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Energy management system based on techno-economic optimization for microgrids

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A B S T R A C T

This paper presents a new Energy Management System (EMS) for a microgrid based on four energy sources: a wind turbine (WT), photovoltaic (PV) solar panels, a battery, and a hydrogen system, which is composed of a fuel cell (FC) and an electrolyzer. This novel control strategy optimizes the total cost of the hybrid system (generation and reposition costs) through lifetime estimations calculated hourly for each energy storage device (the battery and hydrogen system). This control strategy links the expected lifespans of the energy sources to their generation costs, i.e., when the lifespan is low, the generation cost increases and, consequently, this energy source will start to be used less. The performance of the novel EMS, including these estimations, was tested for an isolated load located in Alora (Spain) and compared with two simpler EMSs: EMS-1, which considered fixed generation costs and lifetimes, and EMS-2, which prioritized the use of the battery. Simulation results show the appropriate behavior for the novel EMS to optimize the generation costs and the number of required elements throughout the expected lifetime of the hybrid system (25 years).

1. Introduction

Microgrids or hybrid systems, defined as combinations of energy sources and storage units to meet the energy demands of a given facility or community, is receiving an increasing attention in scientific literature as shown by the number of works focused on their design [1–4]—specifically the effect of the sizing of the system components in its operation and costs, control [1,5–7]—i.e. the development of control strategies to regulate the power exchange among its elements, modeling [5,7] and simulation [3,5,7]—providing useful information to ease other authors to reproduce the experiments, to help new researchers to access this research area, and share information with senior ones. This kind of system offers a feasible solution to supply electricity for small-scale remote and isolated applications such as telecommunication centers, military stations, islands, and rural villages. Although the use of hybrid systems with diesel engines has been widely studied [8,9], this work focuses on systems that are energetically self-sustainable and would work without being affected by fossil fuel price variations. These systems need energy storage devices to save the excess energy generated by renewable sources. Nowadays, it is common the use batteries for this purpose. Apart from that, there are different projects [10] that have already shown the technical feasibility of using hydrogen produced via electrolysis as an alternative means of energy storage (see Table 1, which summarizes the projects that considered microgrids similar to that proposed in this work). The advantages of energy storage by means of hydrogen are the ability to guarantee long storage times and high capacities and the potential for producing both electricity and heat with a very low environmental impact since the only by-products are heat and water [11]. The negative aspect of storing electricity as hydrogen is its high capital cost (expressed in \$/kW). The most recent studies [12,13], which compared it with other storage technologies, estimated – if it proceeded from electrolysis – that it would cost approximately 3000 \$/kW, compared to different battery technologies, which present a cost of around 1000 \$/kW. However, if the reduction of greenhouse gas emissions becomes

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Nomenclature:

$DOD(t)$ depth of discharge (%)
DOD_{nom} nominal battery DOD (%)
$C_{bat}^{h}(t)$ battery generation cost (€/h)
C_{bat}^{ac} battery acquisition cost (€)
C_{fc}^{ac} fuel cell acquisition cost (€)
$C_{fc}^{h}(t)$ fuel cell generation cost (€/h)
C_{lz}^{ac} electrolyzer acquisition cost (€)
$C_{lz}^{h}(t)$ electrolyzer generation cost (€/h)
$Cycle_{fc}(t)$ fuel cell off/on cycle from 0 to a certain power (cycle)
$Cycle_{fc}^{nom}$ complete fuel cell off/on cycle (cycle)
E_{bat}^{nom} battery nominal energy (W h)
$\hat{E}_{bat}^{year}(t)$ expected energy generated by the battery in a year (W h)
HS hybrid system
H_{fc}^{life} fuel cell life in operation hours (h)
H_{fc}^{warr} initial fuel cell warranty (h)
H_{lz}^{life} electrolyzer life in operation hours (h)
$H_{fc}^{total}(t)$ counted operation hours of the fuel cell in a certain period t (h)
$H_{i}^{rem-1}(t)$ remaining number of operation hours at the end of the last year (h)
$\hat{H}_{fc}^{eq365}(t)$ expected equivalent operation hours per year of the fuel cell (h)
$\hat{H}_{lz}^{eq365}(t)$ expected equivalent operation hours per year of the electrolyzer (h)
$\hat{H}_{i}^{eq365}(t)$ expected equivalent operation hours/year of the element i (h)
$\hat{H}_{i}^{rem}(t)$ expected remaining number of operation hours at the end of the current year (h)
i annual interest rate (–)
K_{DOD} discharge constant (–)
$Life_{HS}$ life of the hybrid system (years)
$\hat{L}_{bat}(t)$ expected life of the battery (years)
$\hat{L}_{fc}(t)$ expected life of the fuel cell (years)
$\hat{L}_{lz}(t)$ expected life of the electrolyzer (years)
$\hat{L}_{i}(t)$ expected life of the element i (years)
$N_{cycle}(t)$ counted number of battery cycles during a certain period t (cycles)
$N_{cycle}^{rem-1}(t)$ remaining number of operation cycles at the end of the last year (cycles)
$\hat{N}_{bat}(t)$ expected number of used batteries (–)
$\hat{N}_{fc}(t)$ expected number of used FC (–)
$\hat{N}_{lz}(t)$ expected number of used electrolyzers (–)
$\hat{N}_{i}(t)$ expected number of replacements of the i energy source (–)
NPC_{t}^{A} actual total net present cost at the end of the hybrid system life (€)
$\hat{N}_{cycle}^{eq365}(t)$ expected equivalent operation cycles per year (cycles)
$\hat{N}_{cycle}^{rem}(t)$ expected remaining number of operation cycles at the end of the current year (cycles)
$N\hat{P}C_{bat}(t)$ expected net present cost of the battery (€)
$N\hat{P}C_{fc}(t)$ expected net present cost of the fuel cell (€)
$N\hat{P}C_{fc}^{OM}(t)$ expected net present cost of operation and maintenance of the fuel cell (€)
$N\hat{P}C_{lz}(t)$ expected net present cost of the electrolyzer (€)
$N\hat{P}C_{lz}^{OM}(t)$ expected net present cost of operation and maintenance of the electrolyzer (€)
$P_{bat}(t)$ battery power (W)
$P_{chg}^{l}(t)$ charge power limit (W)
$P_{dis}^{l}(t)$ discharge power limit (W)
$P_{chg}^{l,approx}$ approximate charge power limit included in EMS 1 (W)
$P_{dis}^{l,appro}$ approximate discharge power limit included in EMS 1 (W)
$P_{fc}(t)$ fuel cell power in a certain period t (W)
P_{fc}^{nom} nominal fuel cell power (W)
$P_{load}(t)$ power demanded by the load (W)
$P_{net}(t)$ net power (W)
$P_{pv}(t)$ Power generated by the PV system (W)
$P_{rw}(t)$ power generated by the renewable energy sources (W)
$P_{wt}(t)$ power generated by the wind turbine (W)
$R_{fc}(t)$ degradation rate of the FC output voltage (V/h)
$R_{lz}(t)$ degradation rate of the electrolyzer efficiency (%/h)
R_{lz}^{η} ratio between the electrolyzer nominal and minimum efficiency (–)
$T_{Ri}^{-1}(t)$ year when the last reposition occurred (–)
$\hat{T}_{Ri}^{-1}(t)$ expected year when the source i maybe replaced (–)
t_{min} percentage of time using the control based on the charge and discharge power limits (%)
V_{fc}^{loss} maximum degradation allowed in the fuel cell voltage (V)
Year current year of the HS during the simulation (year)

a primary issue and carbon taxes increase, this could provide an incentive for investing beyond fossil-fuel based technologies and would make hydrogen more competitive [14,15], mainly for small-scale energy system contexts [16]. This idea is supported by the EU hydrogen roadmap, [17] which, despite predicting a low penetration rate for hydrogen use in stationary applications (as illustrative examples, from 0.1% to 1% in 2020 and from 0.5% to 4% in 2030 for the residential sector), highlights that it will be concentrated in remote areas and islands (similar to the system studied in this work).

Focusing on the EMS of these systems, the papers in this field can be classified by their objectives. On the one hand, there are papers whose main objective is to control some variables of the system (such as the DC bus voltage, battery state-of-charge, SOC, or hydrogen level) from a dynamic point of view to face the load power variations. On the other hand, economic issues were taken into account by other works in the design of the EMS to minimize the total Net Present Cost (NPC) of the HS throughout its expected life. Some relevant examples of the first kind of works are [18–20]. In [18], a simple strategy was proposed to control the power flow among the different energy sources of a stand-alone WT/PV/FC system using detailed dynamic models of the components to study their influences on the system behavior. The work presented by Thounthong et al. [19] showed a control algorithm based on DC bus voltage regulation, taking into account the different dynamic responses of the FC, PV, and ultracapacitor (UC) used in the microgrid. In [20], another rule-based EMS was presented for a system composed of a WT, PV, FC, and UC. The simulations carried out in these works had a length of around one day, which was enough to study the dynamics of the system, but did not take into account the operation cost of the microgrid. Thus, the premises considered to choose the source to utilize at any given moment were arbitrary, and prioritized the use of some sources over the rest, which would negatively affect their lives, and thus also the operation cost of the system during its lifetime (which was not considered).