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Complete modeling and software implementation of a virtual solar hydrogen hybrid system

S. Pedrazzi, G. Zini *, P. Tartarini

Facoltà di Ingegneria, Università di Modena e Reggio Emilia, Via Vignolese 905, I-41100 Modena, Italy

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ABSTRACT

A complete mathematical model and software implementation of a solar hydrogen hybrid system has been developed and applied to real data. The mathematical model has been derived from sub-models taken from literature with appropriate modifications and improvements. The model has been implemented as a stand-alone virtual energy system in a model-based, multi-domain software environment. A test run has then been performed on typical residential user data-sets over a year-long period. Results show that the virtual hybrid system can bring about complete grid independence; in particular, hydrogen production balance is positive (+1.25 kg) after a year's operation with a system efficiency of 7%.

1. Introduction

A *solar hydrogen hybrid system* is a combination of systems of different technologies (photovoltaics, electrolyzers, fuel-cells, hydrogen storage, piping, thermal and electrical/electronic systems) capable, as a whole, of converting solar energy, storing it as chemical energy (in the form of hydrogen) and turning it back into electrical and thermal energy when need be [1,2].

Alongside with the growing costs of fossil fuels and their environmental impact, the need to exploit renewable energy sources is often seen as a way to secure energetic independence for every nation [3–5]; such systems are hence receiving a lot of attention due to their capability of storing energy from sources that, by their very nature, are highly uneven.

Notwithstanding the relevance of building and testing real prototypes, it is clear that their design, due to inherent complexity and cost, requires the power and convenience of computing to simulate functioning before actual set-up.

A number of publications have addressed research in this area; Hammache and Bilgen [6] developed a mathematical model to analyze, starting from hourly meteorological data for various locations, the thermal and economical performance of a system comprising of photovoltaics and electrolyzer, capable of producing 20 GJ/year of hydrogen; Hollenberg et al. [7] described a computer model that uses load and solar radiation data to determine performance and optimum number and size of photovoltaic arrays, electrolyzers and hydride storage tanks; Ulleberg and Morner [8] used TRNSYS (a computer program devised to simulate the transient performance of energy systems) to perform parametric studies for system configuration in different climates and loads; Bilgen [9,10] obtained thermal and economical performances of large scale or domestic photovoltaic–electrolyzer systems and an interesting set of correlations between operating parameters and solar irradiation; El-Shatter et al. [11] employed fuzzy logic modeling to draw the highest possible solar energy from photovoltaic arrays under variable solar radiation conditions; Kolhe et al. [12] modeled a photovoltaic system and wind in a stand-alone hybrid system configuration to assess its performance; Maclay et al. [13] developed a model to design an hybrid system using ultra-capacitors as energy storage in combination with batteries, assess its capital costs, devise control strategies, and evaluate system efficiency. A comprehensive review of solar (and wind) hydrogen system models can be found in Deshmukh and Boehm [14].

In this paper we present a complete multi-domain model-based virtual system that we developed as a foundation for our next research activities. We start by outlining the mathematical set of equations and correlations that we use to profile system behavior; then we discuss software implementation and validation pointing out some peculiar aspects of the virtual system, such as its control logic. We finally exhibit results and draw the main conclusions.

It is worth noting that in this paper we define model as the description of a system that accounts for its known or inferred properties and may be used for further study of its characteristics, and where known properties are expressed by equations, inferred properties by statistical relationships (regressions, correlations, etc.) or equations derived from empirical considerations.

* Corresponding author. Tel.: +39 (0) 59 2056146; fax: +39 (0) 59 2056126/6129.
E-mail address: gabriele.zini@unimore.it (G. Zini).

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2. The mathematical model

The overall system is depicted in Fig. 1, where all sub-systems and respective connections are shown (adapted from [15]).

The photovoltaic system is connected through a boost-converter (a step-down DC–DC converter) to a DC bus-bar, the power electrical distribution which acts as the backbone of the hybrid system. Through a buck-converter (a step-up DC–DC converter), the electrolyzer receives current from the bus-bar and produces hydrogen and oxygen that are compressed and stored. When the control logic switches on the fuel-cell depending upon load requests, electrical energy is converted from stored gases and enters the bus-bar by means of a boost-converter. Energy is supplied to the load by a DC/AC inverter connected to the bus-bar; to guarantee smooth functioning, a battery keeps the bus-bar always charged within a controlled power range.

Every sub-system is modeled and implemented as highlighted in the next paragraphs.

2.1. Solar radiation model

The photovoltaic system modules capture portions of the solar radiation reaching the earth's surface: the direct (G_b) and diffuse (G_d) [16–19]. The total solar radiation is indeed expressed by:

$$G_T = G_b R_b + G_d R_d + (G_b + G_d) R_r \tag{1}$$

where R_b is the tilt factor for direct radiation, R_d for diffuse radiation and R_r for reflected radiation. They are given by the following equations:

$$R_b = \frac{\sin\delta\sin(\varphi-\beta)+\cos\delta\cos\omega\cos(\varphi-\beta)}{\sin\varphi\sin\delta-\cos\varphi\cos\delta\cos\omega},$$
$$R_d = \frac{1+\cos\beta}{2}, \quad R_r = \rho\frac{1-\cos\beta}{2} \tag{2}$$

where β is the tilt angle of the photovoltaic modules, φ is the location latitude, $\omega = (12 - t)\ \pi/12$ is the hour angle in radians as a function of time t (in h), ρ is the ground reflectivity (albedo), and δ is the declination angle expressed by:

$$\delta = 23.45^\circ \sin\left[\frac{360^\circ(284+n)}{365}\right] \tag{3}$$

with n the Julian day of the year.

G_b and G_d represent respectively the direct and the diffuse solar radiation on a flat surface at an hour angle ω and are expressed as a function of the daily average total direct solar radiation energy for a horizontal surface (H_{b0}) and the daily average value of the diffuse solar radiation energy (H_{d0}), all expressed in W h/m^2:

$$G_b = \frac{180^\circ}{24}\frac{\sin\delta\sin\varphi+\cos\delta\cos\omega\cos\varphi}{\omega_s\sin\varphi\sin\delta-\cos\varphi\cos\delta\cos\omega_s}H_{b0} \tag{4}$$

$$G_d = \frac{180^\circ}{24}\frac{\cos\omega-\cos\omega_s}{\sin\omega_s-\omega_s\cos\omega_s}H_{d0} \tag{5}$$

where $\omega_s = \cos^{-1}(-\tan\varphi\tan\delta)$ is the sunrise hour angle.

The site data (β, φ, ω, δ, H_{b0}, H_{d0}) that are needed to compute G_T are available in specific databases [20].

2.2. Photovoltaic sub-system

The photovoltaic sub-system converts solar radiation energy into electrical energy; to reach a satisfactory trade-off between model complexity and precision, we profile its behavior with the single-diode model (Fig. 2) [18].

From Kirchhoff's laws, the I–V relationship of the equivalent circuit can be written as:

$$I = I_L - I_0\left(\exp\frac{V+IR_s}{a}-1\right)-\frac{V+IR_s}{R_{sh}} \tag{6}$$

where I_L is the photo current generated when the diode is radiated by solar energy, I_0 is the diode reverse saturation current, R_s is the series resistance, R_{sh} is the shunt resistance. The term a is set equal to (NKT/q) where K is the Boltzmann constant, T the temperature, q the electron charge constant and N is a parameter that depends on

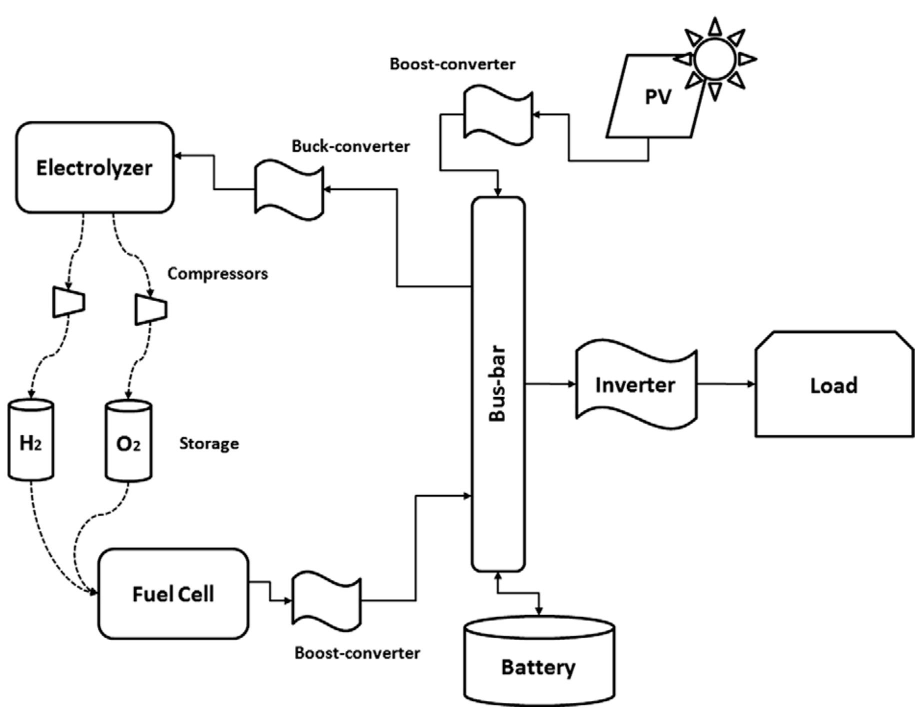

Fig. 1. Hybrid system schematic.