimed at obtaining a low-cost system and presents great simplicity and speed of execution.

Next, the developed energy management strategy is described. Following the sequence of the developed algorithm (see Fig. 3), the energy management strategy must be defined once the fuel-cell size is set. The developed strategy has, as its first aim, to reduce the necessary capacity for the battery bank and, as its second aim, to reduce the consumption of hydrogen, which will affect the size of the necessary hydrogen storage. Once this strategy has been defined, the size of the bank battery that best fits the strategy can be selected in step 4) of the developed algorithm (see Fig. 3), so that, on the one hand, the demanded power is satisfied and, on the other hand, the programmed charge and discharge can be supported by the battery bank.

The developed strategy is based on the following rules. 1) If the power demanded by the load is greater than the fuel-cell rated power, then the power generated by the cell is rated, and the rest of the power will be supplied by the battery; and 2) otherwise, the power generated by the fuel cell is sufficient to simultaneously satisfy the load demand and charge the battery, so that hydrogen consumption is minimized.

In the Appendix, the algorithm that develops the energy management strategy is described in detail.

C. Step 3: Obtaining the H_2 Storage Size

The following statistics are necessary for sizing the hydrogen storage: 1) the estimated number of *serious power disturbances* per year (n); 2) the estimated maximum length of *serious power disturbances* ($t_{\max}$); and 3) the averaged length of *serious power disturbances* (t_{avg}). From these values, the next parameters are calculated

$$t_{\text{backup}} \geq t_{\max} \tag{1}$$

$$t_{\text{backup\_per\_year}} = n t_{\text{avg}} \tag{2}$$

where $t_{\text{backup\_per\_year}}$ is an estimation of the number of operating hours of the backup power system per year. Note that, in this paper, the size of the backup fuel-cell/battery hybrid power system will be set to guarantee supply of the load during a maximum time period of t_{backup} continuously but several times per year. The reason for this is that batteries may be discharged after the backup time, and they must be charged when the grid power is reestablished to be able to supply the load in the next *serious power disturbance*. However, the hydrogen storage size is set to supply several *serious power disturbances*.

It is assumed that the fuel cell is refueled annually. Thus, from previous parameters and other values (fuel-cell power output, fuel-cell efficiency, etc.), the hydrogen storage size can be set. The method developed to size the hydrogen storage includes the following.

1) Calculate the parameter m using the expression

$$m = \mathrm{ceil}\left(\frac{t_{\mathrm{backup\_per\_year}}}{t_{\mathrm{backup}}}\right) \quad (3)$$

where $\mathrm{ceil}(x)$ is a function that calculates the nearest and higher integer of x. Note that the parameter m represents the integer number of intervals of duration t_{backup} that is equivalent to duration $t_{\mathrm{backup\_per\_year}}$.

2) Calculate the hydrogen consumption (cons_{H2}) in an interval of duration t_{backup}. Note that this value depends on several factors: 1) the part of the load profile that is considered inside the interval (see Section III-B); 2) the fuel-cell power output (see Section III-B); and 3) the fuel-cell efficiency curve, which is supposed to be known data.

3) Calculate the hydrogen storage size (st_{H2}) using the expression

$$\mathrm{st}_{H2} = f_{s1} \cdot m \cdot \mathrm{cons}_{H2} \quad (4)$$

where f_{s1} is a security factor, which is recommended for sizing. In Section IV, a value for f_{s1} is proposed.

D. Step 4: Selecting the Battery Type and Obtaining the Battery Bank Size

Lead–acid batteries are the most widespread batteries in backup applications due to their high-quality–price ratio, and they are assumed to be considered in this paper. There are mainly two kinds of lead–acid batteries: 1) flooded batteries and 2) valve-regulated lead–acid (VRLA) batteries. The latter type presents lower installation and maintenance costs, lower pollution, and higher energy density. However, lifetime in flooded batteries is higher, and they are commonly used in UPS applications over 500 kV · A [34].

Once the fuel-cell size, fuel-cell power output, and battery type are set, the battery bank size must be defined. Note that, as the load profile is defined, setting the hourly power generation in the fuel cell means that the battery hourly discharging/charging power is fixed. The battery bank size must be high enough to comply with this hourly discharging/charging power profile.

In order to verify the proper performance of the battery bank, the kinetic battery model is used [35]. Several sizing tools for hybrid systems use this model, e.g., HOMER and HOGA [30].

In this paper, to execute the kinetic battery model, the HOMER tool is used. Nevertheless, HOMER does not allow backup power systems to be analyzed because it is designed for continuously operating systems. In order to solve this problem, a method is developed in this paper to extend the capabilities of HOMER and apply this tool to the sizing of backup fuel-cell/battery hybrid power systems. Section III-F describes this method.

E. Step 5: Calculating Lifecycle Costs

The following considerations are assumed in order to calculate the lifecycle cost of each solution.

1) Fuel-cell lifetime specified in operating hours exceeds that needed in typical backup applications, so degradation will be caused mainly by aging and not by operation [13]. Thus, lifetime due to aging is the most important parameter between both. This value is used to calculate the total fuel-cell replacement cost during the project lifetime.
2) The same consideration from the previous point is applied to batteries.
3) The capital cost of each component (battery bank or fuel cell) includes the capital cost of the equipment and the installation cost (auxiliary devices, electrical installation, enclosure, start-up, etc.).
4) The replacement cost of each component usually only includes the replacement cost of the main equipment.
5) The operation and maintenance (O&M) cost of both power sources is assumed to be an annual constant value.
6) It is assumed that the fuel cell is refueled annually. Thus, the costs of refueling the fuel cell, which are taken into account, are as follows: 1) installation cost of hydrogen storage and 2) annual rental costs of tanks.
7) The salvage value of the component at the end of the project lifetime is proportional to its remaining life.
8) The solutions are ranked by the total net present cost (total NPC). Annual real interest rate and project lifetime are input parameters for calculating the total NPC. Expressions to calculate the total NPC can be found in [20].
9) The size of hydrogen storage is set according to Section III-C.
10) The cost for charging batteries is supposed to be negligible.

These considerations are similar to those used in [2] in order to compare backup solutions based on fuel cells, batteries, and diesel generators. The total NPC of each solution will be calculated at the same time as the battery performance is checked. This means that battery performance and the total NPC of a solution are obtained simultaneously by simulations using HOMER.

F. Method for Obtaining the Battery Bank Size and for Calculating the Total NPC Using HOMER

In general, site-specific weather conditions, load profile, system configuration, technical and cost information for

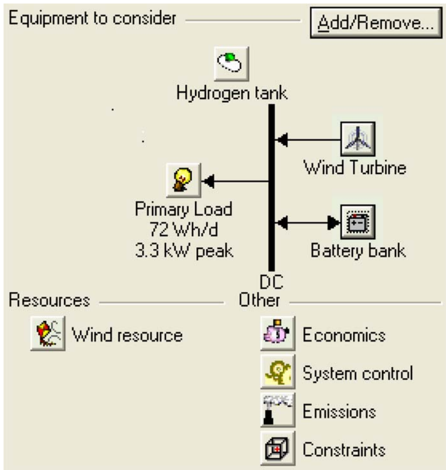

Fig. 4. System configuration entered in HOMER.

components, economic data, operating constraints, and system control inputs have to be entered by the user before a simulation in HOMER. To simulate backup systems, some considerations have to be taken into account: Site-specific weather conditions are not applied, and the load profile is set to zero outside the studied time interval that will be selected according to Section III-B (the one with more demanding conditions and in which duration is equal to the defined backup time). Note that only a *serious power disturbance* is supposed to occur annually in the HOMER simulation, but it is not an inconvenience if more *serious power disturbances* are estimated to happen. The reasons for this are as follows: 1) fuel-cell and battery lifetimes are supposed to be independent of operation hours (and so replacement costs too), and 2) H_2 consumption and H_2 storage size are calculated in step 3) of the algorithm (see Fig. 3), not in the HOMER simulation. Thus, costs for H_2 storage can be known prior to the simulation.

The main problem when simulating backup systems in HOMER is that the energy management strategy cannot be defined. Only the two strategies implemented in HOMER can be running (*load following and cycle charging*), so power system size cannot be optimized. Thus, the fuel-cell power output calculated in step 2) of the developed algorithm cannot be entered in HOMER.

The key to the developed method is the substitution of the fuel cell with a wind turbine whose power output is the same as that specified for the fuel cell. This power output can be directly defined by the user with time series entered using a text file. A similar method can be found in [36], where it was used to substitute converter module power output to optimize the size of a stand-alone PV system using converter paralleling. Using this method, energy management strategies that are different to those implemented in HOMER can be run, specifically those developed in step 2) of the developed algorithm. HOMER calculates hourly energy balances. As a result, there is no inconvenience for the wind turbine to replace the fuel cell in simulations. Moreover, the cost treatment applied by HOMER to the turbine is the one needed for the fuel cell according to what has been stated in Section III-E.

Fig. 4 shows the system configuration entered in HOMER.

Based on the considerations indicated in Section III-E, the following cost information for each HOMER component must be entered.

1) Component *Wind turbine*. As mentioned previously, this component replaces the fuel cell in order to adjust the power output.
   a) Capital cost.
   b) Replacement cost.
   c) Operation and maintenance cost per year.
   d) Lifetime (in years). Note that this parameter is independent of operation hours.
2) Component *Battery*.
   a) Capital cost.
   b) Replacement cost.
   c) Operation and maintenance cost per year.
   d) Lifetime (in years). Note that this parameter is independent of operation hours. The HOMER parameter that contains it is *float life*, and it is in the description of the battery type.
   e) The battery-bank roundtrip efficiency must be modified to enter the battery converter efficiency in the HOMER simulation.
3) Component *Hydrogen tank*. This component is disconnected from all components in the simulation system. Its only function is to insert the hydrogen storage costs in the simulation results. Note that storage size has been set in step 3) of the developed algorithm.
   a) Capital cost. This value represents the H_2 storage installation cost.
   b) Operation and maintenance cost per year. In this parameter, the annual rental cost of tanks is entered because the O&M cost is not considered.
   c) The replacement cost is set to zero. Thus, the value for lifetime is the same.

Other parameters to enter before the simulation are as follows.

1) *Annual real interest rate* and *Project lifetime* in the *Economics* button.
2) Fuel-cell power output in the *Wind resource* button. An hourly time series with 8760 elements must be entered using a text file (with the value zero outside the studied interval). Note that, as these values are to represent the fuel-cell power output, the turbine power curve, i.e., power (in kilowatts) against wind speed (in meters per second), must be set to the function $f(x) = x$. This power curve is available for the user in the *Wind turbine* button.
3) The *Maximum annual capacity shortage* in the *Constraints* button must be set to 100% in order to lighten the operating constraints and, thus, to allow all the solutions to appear in the simulation. The first input for the *operating reserve* in the *Constraints* button must be set to the value considered for the load variability, and the fourth input must be set to zero because the wind turbine is replacing the fuel cell.

The *operating reserve* provides a margin to account from intrahour deviation from the hourly average of the load or the renewable power output. Since the wind turbine is used to

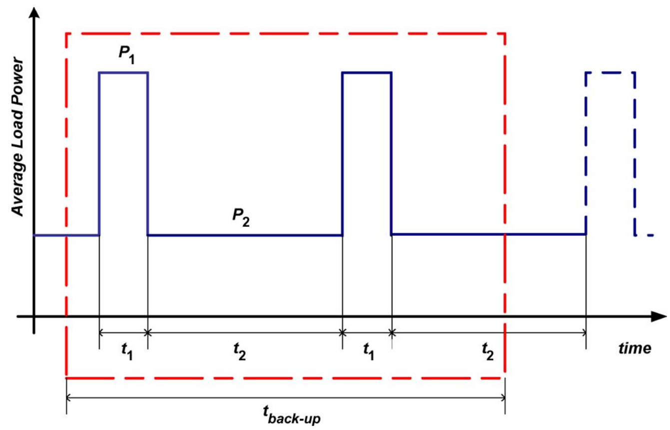

Fig. 5. Typical telecommunication system load.

emulate the fuel cell, its power is not subject to fluctuations, and the parameter associated to the *operating reserve* due to the wind resource must be set to zero. Also, the reserve provided by the wind turbine is zero because, unlike the fuel cell, it is not a dispatchable power source. As a result, all the required *operating reserve* is supported by the battery bank. This represents a more unfavorable situation than in the actual case, so it is supplied with another security margin for the battery bank size. The unmet required *operating reserve* is computed by HOMER as *capacity shortage*.

In short, fuel-cell size, fuel-cell power output, battery type, and hydrogen storage size are already set. Therefore, several numbers of batteries must be considered for the simulation. Among these solutions, the one with the lowest number of batteries and without capacity shortage in simulation results must be selected. In addition, the total NPC shown by HOMER for this solution must be noted.

Since battery performance is uncertain and described with difficulty by a model, and it worsens with time (due to temperature and other factors), a security factor (f_{s2}) is recommended in order to obtain the definitive battery bank size. In Section IV, a value is proposed for f_{s2}. Note that replacing batteries relatively early decreases the uncertainty in its performance due to degradation.

IV. Application Example

As an application example, the developed methodology will be applied to the backup power system for a telecommunication system. It is common for the power requirement for telecommunication systems to present two different levels in a day [37], [38]. Fig. 5 shows a generic load profile found usually in remote telecom sites, where parameter t_2 is significantly higher than t_1 (typically 85%–80% against 15%–20%), and value P_1 is also higher than P_2 [39]–[41]. For calculation purposes, values P_1 and P_2 are considered in the dc bus. The following typical values for parameters from the previous load profile are considered: $t_1 = 2$ h, $t_2 = 10$ h, $P_1 = (3/\eta_{\text{loadconverter}})$ kW, and $P_2 = (0.65/\eta_{\text{loadconverter}})$ kW, where $\eta_{\text{loadconverter}}$ is the efficiency of the power electronic stage between the dc bus and loads. The backup time is set to 22 h.

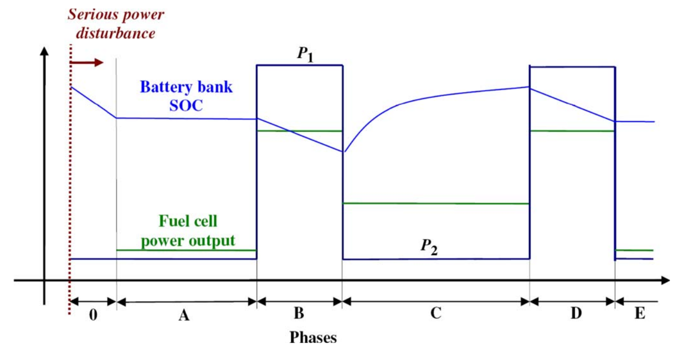

Fig. 6. Energy management strategy.

The features of this profile and the long runtime invite us to look for a fuel-cell/battery hybrid power system for the backup solution.

A. Operation of the Backup Power System

When a *serious power disturbance* happens, the backup power system must be able to supply the load for a minimum of t_{backup} hours or until the grid power is restored or the power quality comes back inside the tolerance range of the UPS. Once one of these events happens, the charging of the battery bank must be carried out by the electric grid.

The operation phases of the backup power system are shown in Fig. 6. According to the energy management strategy developed in Section III-B, the fuel cell works at its rated power in phases B and D, it provides the full load in phases A and E, and it provides the load and charges the battery bank in phase C.

A new phase, namely, phase 0 (see Fig. 6), may be considered in the system operation. Although this phase is not taken into account for the sizing of the system, it is, however, interesting to consider it for improving the system performance. If the *serious power disturbance* occurs in a low-power period, the battery bank starts to supply the load, and phase 0 begins. This phase must be very short since it was not taken into account during sizing. Phase 0 eliminates false start-ups of the fuel cell or start-ups for short *serious power disturbances*. In this way, the numbers of start-ups and operation hours of the fuel cell are reduced, and so is its degradation. In any case, for backup applications, fuel-cell lifetime due to aging is more important than operation lifetime. However, avoiding fuel-cell operation reduces hydrogen consumption. Note that charging batteries is more cost efficient than refueling fuel cells. Note also that reduction in hydrogen consumption is very advantageous in remote locations, where the supply of hydrogen tanks is costly and problematic.

Transitions between phases can be ordered by measuring the level of demanded power. A state machine must be used to manage the sequence of phases. The completion of phase H will be carried out by measuring the energy contents in the hydrogen storage. In any case, the battery-bank state of charge (SOC) must not drop below the minimum value recommended by the manufacturer.

The selection of the method for measuring energy content in batteries and hydrogen storage is beyond the scope of this paper.

Nevertheless, some comments will be done. The hydrogen content in compressed cylinders can easily be measured from the pressure of the gas. In other hydrogen storage methods, e.g., metal hydrides, this relation is more complex [42]. The SOC of batteries is also difficult to measure. One of the most common online methods is current integration. However, this method needs recalibration. A comparison of several methods can be found in [43].

B. Input Data

The following data are considered for the sizing.

1) Fuel cell:
   a) capital cost: \$10.850/1.2 kW;
   b) replacement cost: \$9300/1.2 kW;
   c) operation and maintenance cost: \$78/(1.2 kW · year);
   d) lifetime: 15 years;
   e) efficiency curve: linear passing through (20% $P_{\mathrm{FC},n}$, 0.47) and ($P_{\mathrm{FC},n}$, 0.40).
2) Battery bank:
   a) type: Vision 6FM55D, VRLA battery;
   b) features: 12 V; $C_{20} = 55$ A · h;
   c) float life: five years;
   d) minimum SOC: 40%; round-trip efficiency: 80%;
   e) round-trip efficiency for the HOMER simulation (including energy losses in the battery converter): 0.65;
   f) capital cost: \$120/unit;
   g) replacement cost: \$120/unit;
   h) operation and maintenance cost: \$20/(unit · year).
3) H_2 storage:
   a) annual tank rental cost: \$668/(KgH_2.year);
   b) capital cost (H_2 storage installation cost): \$3000;
   c) replacement cost: none.
4) Economic input:
   a) annual real interest rate: 6%;
   b) project lifetime: 15 years.
5) Efficiency of power electronic devices (see the Appendix):
   a) $\eta_{\mathrm{FCconverter}} = 0.9$;
   b) $\eta_{\mathrm{BATconverter}} = 0.9$;
   c) $\eta_{\mathrm{loadconverter}} = 0.9$.
6) HOMER simulation constraints:
   a) maximum annual capacity shortage: 100%;
   b) inputs for the required operating reserve: 1) as a percent of hourly load: 10%; 2) as a percent of annual peak load: 0%; 3) as a percent of wind power output: 0%; and 4) as a percent of solar power output: 0%.
7) Statistics for serious power disturbances:
   a) estimated number of *serious power disturbances* per year (n): five;
   b) estimated maximum length of *serious power disturbances* $(t_{\max})$: 20 h;
   c) average length of *serious power disturbances* (t_{avg}): 8 h.

For simplicity, costs are supposed to be linear with component sizes. Cost data are based on present values. From previous statistics, the parameter m used for sizing the H_2 storage is calculated using (2) and (3). Thus, $m = 2$.

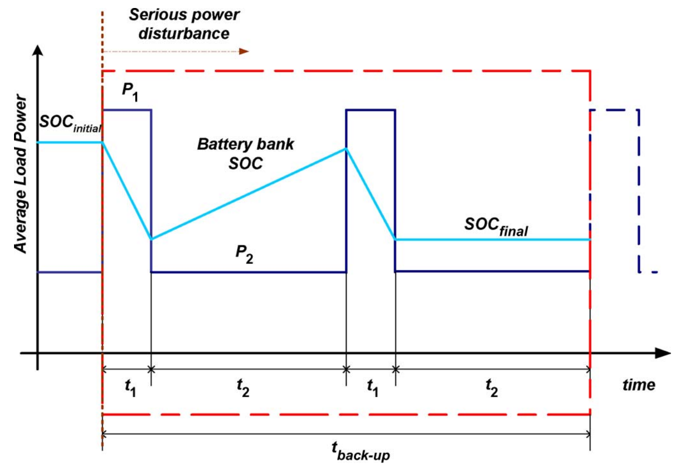

Fig. 7. Scenario I.

C. Sizing Results

The time interval that will be selected according to Section III-B (the one with more demanding conditions and in which duration is equal to the defined backup time) is shown in Fig. 7 (scenario I). In scenario I, the battery bank must supply two whole high-power periods. Then, for each fuel-cell rated power that is going to be tested, scenario I is used to generate the fuel-cell power output according to Section III-B, to obtain the resulting H_2 storage size according to Section III-C, and to size the battery tank according to Section III-D.

Next, the range of fuel-cell rated powers that are going to be tested is defined. Checking the considerations in Section III-A, the minimum fuel-cell rated power will be higher than 1.33 kW (average load for a fuel cell in scenario I), and the minimum fuel-cell power must be lower than 803 W (the minimum load for a fuel cell) if it is assumed that only one fuel cell is installed. The minimum fuel-cell power recommended by manufacturers is supposed to be 20% $P_{\mathrm{FC},n}$, i.e., $P_{\mathrm{FC},n}$ must be < 4.01 kW in the case of installation of only one fuel cell. Moreover, the maximum load average power seen by the fuel cell is 3.7 kW.

Thus, the following solutions are tested:

1) kilowatt fuel cell + small battery to assist the fuel cell for short periods;
2) 2.4 kW fuel cell + battery bank;
3) 1.5-kW fuel-cell system + battery bank;
4) only the battery bank.

Table I shows the results of sizing obtained from simulations, where the values for sizing security factors are $f_{s1} \approx 1.10$ and $f_{s2} \approx 1.20$.

Based on the values considered for input data, the best solutions are the hybrid solutions over both the solution based on the fuel cell without the battery bank and the solution based only on the battery bank. Although the most economical solution is solution 4), the excessive number of batteries (100) makes this solution nearly impracticable. Between solutions 2) and 3), the most economical one is solution 3). Observe that, due to the present high capital cost of fuel cells, the most economical solution in this example is based on the smallest fuel cell. Nevertheless, solution 2) involves fewer batteries than solution 3).

TABLE I
SIZING RESULTS

Solution	FC size (kW)	Annual H_2 consumption (Kg)	H_2 storage size (f_{s1}≈1.10)	Sufficient number of batteries *	Total NPC with * ($)	Selected number of batteries ** (fs_2≈1.20)	Total NPC with ** ($)
1	4	4.03	4.50	-	-	small battery	70887
2	2.4	3.91	4.3	9	58357	12	59769
3	1.5	4	4.4	14	52662	18	54454
4	-	-	-	83	39087	100	47092

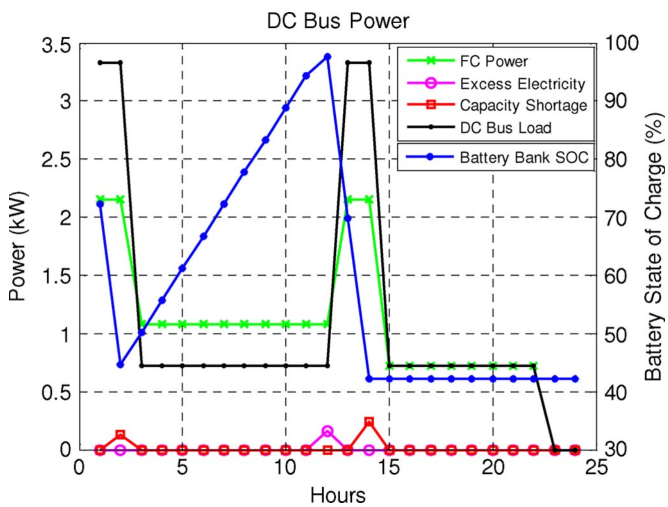

Fig. 8. Simulation of 2.4-kW fuel cell + 8 × 55-A · h batteries in scenario I.

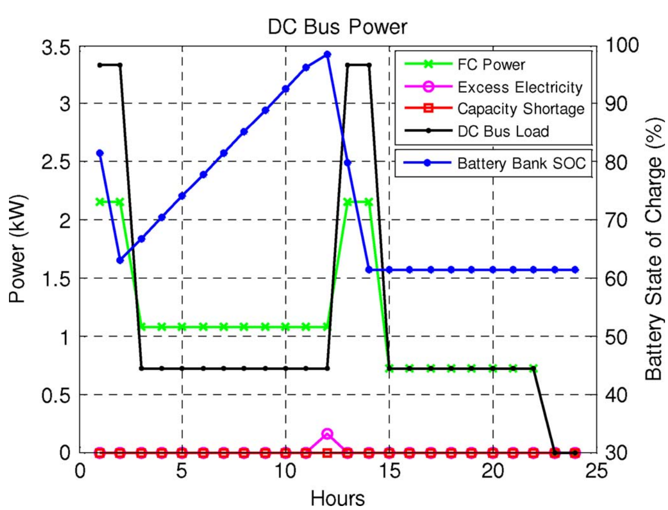

Fig. 9. Simulation of 2.4-kW fuel cell+12 × 55-A · h batteries in scenario I.

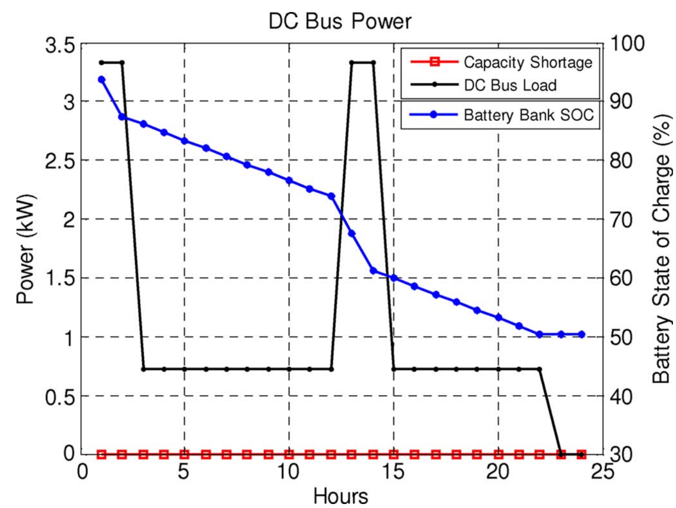

Fig. 10. Simulation of 100 × 55-A · h batteries in scenario I.

Figs. 8–10 show the following simulations: 1) 2.4-kw fuel cell + 8 × 55-A · h batteries in scenario I; 2) 2.4-kw fuel cell + 12 × 55-A · h batteries in scenario I; and 3) 100 × 55-A · h batteries in scenario I.

Simulations show the following concepts: dc load, fuel-cell power, excess electricity, capacity shortage, and battery SOC (see the legends). Excess electricity could appear in the last moment of the charging period because charge power must be reduced at the end of this period, and HOMER considers constant power for each hour. Capacity shortage indicates whether the number of batteries to be studied is sufficient to satisfy the demanded power and the required *operating reserve*. There can be two reasons for an insufficient number of batteries: 1) discharge power is too high, and more batteries are necessary, and 2) the battery-bank SOC reaches the allowed minimum value, so more batteries are also necessary. SOC and excess electricity signals help to distinguish which reason it is.

V. CONCLUSION

The developed methodology allowed backup fuel-cell/battery hybrid power systems to be sized, according to a minimum lifecycle cost criterion, from any defined hourly load profile and any defined backup time. Based on an existing sizing tool for hybrid systems, namely, HOMER, the methodology allowed both fuel-cell and battery-bank sizes to be selected in order to find a minimum-cost backup power system for the defined application. For this purpose, the initial capabilities of the sizing tool have been extended in order to consider backup performance. An energy management strategy, based on the knowledge of the load profile, was developed in order to minimize the size of power sources. As a practical application, the methodology was used to size a backup power system for a telecommunication system, where a typical load profile and a long backup time were considered. As for the results, the found hybrid solutions are better than solutions based on fuel cells or batteries separately. Thus, hybridization has been proved to be suitable for the considered example and potentially interesting for any backup application with long runtime and known load profile. For readers who are interested in testing the developed methodology (comments and criticisms are welcomed), we provide the following URL for download: http://www.uhu.es/manuel.vasallo/fuelcellbat.

Appendix

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Algorithm for energy management strategy

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Input data

t_{backup} % backup time

$P_{\text{load}}(k)$; $k \in \{1, 2, \ldots, N\}$; $N = t_{\text{backup}}/\Delta T$ % demanded power on dc bus

$P_{\text{FC},n}$ % fuel-cell rated power

ΔT % simulation step

$\eta_{\text{FC}}(P_{\text{FC}}) = aP_{\text{FC}} + b$ % fuel-cell efficiency. The efficiency curve is

% supposed to be linear between minimum fuel-cell

% power (maximum efficiency) and maximum fuel-

% cell power (minimum efficiency)

η_{FCconv} % fuel-cell converter efficiency

η_{BATconv} % battery-bank converter efficiency

η_{disch} % battery-bank discharging efficiency

η_{ch} % battery-bank charging efficiency

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Defining *"peak," "offpeak," "transition,"* vector *transition*

step $k \in$ *a* "***peak***" when $((P_{\text{load}}(k)/\eta_{\text{FCconv}}) - P_{\text{FC},n}) \geq 0$, otherwise, step $k \in$ an "***offpeak***;" $k \in \{1, 2, \ldots, N\}$

step k is a "***transition***" when (step $k \in$ a "***peak***" and step $k + 1 \in$ an "***offpeak***") or (step $k \in$ an "***offpeak***" and step $k + 1 \in$ a "***peak***")

if step 1 $\in s$ a "***peak***," then "***transition***" 0 is defined

define vector *transition* such that *transition*(*i*), $i \in \{1, \ldots, M\}$, are all "***transitions***"

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Calculating the fuel-cell power output in the fist interval when it is an

% "*offpeak*"

if $M > 0$ % one "*transition*" exists at least

  if step 1 $\in$ an "***offpeak***," then

    $P_{\text{FC}}(i) = P_{\text{load}}(i)/\eta_{\text{FCconv}}$; $i \in \{1, \ldots, \text{transition}(1)\}$

  end

else % $\boldsymbol{P_{\text{FC},n} < P_{\text{load}}(i)/\eta_{\text{FCconv}}}$ $\boldsymbol{i \in \{1, 2, \ldots, N\}}$

  $P_{\text{FC}}(i) = P_{\text{FC},n}$; $i \in \{1, 2, \ldots, N\}$

  return % the algorithm is over

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Loop for calculating the FC power output for all sets "*peak*"–"*offpeak*"

% Calculating the final index for the loop

if $M > 2$ and M is even, then final_index $= M - 3$

if $M > 2$ and M is odd, then final_index $= M - 2$

if $M > 2$, then % one set "*peak*"–"*offpeak*" exists at least

  $E_{\text{total\_disch}} = 0$ % total energy discharged by the battery bank

  for $i = 1:2:$ final_index % for all sets *"peak"*–"offpeak"

    % Calculating the energy lost by the battery bank in the "*peak*"

    $E_{\text{disch}}(i) = \sum_{j=\text{transition}(i)+1}^{j=\text{transition}(i+1)}((P_{\text{load}}(j) - \eta_{\text{FCconv}} P_{FC,n})\Delta T/\eta_{\text{BATconv}}\eta_{\text{disch}})$

    % Calculating the energy unresolved for charging in the battery bank

    $E_{\text{total\_disch}} = E_{\text{total\_disch}} + E_{\text{disch}}(i)$

    % Calculating the maximum possible charging in the "*offpeak*"

    $E_{\text{ch\_max}}(i) = \sum_{j=\text{transition}(i+1)+1}^{j=\text{transition}(i+2)}(P_{FC,n}\eta_{\text{FCconv}} - P_{\text{load}}(j))\eta_{\text{BATconv}}\eta_{\text{ch}}\Delta T$

    % Calculating the fuel-cell power output in the "*peak*"

    $P_{\text{FC}}(j) = P_{\text{FC},n}$; $j = \text{transition}(i) + 1 : 1 : \text{transition}(i + 1)$

    % Calculating the fuel-cell power output in the "*offpeak*"

    if $E_{\text{total\_disch}} < E_{\text{ch\_max}}(i)$, then % the full charging is possible

      % minimizing H_2 consumption: convex optimization

      % problem.

      calculate

      $P_{\text{FC}}(j); j \in \{\text{transition}(i+1)+1, \ldots, \text{transition}(i+2)\}$

      such that:

      1) $\min J = \sum_{j=\text{transition}(i+1)+1}^{j=\text{transition}(i+2)}(P_{\text{FC}}(j)/b + aP_{\text{FC}}(j))$

      2) $\sum_{j=\text{transition}(i+1)+1}^{j=\text{transition}(i+2)}(P_{\text{FC}}(j) - (P_{\text{load}}(j)/\eta_{\text{FCconv}})) = (E_{\text{total\_disch}}/\eta_{\text{FCconv}}\eta_{\text{BATconv}}\eta_{\text{ch}}\Delta T)$

      3) $(P_{\text{load}}(j)/\eta_{\text{FCconv}}) \leq P_{\text{FC}}(j) \leq P_{\text{FC},n}$

      $E_{\text{total\_disch}} = 0$

    else

      $P_{\text{FC}}(j) = P_{\text{FC},n}$; $j \in \{\text{transition}(i+1)+1, \ldots, \text{transition}(i+2)\}$

      $E_{\text{total\_disch}} = E_{\text{total\_disch}} - E_{\text{ch\_max}}(i)$

    end

  end % end of loop

end % end of if

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Calculating the fuel-cell power output for the last intervals.

% There is no charging in the last "*offpeak*."

if M is even, then

$P_{\mathrm{FC}}(j) = P_{\mathrm{FC},n}; \quad j \in \{\text{transition}(M-1)+1, \ldots, \text{transition}(M)\}$
$P_{\mathrm{FC}}(j) = (P_{\mathrm{load}}(j)/\eta_{\mathrm{FCconv}}); \; j \in \{\text{transition}(M)+1, \ldots, N\}$
else
$P_{\mathrm{FC}}(j) = P_{\mathrm{FC},n}; j \in \{\text{transition}(M)+1, \ldots, N\}$
end

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