INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 2927–2938

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

# Electrolyzer models for hydrogen production from wind energy systems

Raúl Sarrias-Mena [a], Luis M. Fernández-Ramírez [a,*], Carlos Andrés García-Vázquez [a], Francisco Jurado [b]

[a] Research Group in Electrical Technologies for Sustainable and Renewable Energy (PAIDI-TEP-023), Department of Electrical Engineering, University of Cadiz, 11202, EPS Algeciras, Algeciras (Cadiz), Spain

[b] Research Group in Research and Electrical Technology (PAIDI-TEP-152), Department of Electrical Engineering, University of Jaen, 23700, EPS Linares, Linares (Jaen), Spain

ARTICLE INFO

*Article history:*
Received 15 October 2014
Received in revised form
21 December 2014
Accepted 29 December 2014
Available online 23 January 2015

*Keywords:*
Electrolyzer
Hydrogen
Modelling
Wind turbine

ABSTRACT

The continuous progress on the expansion of renewable energies leads to the development of hybrid power systems, where several power sources contribute to provide a clean and reliable alternative to traditional fossil fuels. The hydrogen technology is viewed with particular interest in this regard. Hydrogen is an outstanding energy carrier that can be exploited for various applications, including electricity generation. Hence, production of hydrogen from renewable sources has received the attention of many researchers lately. With this purpose, this paper deals with the coupled operation of electrolyzer (EZ) and wind turbine. Four different EZ models are presented and evaluated in this work. These models are aggregated to a variable speed wind turbine model using MATLAB/Simulink. The four configurations are evaluated, and their responses compared, under variable wind speed and grid demand.



## Introduction

Renewable energy systems experience continuous advances pursuing higher power rates, improved efficiency, reduced impact on electric power systems, etc. Nowadays, many studies are trending towards hybrid configurations, with several energy sources working co-ordinately [1–3]. As a main advantage, the hybrid option aggregates the prime qualities of all the elements involved. Subsequently, the weaknesses of each individual component can be minimized and compensated by the characteristics of other devices [4]. Following this concept, hybrid power systems based on wind energy as the main source have been evaluated in the literature [5,6]. Given the natural origin of the power source, wind generation is often intermittent and unpredictable. Additionally, it cannot be handled on demand, since favourable wind conditions are required. Hence, it is possible to bear situations when an excess of wind generation is wasted as it cannot be absorbed by the grid, as well as many other circumstances with low wind power production during a peak on demand. The ability to store the energy surpluses in the adequate devices greatly improves the performance of wind power systems, thus enhancing their grid penetration under more reliable conditions.

* *Corresponding author*. Tel.: +34 956 028166; fax: +34 956 028001.
E-mail addresses: raul.sarrias@uca.es (R. Sarrias-Mena), luis.fernandez@uca.es (L.M. Fernández-Ramírez), carlosandres.garcia@uca.es (C.A. García-Vázquez), fjurado@ujaen.es (F. Jurado).

http://dx.doi.org/10.1016/j.ijhydene.2014.12.125
0360-3199/

Different energy storage systems (ESSs) are considered adequate for coupled operation with renewable energy sources. Depending on the technology, some characteristics prevail over others. For instance, several battery types are well developed for large scale energy storage in the range of hours [7,8], whereas ultracapacitors or superconducting magnetic energy storage are better suited for very fast power exchange applications [5,8,9]. The hydrogen technology appears as an exceptional long-term storage alternative in the so-called power-to-gas plants [10]. Alternative technologies based on the storage of energy in the form of heat are also interesting options for the long-term, especially for energy infrastructures with a large participation of fluctuating renewable sources and combined heat and power (CHP) production systems [11]. In this regard, heat pumps and/or electric boilers can use the excess electricity provided by renewable sources to produce heat that can be conserved in a heat storage [11], thus reducing the need for consuming fossil fuels for heat generation while increasing the flexibility of the system to supply the electricity and heat demands. Likewise, EZs may play a relevant role in this generation scheme, since they can use the excess electric power from renewable sources to produce hydrogen for the CHP system [11]. Additionally, pumped hydro and compressed air energy storage appear as two valid choices for large-scale storages, which are also able to curtail generation surpluses from wind power. Nonetheless, these are usually handicapped by the particular characteristics required on the installation site [7].

The excess energy generation from renewable sources can be utilized to produce hydrogen in an EZ. The obtained hydrogen can be stored in various ways, and eventually employed in fuel cells to deliver electric energy. This option offers a practically inexhaustible supply of clean energy, since the tanks where hydrogen is stored can accumulate high quantities of this element. Moreover, they can be emptied and the hydrogen transported to a different location. Hence, the EZ can operate continuously with almost inexistent storage boundaries. However, the applications of the hydrogen obtained from EZs are not limited to electricity production in fuel cells. Alternatively, this element can be used as a raw material in the synthesis of renewable transport fuels by combination of hydrogen with carbon obtained from recycled $CO_2$ or biomass [12,13]. The use of hydrogen in these applications provides a dual benefit: firstly, it reduces the amount of biomass (which is a limited resource) needed to produce clean fuels; and secondly, it adds flexibility to the electric power system, thus allowing a higher integration of intermittent renewable sources [12]. Such renewable fuels are expected to gain great importance in the development of future transport systems based on clean sources [12], since they can overcome some of the problems related to the production of biofuels, thus rising as a supplement or substitute for them in scenarios with high rates of renewable energies [13]. The growth of this industry demands a further evolution of EZs [13]. Due to this flexibility, as well as the variety of applications and potential utilization of the product delivered, an EZ has been chosen as energy storage device in the hybrid system considered in this paper.

The implementation of EZ in hybrid power systems with renewable sources has been addressed in the literature from various perspectives. Coupled operation with solar photovoltaic systems was dealt in Refs. [14,15]. In both cases, a stand-alone application including fuel cells was investigated, thus not influencing the activity of a large power system. How the hydrogen technology improved the integration of wind generation was studied as an optimization problem in Ref. [16]. An optimal power flow routine maximized the wind power injection to grid, with the singularity that a certain external hydrogen demand must be satisfied meanwhile. Several costs involved in the operation of the hybrid system were considered, and the wind farm was modelled through equality constraints to the optimal solution, thus neglecting their dynamic performance. Zhou et al. presented in Ref. [17] an EZ model and control strategy for a hybrid configuration, including the necessary power converters. Moreover, a hardware-in-the-loop simulation was carried out to test the proposed models. Nonetheless, the wind turbine dynamics were not considered, thus not being able to observe the overall response of the hybrid configuration and the total power exchange with the grid. An actual hybrid demonstration plant was evaluated in Ref. [18] using registered data from the installation deployed in Utsira, Norway. The most interesting results of their study were discussed, whereas the modelling process of the power sources and auxiliary equipment was not introduced. Carton and Olabi [19] raised the challenge to develop a hybrid pilot plant in Ireland, similarly to that implemented in Ref. [18]. The authors listed the many benefits of such hybrid configurations, and protested the necessity to improve the capacity of the Irish power system, proposing the hybrid wind/hydrogen configuration as a viable solution. A complete hydrogen micro-system including EZ, hydrogen storage and fuel cell was used in Ref. [20] to support grid integration of a wind generator. A thorough depiction of the control systems was carried out. However, low power devices were considered, also disregarding the description of their modelling process. Hydrogen production systems can also provide frequency regulation support to wind farms, as reported in Ref. [21]. Smoothing the output power of a wind farm via hydrogen generation was contemplated in Ref. [22]. A line power reference was determined for the wind farm, being the EZ devices responsible for absorbing the excess power. Such strategy reduced the switching operation of the EZ, but the grid demand was not considered as an input in the control scheme.

So far, a study with a similar approach to that accomplished herein has not been carried out. The main motivation of this paper is to develop a comparative analysis of four different EZ models presented in the literature. In most of the cases, researchers put their focus on the design, description and simulation of new or improved EZ models. Therefore, the evaluation of these models as a part of a more complex energy system is often neglected. This is especially true in the case of detailed proton exchange membrane (PEM) EZ models. As a consequence, this article aims at drawing attention to the coupled operation of PEM EZ models with other renewable energy sources, as is the case with wind power. Hybridization of wind energy systems by using EZ devices as energy storage optimizes the energy capture of such renewable source, and thus its overall performance. Hence, it is worth increasing the existing knowledge on the coordination and the energy