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Sizing optimization of a stand-alone street lighting system powered by a hybrid system using fuel cell, PV and battery

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ABSTRACT

Currently commercialised stand-alone street lighting systems based on the classical configuration coupling photovoltaic cells (PV) and battery cannot work all the year round in regions that are far from the equator. To improve the classical system, a hybrid system coupling a PV, a battery and a fuel cell is proposed. However, the sizing method of hybrid systems is a key issue in obtaining the cheapest system. To optimise the system, an original time-saving method is applied. Two optimization methods are used: first the genetic algorithms, then the simplex algorithms. A simulation model is used to evaluate the validity of the different hybrid configurations. After presenting the problem of stand-alone street lighting, the optimization methodology and the simulation model are detailed. Finally, an optimal configuration is obtained and shows that a 60 W street light would cost 7150€ with a lifetime of 25 years. The optimised parameters are also given and analysed.

1. Introduction

Nowadays, street lighting is something essential in our society in order to ensure comfort and security. The installation of street lighting in a city involves complex and expensive work. Moreover, to supply the lights, an electrical network is needed. The problem is the same in remote areas where lighting is needed, for instance, on the sides of roads. One solution is to use stand-alone street lighting systems. Such systems are currently sold and are commonly powered by solar cells and batteries to store the energy. However, in regions that are far from the equator the current system cannot work all the year round because the solar power is weak and varies significantly according to the seasons. The photovoltaic cells (PV) surface should be hugely increased as well as the battery capacity to supply the system during critical periods (especially in winter). That is why a hybrid power system is proposed. An electrical generator is added to the classical PV battery configuration for the critical periods. However, regarding environmental concerns, this additional generator should not produce greenhouse emissions unlike a classical diesel generator, currently used in many cases [1]. In this paper, a fuel cell (FC) is used to generate electricity [2]. Hydrogen supplying the FC is produced on a different site from renewable energies. However, in all hybrid systems, the problem is to suitably size the different elements: PV, battery, fuel cell, hydrogen tank, etc. Indeed, the minimum cost configuration has to be found without any analytical relation linking the parameters to the system cost. A first approach is to analyse the influence of one parameter on the others through a simulation model. Then, an optimal sizing using iterative methods is deduced, without being sure to find the global optimum. The following papers deal with this approach [3–7].

A more interesting method is to use genetic algorithms (GAs). This method of optimization based on evolutionary programming is used in many applications relating to power sources [8,9]. Some experiments have been carried out based on average weather data [10,11], and others, more precise, based on real weather data (insolation, wind speed, temperature, etc.) [12–15]. On one hand, it allows to find a global optimum to the problem of sizing. On the other hand, it is time consuming because of the large number of generations needed to obtain a complete convergence of the algorithm.

That is why, in this paper, the use of two optimization algorithms on the bounce is proposed: first a GA to find the approximate global optimum and then a simplex algorithm (SA) to enhance the previous result [16]. Furthermore, a parameter, quite often neglected is considered here: the PV tilt angle. The importance of this parameter has been well developed in Refs. [17,18]. The control parameter, like the battery state of charge (SOC), is also taken into account.

After introducing the formulation problem, the simulation model is detailed and then the methodology applied to size the hybrid system using the genetic and simplex optimizations is explained. The results are discussed and the energetic behaviour of the optimised system is shown.

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Notations

A_{pv}	PV panel area
C_b	battery cost
C_{fc}	fuel cell cost
CN_{fc}	numbers of start and stop cycles of the fuel cell over 1 year
$C_{penalty}$	penalty cost
C_{pv}	PV cost
C_{total}	total cost of the system
E_b	stored energy in the battery
$E_{b_{min}}$	Minimum stored energy in battery over 1 year
η_b	battery efficiency
η_{fc}	fuel cell efficiency
η_{pv}	PV efficiency
Q_{H_2}	consumed energy under hydrogen form over 1 year
E_{pv}	PV energy produced over 1 year
$E_{surplus}$	excess of energy produced over 1 year
G_{pv}	PV gain for modelling
HN_{fc}	working hours of fuel cell over 1 year
$I_{dif\ h}$	horizontal diffuse insolation
$I_{dir\ i}$	diffuse insolation on an inclined surface
$I_{dir\ h}$	horizontal normal direct insolation
$I_{dir\ i}$	direct insolation on an inclined surface
$I_{global\ h}$	horizontal global insolation
$I_{global\ i}$	global insolation on an inclined surface
b	battery indice
fc	fuel cell indice
LED	LED indice
pv	photovoltaic cell indice
I_N	normal insolation (does not depend on the declination)
LT	system lifetime in years
LT_b	battery lifetime
LTC_{fc}	fuel cell lifetime in start and stop cycles
LTH_{fc}	fuel cell lifetime in hours
N_{fc}	number of fuel cells needed for the system lifetime
P_b	battery power
$P_{b\ charging}$	battery charging power
$P_{b\ discharging}$	battery discharging power
P_{fc}	fuel cell power
P_{H_2}	chemical power of hydrogen
P_{LED}	LED power
P_{pv}	PV power
Q_b	battery capacity
SOC_{max}	battery SOC stopping FC
SOC_{min}	battery SOC starting FC
$UC_{P_{fc}}$	unit cost of FC power
$UC_{P_{pv}}$	unit cost of PV power
UC_{Q_b}	unit cost of battery capacity
$UC_{Q_{H_2}}$	unit cost of hydrogen

2. Architecture of the system

2.1. Classical PV battery system

In a first approach, the classical case using only PV and battery can be studied. The system is presented in Fig. 1. In this configuration, PV charges the battery during the day and then it supplies the street lights during the night.

2.1.1. Battery

The lead-acid battery is commonly associated with stationary solar systems. In this application, this type fits well with the system: a very fast response time is not necessary since the load is always constant, and the important weight of this battery has no influence in stationary applications. Furthermore, its efficiency is at least $\eta_b = 80\%$ [19].

2.1.2. Lights

Nowadays, most of the street lamps are from gas-filled technology and last an average of 12,000 h (less than 3 years). With 50,000 light hours, LED lamps do not have to be changed for 12 years. LED street lamps are twice as expensive as current street lighting with a similar design, but this is compensated by the longer lifespan and the low consumption which is around 60 W in this case (lifetime is given as an indication from Ref. [20] and LED manufacturers). At present, the price of LEDs is decreasing because the production capability has increased. This price is assumed to be around 10€/W. Changing two times the LED, the cost of this device will be 1200€. Reflectors and lens are not taken into account in this price. Dimming these LEDs could be considered in order to reduce consumption under certain operating conditions.

2.1.3. Electrical converters

Three DC–DC converters are needed. The first one is used to obtain the PV maximum power using an MPPT (Maximum Power Point Tracking) algorithm because of the non-linear nature of this source. The second converter controls the current flowing through the load and the third one controls the FC current. Obviously, a direct connection between the PV and the battery also works. However, there are no guarantees that the PV would supply the maximum power. For the street lighting application, it should be remarked that a direct connection between PV and LEDs would

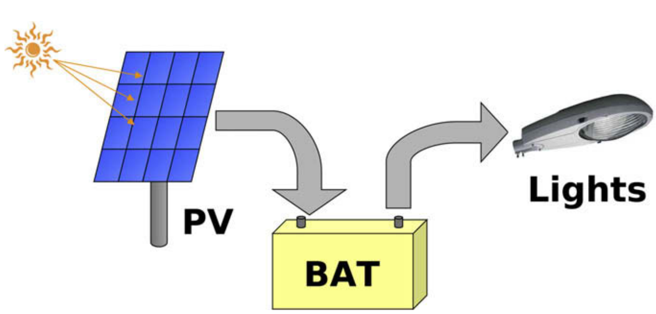

Fig. 1. Classical configuration layout.

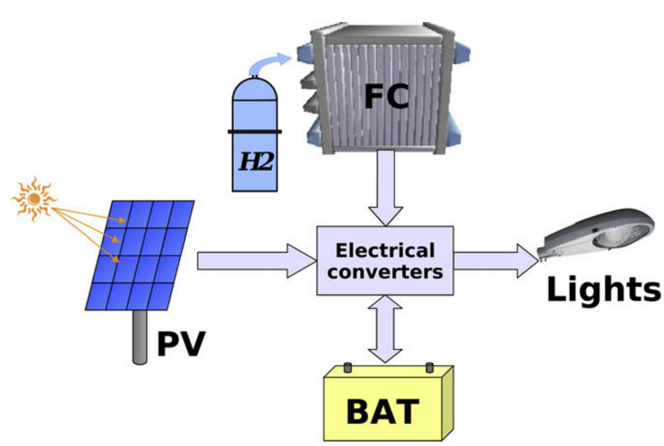

Fig. 2. PV BAT FC configuration layout.