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Optimal economic exploitation of hydrogen based grid-friendly zero energy buildings

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ABSTRACT

This paper presents economically optimized energy and power management strategies for grid-friendly hydrogen based Zero Energy Buildings (ZEBs). The proposed energy management strategy is an adaptative optimization-based strategy that minimizes the operation cost of the facility taking into account RES generation prediction errors. It is shown that with an Adaptative Optimized Five-step Charge Controller (AOFC2) the use of the different equipment is optimized and the overall operation cost is minimized considering the entire life of the facility. The proposed energy management strategy is coordinated with power management strategies to offer advanced functionalities (peak-shaving, reactive power control and back-up service) that provide added-value to the facility. The paper demonstrates by means of offline and real-time simulations, that an adequate energy and power management structure permits the optimal economic exploitation of an advanced ZEB (that includes an energy storage system), providing not only a zero energy annual balance but also interesting added-value features to the grid and to the local consumers.

1. Introduction

Energy efficiency is a top priority in the international agenda towards a more sustainable energy future [1]. Indeed, according to the International Energy Agency (IEA) it is considered to be the most cost-effective concrete action that governments can take in the short term to address climate change and to reduce energy consumption [2].

Buildings are one of the most important sectors where there is significant potential for improving energy efficiency. The residential sector alone currently accounts for 30% of all electricity consumed in developed countries, corresponding to 21% of energy-related CO2 emissions. According to the World Business Council for Sustainable Development (WBCSD) energy use in buildings can be cut by 60 percent by 2050 if immediate actions to transform the building sector are taken [3].

In this context, several institutional initiatives have been taken to promote energy efficiency in buildings. For instance, in 2002 the European Parliament published the directive 2002/91/CE aimed and promoting energy efficiency in buildings. In April 2009, the European Parliament Industry Committee developed a report to reform the 2002 directive. This report proposes that by 31st December 2018 at the latest, EU Member States must ensure that all newly-constructed buildings will be Zero Energy Buildings (ZEB). In this proposal a ZEB is defined as "a building where, as a result of the very high level of energy efficiency of the building, the overall annual primary energy consumption is equal to or less than the energy production from Renewable Energy Sources (RES) on site" [4].

This concept does not settle any specific requirement on power consumption/generation patterns. Consequently, the power exchange with the grid will generally take place according to parameters like instantaneous home consumption needs and availability of renewable energy resources. Thus, even if a zero energy balance is achieved, the behavior with respect to the grid may be far from optimal (i.e. ZEBs contribution to grid operation is uncertain).

Nevertheless, a "grid-friendly" dimension can be given to the original "environmentally friendly" concept by incorporating energy storage systems and adequate energy and power management strategies to the building. As a result, these advanced ZEBs, will be able not only to (1) improve their energy efficiency but also

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to (2) assure grid-friendly operation by providing ancillary services (peak-shaving and reactive power compensation) and to (3) offer back-up services to locally connected loads.

There are several energy storage technologies that can be potentially used in these advanced ZEB applications. While batteries and/or supercapacitors are an appropriate choice for short-term energy storage [5–8], the storage in hydrogen might be a more suitable solution for the long-term due to its higher energy density [9,10]. In this regard, several stand-alone and grid-connected experimental facilities have already demonstrated the technical viability of the combination of RES and hydrogen storage systems [11–14]. In these H_2 based facilities hydrogen is generated during low demand periods by water electrolysis by means of an electrolyzer. Then, during high demand periods, hydrogen is reconverted into electricity with a fuel cell. In some cases, the long-term energy storage in form of hydrogen can be combined with a battery bank providing high dynamics short-term functionalities to the facility [15–17].

The introduction of energy storage systems not only gives an additional degree of freedom to the facility, but it also increases the complexity of the management system as the periods of charge, discharge and standby of the energy storage system must be determined. The determination of these periods has a critical impact on the overall performances of the facility as it defines critical aspects as the behavior with respect to the grid or the exploitation cost of the facility (considering that the price of the imported/exported energy may vary during the day). In the case of H_2 based facilities several energy management strategies have been proposed. These strategies can be split up into two main categories: rule-based and optimization-based solutions [18].

On the one hand a rule-based strategy is based on heuristics, intuition, human expertise, and mathematical models [19]. A set of rules, whose definition might be subjective, determines the actions to be taken on the adopted assertion set. Consequently, these strategies, which are well fitted for online implementation, do not necessarily achieve an optimal solution. On the other hand Optimization-based solutions are implemented by applying optimization algorithms that minimize a cost objective function. Global optimization strategies cannot be used directly for real-time energy management but they can provide a basis for designing rules for online implementation and they can also be useful for comparing the performances of different control strategies.

The energy management in existing H_2 based demonstration plants is mainly based on rule-based solutions, using strategies like load following, five steps charge controllers or fuzzy logic [20–22]. In these cases, the energy flows are managed taking into account the state of charge of the electric and hydrogen storage systems but without considering the future estimated evolution of main system parameters (i.e. RES generation forecasts) and the economic aspects related to the facility.

Optimization-based techniques have also been reported in the literature, applied for the optimal economic management of rule-based solutions [23]. In these applications, genetic algorithms are used to calculate the optimal setpoints of the facility assets, in order to minimize the overall operation cost for given RES generation and load demand profiles.

In this paper the optimal economic exploitation of a hydrogen-based "Grid-Friendly" ZEB is proposed.

In the first part an adaptative optimization-based energy management strategy is proposed, which minimizes the operation cost of the facility taking into account RES generation prediction errors.

In the second part a power management algorithms is presented in order to provide added-value functionalities both to the grid, in grid-connected mode (ancillary services as peak-shaving and reactive power control) and to local energy consumers, in stand-alone mode (back-up services). The paper demonstrates by means of offline and real-time simulations, that an adequate energy and power management structure permits the optimal economic exploitation of an advanced ZEB (that includes an energy storage system), providing not only a zero energy annual balance but also interesting added-value features to the grid and to the local consumers.

2. Case study description

2.1. Main characteristics

The proposed case-study is based on a residential hybrid power facility ZEB-H_2, which is composed of several generation systems (a fuel cell, an electrolyzer and RES generators), two different energy storage systems (hydrogen and batteries) and loads. These subsystems are connected to a common internal AC bus directly or by means of power electronic interfaces, as shown in the simplified diagram of Fig. 1.

The facility has been designed in order to be exploited as a Grid-Friendly ZEB, with the characteristics presented in Table 1.

The main criteria used for the rating of the main elements are:

- The fuel cell must cover the load peak demand in case of unavailability of both the main grid and the renewable generation.
- The electrolyzer must be able to consume the maximum renewable generation with zero load demand.
- The hydrogen storage system is composed of 15 tanks of 1,25 m^3 where the hydrogen is stored at 200 bar. This volume allows at least 9 days of operation without renewable energy production and grid unavailability.

2.2. Operation principle and functionalities

The overall objective of the facility is to achieve a zero annual energy balance between locally generated and consumed energy. To fulfill this objective, the basic condition is that local annual RES energy generation must be at least equal to the local annual energy consumption.

In order to optimize the use of local energy resources and obtain a grid-friendly ZEB, the hydrogen generation and consumption is continuously managed by controlling the operation of the electrolyzer and the fuel cell through energy management strategies

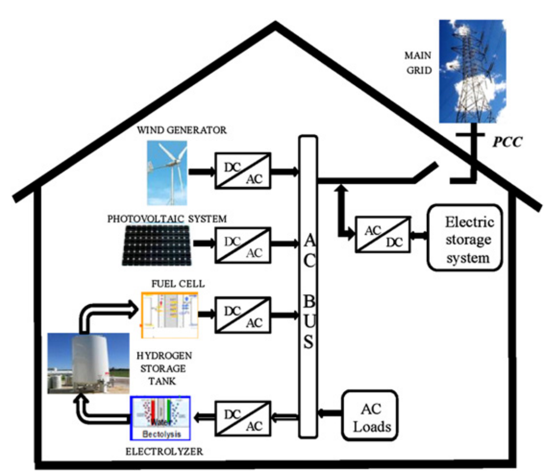

Fig. 1. ZEB-H_2 facility schematic distribution.