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Model for energy conversion in renewable energy system with hydrogen storage

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Abstract

A dynamic model for a stand-alone renewable energy system with hydrogen storage (RESHS) is developed. In this system, surplus energy available from a photovoltaic array and a wind turbine generator is stored in the form of hydrogen, produced via an electrolyzer. When the energy production from the wind turbine and the photovoltaic array is not enough to meet the load demand, the stored hydrogen can then be converted by a fuel cell to produce electricity. In this system, batteries are used as energy buffers or for short time storage. To study the behavior of such a system, a complete model is developed by integrating individual sub-models of the fuel cell, the electrolyzer, the power conditioning units, the hydrogen storage system, and the batteries (used as an energy buffer). The sub-models are valid for transient and steady state analysis as a function of voltage, current, and temperature. A comparison between experimental measurements and simulation results is given. The model is useful for building effective algorithms for the management, control and optimization of stand-alone RESHSs.

Keywords: ARMA; Battery; Electrolyzer; Fuel cell; Photovoltaic array; Wind turbine

1. Introduction

The use of a stand-alone renewable energy system (i.e. one using wind and photovoltaic energy) in remote areas requires an energy storage device to smooth out the intermittent power input from these sources. Recent system designs [1–4] rely on batteries for short-term energy storage, while hydrogen is used for long-term energy storage. In these systems, the hydrogen (H_2) has been produced through an electrolyzer powered by the surplus energy available from the primary sources (wind turbine and photovoltaic array). When the input power is insufficient to feed the RESHS load, previously stored hydrogen is reconverted through a fuel cell (FC) to produce the required electricity. The design, management and optimization of such a system require a useful model.

We present a model to describe the dynamics of an RESHS. It integrates sub-models of the electrolyzer, the fuel cell, the batteries, the power interfaces (buck and boost converters) and the storage system. Interdependency issues (hydrogen consumption cannot exceed production) are taken into account. Special attention is given to the characterization of the system's major components in the transient state, and we use simple and realistic assumptions to describe the behavior for short- and long-term operation of the RESHS. Most of the sub-models are specified by the component's polarization curves characteristics (current–voltage–temperature). The model is validated by comparing its output to that of the Hydrogen Research Institute's (HRI) renewable energy system test bench, which is completely described in [4,6] and whose configuration and specifications are given, respectively, in Fig. 1 and Table 1. A scenario built with realistic residential power consumption needs and typical power production by wind turbine (WT), and photovoltaic (PV) array is also simulated and analyzed.

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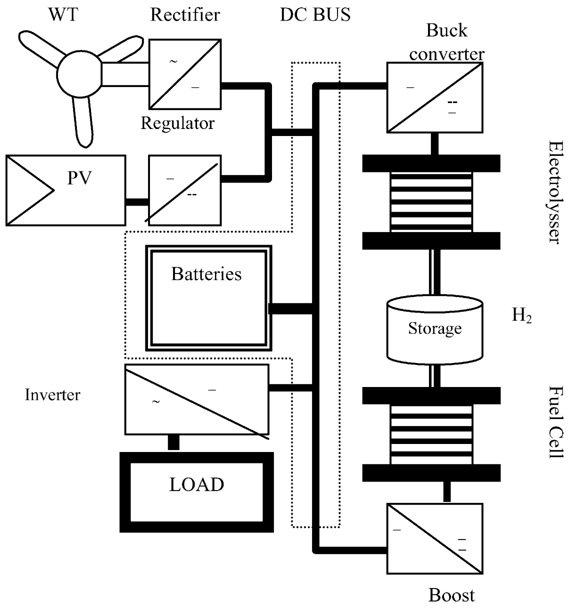

Fig. 1. Block diagram of the renewable energy system test bench of the HRI.

2. Modeling of the components

Generally, a RESHS is designed for a nominal dc bus voltage, which, in the case of the HRI test bench, is about 48 V. However, the real voltage on the dc bus depends on the operating conditions of the system. When the energy production exceeds what is needed and the battery (short-term energy storage device) is being charged, the input power devices tend to impose their output voltage on the dc bus. Wind gusts can, for example, increase that bus voltage from 48 V to 56 V in a fraction of a second. Similarly, when input energy production is below what is needed and the load draws on the battery, it is the battery that will impose its voltage on the dc bus. This variability of the bus voltage is a major control problem, as quite clearly this voltage cannot be considered as a reliable variable to describe the evolution of the state of the RESHS. Instead, it is the battery energy that will be used as a system-controlling variable (see Section 2.1).

Table 1
RE test bench technical specifications

Components	Type	Power (kW)	Voltage (V)
Photovoltaic (PV)		1	48
Wind turbine generator and regulator		10	48
Electrolyzer	Alkaline	5	26–48
Buck converter	Multiphase PWM	5	26–48
Fuel cell (FC)	PEM	5	24
Boost converter	Multiphase PWM	5	24–48
Inverter		5	110 ac
Load		0–5	110 ac
		Capacity (kWh)	
Batteries	Lead–acid	10.5–55	48
Storage H_2		125	

PWM: pulse width modulation; PEM: proton exchange membrane.

In this paper, most of the models are described as functions of time, current, voltage, and temperature. For simulation purposes, the input signals are the wind generator rectifier output current (I_{WT}), the PV array regulator output current (I_{PV}), and the load current (I_L). Due to the intermittent nature of the renewable energy sources, sampled signals will be used to represent all of them. This way, any energy production and load profile can be modeled at will. In the following sections, the models of the sub-units are presented in the order in which they are traversed by the energy flux: battery, buck converter, electrolyzer, boost converter, fuel cell, and hydrogen storage.

2.1. Battery model

The battery is the main component on the dc bus, and plays the role of an energy buffer to handle current spikes and for short-term energy storage. Different models for batteries are available, in particular those suitable for electrical vehicle applications [5,11,12,15]. For stationary applications, such as the RESHS, the models described in [2] use many experimental parameters that cannot be estimated easily, such as the overcharge effect (though in a properly-controlled RESHS, this effect does not happen, and hence is not included in the model). The main parameters, which determine the battery's performance, are its internal resistance, the polarization effect, and the long-term self-discharge rate. This self-discharge rate is difficult to estimate, and is itself subject to a number of factors, such as the operating temperature, the number of operation cycles, and the materials and technology used in its manufacture [9,14].

The battery voltage $U_B(t)$, which takes these three parameters into account is given by,

$$U_B(t) = (1 + \alpha t)U_{B,0} + R_i(t)I(t) + K_i Q_R(t) \qquad (1)$$

where α is the self-discharge rate (s^{-1}); $U_{B,o}$ is the open circuit voltage (V) at $t = 0$; $R_i(t)$ is the internal resistance (Ω), K_i is the polarization coefficient ($\Omega\,h^{-1}$), and $Q_R(t)$ is the rate of accumulated ampere hours. If $I(t) > 0$ then the battery is charging; if $I(t) < 0$ then the battery is discharging. The battery energy is then,

$$W(t) = W_0 + \int_0^t P_{in}(t')\,dt' \qquad (2)$$

where $P_{in}(t') = U_B(t)I(t)$ is the input power to the battery and W_0 is the battery's initial energy. As we will see later, the decision algorithm (as to whether electrolyzer or fuel cell are to be activated to rebalance the battery energy) will depend on the battery's state of charge (SOC), defined by,

$$\mathrm{SOC}(t) = \frac{W(t)}{W_{max}} \qquad (3)$$

where W_{max} is the maximum battery energy without overcharge.