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Experimental assessment of a residential scale renewable–regenerative energy system

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ABSTRACT

An experimental assessment of a hydrogen based regenerative (electrolyser-fuel cell) system is presented. The experiment was conducted on a residential scale Integrated Renewable Energy Experiment (IRENE) test-bed under conditions that are representative of the real demands that would be placed on a solar based, regenerative system, with a focus on dynamic operation under transients in both load and renewable energy supply profiles. A control algorithm employing bus voltage constraints and device current limitations is outlined. Results for a 2 week operating period indicate that the system response is very dynamic but repeatable.

The overall system energy balance reveals that the energy input from the renewable source was sufficient to meet the demand load and generate a net surplus of hydrogen. The energy loss associated with the various system components as well as a breakdown of the unused renewable energy input is presented. In general, the technical challenges associated with hydrogen energy buffering can be overcome, but the round-trip efficiency for the current system is only 22%.

1. Introduction

1.1. Scope

As sustainability issues arise with our current energy system, pressure is being applied on policy makers, governments, and the energy sector to provide the energy services we have grown accustomed to with less overall impact on the environment [1]. Renewable resources such as wind, solar and tidal have the potential to supply clean-energy, but their variability poses problems for applications that require a continuous supply of energy.

Energy buffering plays a vital role in enabling transient renewable resources to service user demands. Hydrogen as an energy storage media has potential to address both daily and seasonal buffering requirements. Renewable–regenerative system that employ an electrolyser to convert excess electricity into hydrogen coupled with hydrogen storage and regeneration using a fuel cell (or IC engine) can in principle provide power with zero (or near zero) emissions.

The development of a residential-scale renewable–regenerative system with hydrogen energy buffering was presented in [2]. This paper builds on that prior work and explores the dynamic operation of the hydrogen energy buffer. Detailed experimental data is presented to (a) expose the operational characteristics of the coupled system, (b) quantify the energy flows within the system, and (c) outline the areas where losses occur. The experimental study was motivated by the need to develop an accurate knowledge of the system response under real operating conditions and to provide experimental data for model validation. Each of the system components has time-dependent characteristics which influence the operation of the combined system. In general, the dynamic aspects of system operation are not adequately considered in the theoretical models of renewable–regenerative systems. Understanding the nature of the interactions and response characteristics for the combined system is essential for designing efficient regenerative systems.

1.2. Background

A review of the theoretical models for hydrogen-based renewable–regenerative systems and prior experimental work was given in the previous paper [2]. Several noteworthy additions to the literature have been published in the intervening period.

Modeling efforts have focused on the implementation of hydrogen energy buffering to allow high penetrations of renewable resources into existing power grids [3,4], and the technical feasibility of hydrogen based stand-alone power systems for autonomous mini-grid systems [5–8]. Several models for residential scale

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renewable–regenerative systems have been reported [9–11] that investigate hybrid energy storage systems. A detailed review of individual component models for renewable–regenerative systems is given in [12]. Many of the models discussed in this excellent reference are more sophisticated than those employed in the bulk of the system models described thus far. Finally, issues related to the optimization of control strategies for stand-alone renewable energy systems are addressed by [13,14].

Since the start of the current study, several new renewable–regenerative systems have been or are in development at other research institutes. The HaRI project at West Beacon Farms, Leicestershire, UK, utilizes an assortment of renewable conversion devices, loads and storage technologies as reported in [15]. Two integrated wind-hydrogen renewable energy projects have been developed on remote islands [16,17]. Both are designed as demonstration projects and service a small number of residences (PURE project on Island of Unst, UK, services 5 small business; Utsira on the Island of Haugesund, Norway, supplies 10 households). These projects incorporate hydrogen generation, storage and utilization to buffer the variability of the renewable resource. Common issues reported include underestimation of the wind resource, challenges in system development due to the high number of device interfaces, and regulation/control problems during periods with large power generation and low demand. A fourth system, SYSLAB, incorporating a variety of renewable energy technologies is under development at Riso in Denmark [18]. Experimental work with this platform is focused on control aspects for distributed and decentralized systems.

2. Experimental system overview

The Integrated Renewable Energy Experiment (IRENE) test-bed is a residential-scale energy system that employs regenerative components (electrolyser and fuel cell) to enable intermittent energy sources to service time-varying loads. During the system conceptual design stage, sizing issues were considered, taking into account a range of practical constraints including: project budget, available laboratory space, size and capacity of relevant commercial components (renewable energy converter, fuel cells, electrolysers, inverters etc.), and the scale of systems typically modeled in the literature. The outcome was the selection of a target system capacity in the 3–4 kW range. This capacity is similar to the typical electric demand of a Canadian residence [19]. The basic IRENE system schematic is presented in Fig. 1 and a summary of the primary system components is listed in Table 1.

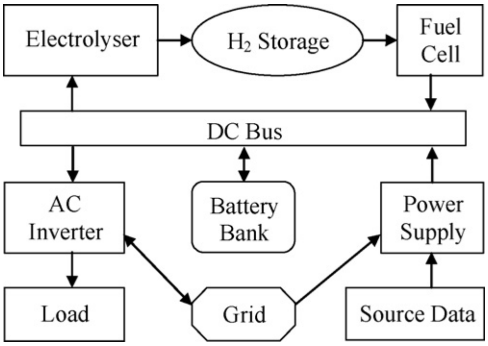

Fig. 1. IRENE test platform schematic.

A detailed description of the IRENE system is given in [2]. A brief overview to provide context for the current work follows. Energy fluxes, measured in real time (or time series from other sites), are processed by suitable transfer functions representing a renewable energy conversion device (i.e., wind turbine, solar array, micro-hydro plant). The output is used to control a 15 kW Lambda EMI ESS programmable power supply which provides power to IRENE's common 48 V DC bus. A 4 kW Xantrex inverter supplies AC power from the bus to the load. The output hardware is configured to support real loads (induction motors, switching loads, etc.) as well as a 3 kW NHR programmable load bank that can simulate a residential load profile.

During periods in which the input power exceeds the demands, excess electrical energy is converted to hydrogen via a 6 kW Stuart Energy electrolyser. IRENE is outfitted with metal hydride and gaseous (10 and 200 bar) hydrogen storage systems. A 1.2 kW Ballard Nexa fuel cell is employed to convert stored hydrogen to electricity during periods of insufficient renewable input. Interfacing the fuel cell into the DC bus was accomplished by floating the fuel cell on a secondary power supply which increases the apparent output from the 'fuel cell system' to approximately 2 kW. A small 272 AHr battery bank maintains bus stability under transient loads but is not sized for primary energy storage.

The test-bed is fully instrumented to measure energy and mass flows between system components. An integrated PC-based control system allows for long-term operation of the system following a user specified control algorithm.

A primary motivation for developing the IRENE test-bed was to create a platform for examining the operating characteristics of a renewable–regenerative system in a controlled environment. The goal was to observe the dynamic response and interplay between components as the system responds to the demands of a time varying load and resource input. To this end, an experimental investigation coupling all of the IRENE sub-systems was undertaken. The results from this multi-week experiment are presented fol-

Table 1
Summary of primary system components.

	Manufacturer/type	Maximum current (A)	Potential (V)	Power (W)
Bus	n/a	>250	42–56 48 nominal	n/a
Fuel cell	Ballard Nexa PEM	0–45	46 V at 0 A 22 V at 45 A	1,200
Electrolyzer	Stuart Energy SRA	107	42–56	6,000
Battery	GNC Absolyte IIP deep cycle AGM	272 A h	42–56 48 nominal	
DC power supply	Lambda EMI ESS	250	0–60	15,000
Load	NHR model 4600	27	110 VAC	3,000
Inverter	Xantrex SW4840	180 peak for short duration	44–62 48 nominal	4,000