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Definition, analysis and experimental investigation of operation modes in hydrogen-renewable-based power plants incorporating hybrid energy storage

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ABSTRACT

This paper is concerned with Operating Modes in hybrid renewable energy-based power plants with hydrogen as the intermediate energy storage medium. Six operation modes are defined according to plant topology and the possibility of operating electrolyzer and fuel cell at steady-power or partial load. A methodology for the evaluation of plant performance is presented throughout this paper. The approach includes a set of simulations over a fully validated model, which are run in order to compare the proposed operation modes in various weather conditions. Conclusions are drawn from the simulation stage using a set of Key Performance Indicators defined in this paper. This analysis yields the conclusion that certain modes are more appropriate from technical and practical standpoints when they are implemented in a real plant. From the results of the simulation assessment, selected operating modes are applied to an experimental hydrogen-based pilot plant to illustrate and validate the performance of the proposed operation modes. Experimental results confirmed the simulation study, pointing out the advantages and disadvantages of each operation mode in terms of performance and equipment durability.

1. Introduction

Due to increasing pressures to reduce CO_2 emissions and the depletion of traditional fossil fuels, renewable energies have received great interest and development. However, due to the unpredictability, non-dispatchability and high variability of renewable energy sources, such as wind or solar, new challenges have arisen for including them into the current electrical system. Major concerns are related to problems of stability and reliability of electrical supply caused by the natural fluctuations of this type of energy. The use of energy storage systems to store surplus power in off-peak hours and to supply peak demand could provide a feasible solution to the aforementioned issues and contribute to a more secure and reliable grid infrastructure.

Among the possible energy storage systems, those based on hydrogen production by electrolysis and subsequent utilization in fuel cells offer an attractive alternative to conventional systems (water pumping, compressed air, batteries, etc.), in terms of flexibility, energy density, long-term efficiency and added value as a marketable chemical for industry [1]. However, a major effort in applied research and demonstration projects must be made in order to make this technology more reliable, competitive and efficient. Therefore, to further the development of such applications, it is necessary to have a validation of the technology in real conditions, study of system design and investigation of operation strategies, among other issues.

A renewable power plant based on hydrogen energy storage consists of a renewable source (typically wind or solar), an electrolyzer (a machine that produces hydrogen using electricity), hydrogen storage (compressed, liquefied metal hydride) and an energy conversion system, typically a fuel cell, as shown in Fig. 1.

The design and operation of hydrogen-based power plants is a highly complex problem as it requires the characterization of hydrogen production/consumption, control of the renewable power and the stability of the power supplied by the fuel cell. In these plants, hybridization has positive impacts on system efficiency and flexibility. Energy-intensive and power-intensive storage devices can be combined to add flexibility and more potential sources of revenue for grid balancing and renewable-energy shifting in a configuration such as the one shown in Fig. 2 [3]. However, the inherent complexity of hybridization brings with it technical and economic questions which have not yet been fully answered.

Many concerns are related to how to manage the energy in the system in an effective manner which leads to increased performance and economic benefit for the plant. Thus, one of the

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Nomenclature

Batt	battery
Batt rated	battery at rated power
C	cost
C^{dp}	cost of sudden power changes
C^{i}	investment cost
C_N	nominal capacity of the battery bank (A h)
$C^{\mathrm{O\&M}}$	operation and maintenance cost
$C^{\mathrm{on-off}}$	unitary cost of switch on and switch off
E_{demand}	electrical energy demand (kW h)
$E^{\mathrm{in}}_{\mathrm{grid}}$	electricity imported from the grid (kW h)
Eff	efficiency
REG	Renewables Exported to Grid (%)
ELY	electrolyzer
$E^{\mathrm{exp}}_{\mathrm{grid}}$	energy exported to the grid (kW h)
E_{RES}	electrical energy produced by the renewable sources
ELY rated	electrolyzer working at rated power (kW h)
FC	fuel cell
FC rated	fuel cell working at rated power
GRID	utility grid
GSD	Grid Supplied Demand
HTL_f	hydrogen storage final level of the tank
KPIs	Key Performance Indicators
LHV	lower heating value (MJ/kg)
$\dot{m}_{\mathrm{H2}}$	hydrogen flow rate (kg/s)
Max Eff	maximize efficiency operation mode
Max H2	maximize hydrogen production
MH	metal hydride
MHL	metal hydride level (%)
N_{batt}	number of batteries in parallel
N_{cycles}	number of equivalent cycles
NET	net value between generation and demand
nStart–Stop	number of start & stop events
N^{T}	total number of cycles of the alloy

P. load	partial load
P_e	electric power
P_{in}	energy entering the plant
P_{out}	energy coming out of the plant
P_{stored}	power in/out the storage devices
PV	photovoltaic field
RES	renewable energy source
SOC	battery state of charge (%)
V_{DC}	nominal voltage of the battery bank (V)
$\delta_{\mathrm{on-off}}$	switch-on and switch-off event
η_{bat}	battery efficiency

Subscript & superscripts

ez	electrolyzer
fc	fuel cell
MH	metal hydride tank
$W(t)$	variable power
W	steady power
out	power out
in	power in
LOAD	load demand
RES	renewable energy source
ELY	electrolyzer
FC	fuel cell
NET	net power
$\mathrm{MIN}_{\mathrm{FC}}$	minimum power to activate the fuel cell
$\mathrm{MAX}_{\mathrm{FC}}$	maximum power of the fuel cell
$\mathrm{MIN}_{\mathrm{ELY}}$	minimum power to activate the electrolyzer
$\mathrm{MAX}_{\mathrm{ELY}}$	maximum power of the electrolyzer
RATED	rated power
GRID	grid power
BATT	battery

main topics that the literature explores is how to operate these sources, storage and loads under most favorable operating regimes, which has great potential to improve their competitiveness and reduce costs [4–7].

Obviously, operating-mode possibilities will be a function of the plant topology. Fig. 2 illustrates an example of a complex topology that can be created using a high degree of hybridization. It incorporates hybrid renewable energy (wind and solar) and hybrid energy storage technology as well. In this topology, energy-intensive technologies are combined with power-intensive ones. Alternately, power-intensive devices can be used instead of ultra-caps, such as flywheels or super magnetic conductors [8]. Clearly, energy management plays a fundamental role in a heterogonous system such as the one discussed herein, and has potential applications to any type of hybrid system such as microgrids [9]. The correct design and control of these systems, integration and definition of the most appropriate operating modes for each type of renewable energy (solar or wind) and energy-storage technology is a complex function of climatic conditions, existing generation, storage capacity, energy cycling efficiency, equipment degradation and electricity demand at all times, among other factors. In addition, it has been demonstrated that equipment lifespan is strongly dependent on the manner in which they are operated. This will result in the economic viability of the facility, not to mention the potential economic benefits arising from the proper management of electrical energy in different tariff periods [10].

Previous work done on operation modes falls mainly into the group of the so-called “Hysteresis band control technique” [4,11,12]. This is characteristic of hybrid systems where the control is fundamentally based on heuristic rules. In this strategy, energy storage devices’ state of charge plays a central role as decision variable. Variations of this strategy can be found where authors have considered a different parameter as key for control. In these cases, the hydrogen inventory [13] or bus voltage [14] can be considered the key parameter.

A different approach based on the net power as decision variable has also been studied in the literature. The principle of operation is to select the equipment with the lowest cost for each time it stores/delivers power. This principle assumes the equipment operation cost as a function of the net power. The drawback observed in this strategy is that sudden power variations, typical of renewable power, can cause frequent switching between plant equipment. An improved method can be obtained by adding a dead band in order to reduce the frequent switching between operation modes [15]. In this group the so-called “optimal control strategies”, such as Genetic algorithms or Model Predictive Control, can be also included, as they share the net energy between the energy storage devices. Although it has been demonstrated that off-line and on-line optimization techniques can be applied to control the energy flows in these types of plants [16–18], they are frequently optimized for specific operating conditions. Thus, to guarantee robust operation in different situations, the optimization should be recalculated at different set-points, achieving different operating modes.

Some authors [19,20,12] incorporate new sub-cases based on the Hysteresis Band algorithm, thus increasing the efficiency and