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Renewable energy systems based on hydrogen for remote applications

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Abstract

An integrated renewable energy (RE) system for powering remote communication stations and based on hydrogen is described. The system is based on the production of hydrogen by electrolysis whereby the electricity is generated by a 10 kW wind turbine (WT) and 1 kW photovoltaic (PV) array. When available, the excess power from the RE sources is used to produce and store hydrogen. When not enough energy is produced from the RE sources, the electricity is then regenerated from the stored hydrogen via a 5 kW proton exchange membrane fuel cell system. Overview results on the performances of the WT, PV, and fuel cells system are presented. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Hydrogen; Renewable energy; Wind turbine; Photovoltaic array; Electrolyzer; Fuel cells

1. Introduction

The last few years have seen the development of renewable energy (RE) systems based mainly on wind and solar power. Such systems are especially relevant to off-network communities, and remote areas like the Canadian north, which is particularly sensitive to pollution. These RE systems rely on highly transient energy sources and exhibit strong short-term and seasonal variations in their energy outputs. They thus need to store the energy produced in period of low demand in order to stabilize the output when the demand is high. While batteries are most commonly used for this purpose, they typically lose 1–5% of their energy content per hour and thus can only store energy for short periods of time [1,2]. There are presently no practical means available for long-term storage of excess electrical energy produced by the RE sources.

Few studies are related to the use of hydrogen for the electrical energy produced by RE sources such as wind and solar power [3–7]. This is being investigated at the hydrogen research institute (HRI). Hydrogen is produced by an electrolyzer powered by the excess electrical energy from the RE source. The hydrogen can then be used to feed an energy conversion device (such as a fuel cell or an internal combustion engine), which will act as a secondary power source in periods of high demand. Such a system is set up at HRI for remote areas applications such as communication stations. The RE sources at HRI are a wind turbine (WT) capable of generating a maximum electrical power of 10 kW and photovoltaic (PV) cells of 1 kW maximum power. The excess energy available from the RE sources is directed to an electrolyzer. The hydrogen produced is then stored in a pressurized tank. This hydrogen is then fed to a proton exchange membrane fuel cell (PEMFC) system [7] that would be used as a load-leveling electrical system when unfavorable weather conditions arise.

The objectives of these studies include the development and experimental testing of the best methods for design optimization and control strategies. Here, we present an overview of the PEMFC system, the hydrogen production and storage subsystem. The integration of the fuel cell into a power source for the remote communication station is also discussed.

2. Description

A schematic of the complete RE system is presented in Fig. 1. It includes the following components:

1. An hybrid energy system from Bergey Windpower Co, model Excel. This is composed of a permanent magnet WT that can deliver a maximum output power of 10 kW. The wind system is coupled to a PV array that can

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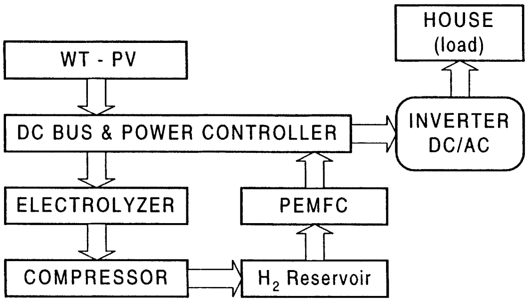

Fig. 1. RE system diagram.

deliver a maximum output power of 1 kW. The voltage produced by these sources is regulated and converted to a 48 V on a controlled dc bus. A set of deep-discharge batteries, connected in a series/parallel configuration, act as a buffer between the load and the power sources.

2. A 5 kW electrolyzer made by Stuart Energy Systems that can deliver up to 1 $m^3 h^{-1}$ of purified hydrogen compressed at 7 bars.
3. The hydrogen is further compressed to 10 bars, and directed to a storage tank of 3.8 m^3 (water capacity). This represents 125 kWh of stored energy based on high heating values (HHV) (the maximum energy density of H_2 is 285 kJ $mole^{-1}$).
4. A 5 kW-24 V dc Ballard fuel cell stack model MK5-E.
5. Some 48 V deep-discharge batteries for voltage stabilization.
6. A dc bus controller that includes the batteries for energy transfer.
7. An intelligent dc–ac inverter that can deliver a constant 60 Hz 115 V output to the load.

In addition to the above basic system, we use a 10 kW Elgar programmable source to simulate the output of the WT–PV power sources for a given set of wind speed and sunlight data. In order to make preliminary tests on the fuel cell system, we use a 12 kW water-cooled TDI-Dynaload programmable load.

Each component of the RE system was tested under real operational conditions. We also investigated different operational strategies. The control system is composed of a dc bus and a power controller. The dc bus receives the electricity from the WT, PV array and fuel cells. The load, the electrolyzer and the compressor are connected to the same bus. A battery array maintains the stability of the voltage on the bus. The test bench controller manages the available power and the load demand.

3. Hydrogen production and storage subsystem

The electrolysis process is inherently clean and efficient. The hydrogen production rate of the electrolyzer is 1 N $m^3 h^{-1}$ at 5 kW input. Figs. 2 and 3 show, respectively, the polarization curve for two different temperatures and the operating curves (voltage, temperature and hydrogen flow) of the electrolyzer. The electrolyzer efficiencies without compressor are 65% at ambient temperature around 23°C and 71% for 55°C. These efficiencies decrease by 5% when the hydrogen is compressed. Compressor drive currents are the ripples on the current curve of Fig. 3. Thus, for an average wind speed at the test location of 6 m s^{-1} which translates in an average WT power of 2 kW, the hydrogen production rate is about 0.4 N $m^3 h^{-1}$. This is fed from the buffer tank via a compressor to the hydrogen storage system

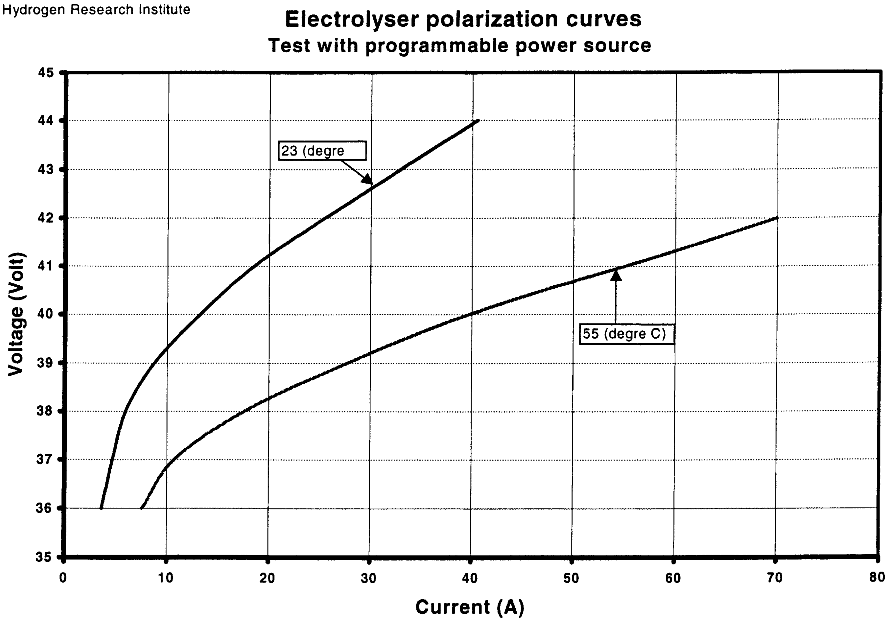

Fig. 2. Electrolyzer polarization curves.

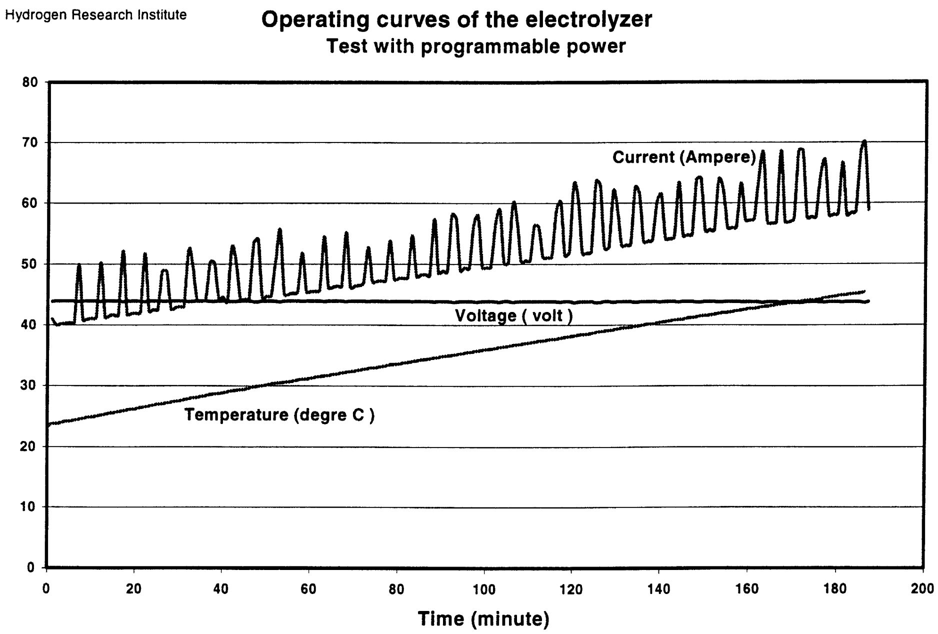

Fig. 3. Operating curves of the electrolyzer.

at 10 bar. In addition to the low-pressure storage, we are also testing a high-pressure storage option at 207 bar using a small high-pressure compressor made by FuelMaker Corporation. It has a 4.5 N m^3 h^{-1} flow and uses 1.6 kW input power. The compressed hydrogen will be stored in seven high-pressure tanks of 110 L each. This represents 154 m^3 of hydrogen at normal temperature and pressure and a capacity of 507 kWh.

Hydrogen is considered the fuel of the future and many resources have been invested in the development of advanced production and storage. Other storage techniques are under development at our institute. Nanocrystalline metal hydrides can be used advantageously as safe, reversible, hydrogen storage materials and can contribute significantly to an environmentally clean storage energy technology [8]. It is characterized by the presence of a large number of grain boundaries and interfaces which confer to this alloy enhanced kinetics and volumetric hydrogen packing densities. Physisorption on carbon offers a promising avenue for lowering the storage pressure of compressed gas fuels such as hydrogen [9]. The recent advent of carbon nanotubes capable of storing large amounts of hydrogen similar to the amount absorbed by metal hydrides at ambient pressure and temperature makes the adsorption storage technology quite promising.

4. WT system and hydrogen production

The WT is installed on a 30 m tower. The production of electricity starts from a minimum wind speed of about 3.4 m s^{-1} and reaches the maximum rated output power of 10 kW for winds attaining 13.0 m s^{-1}. Fig. 4 represents the power output during a 5-day period. The figure also shows the corresponding hydrogen production during the same period when all produced electricity is fed to electrolyzer.

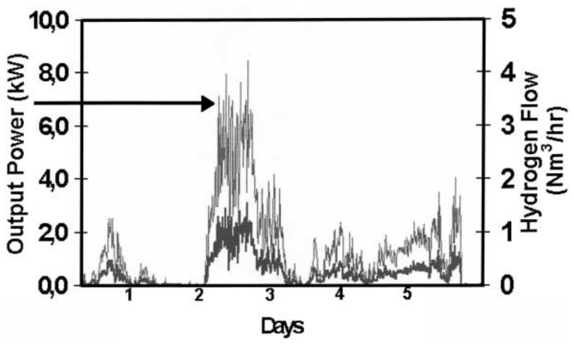

Fig. 4. Hydrogen flow and output power versus time.

The efficient operation of the WT station requires a minimum amount of information about the wind characteristics. The anemometer on the WT tower at a height of 15 m provides these data. The information on the wind characteristics at our observation site is obtained by measuring wind speed (with a NRG Systems anemometer) every 2 s and obtaining an average every 10 min.

5. Load-leveling electrical system

This part of the system is composed of a 5 kW fuel cells system connected to the dc bus, via a regulated dc/dc converter (24/48 V) designed at our institute and acts as a load-leveling device.

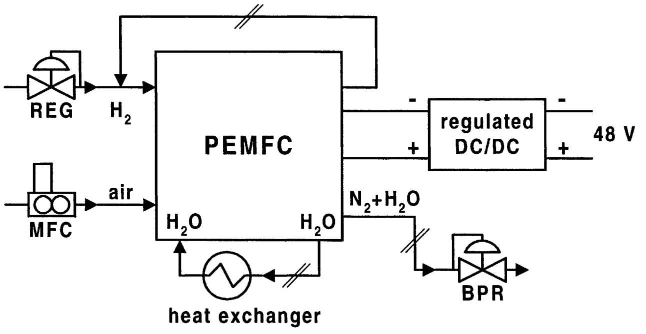

Fig. 5. PEMFC system diagram.

Fig. 5 depicts a simplified diagram of the fuel cell system and the dc/dc converter. Fuel cells have the advantage of being environmentally clean, highly efficient, and reliable since they do not have moving parts [7]. The fuel cell system is the model PGS-105 from Ballard Power Systems. The heart of this system is a Ballard fuel cell stack model MK5-E, which has a total of 35 cells connected in series. Each cell has a surface area of 225 cm/sup/2. The membrane electrode assembly (MEA) consists basically of graphite electrodes and a Dow$^{\mathrm{TM}}$ membrane. The reactant gases (hydrogen and air) are humidified within the stack. The hydrogen is recirculated at the anode, while the oxidant (air) is flowing through the cathode. The hydrogen pressure at the stack anode inlet is kept at 3 bars by a regulator (REG) and the air pressure at the cathode inlet and outlet is maintained at 3 bars by a backpressure regulator (BPR). The oxygen flow is automatically adjusted by computer as a function of the load via a mass flow controller (MFC).

The dc/dc converter has efficiency better than 95% and the use of eight conversion circuit (power switch MOSFET) levels minimizes the ripples normally associated with this kind of device.

An automatically controlled switching device in the converter drives the required power from the fuel cells. We have shown in a previous publication [10] that the efficiency of the fuel cell system in converting hydrogen into electricity is better than 45% when delivering a power of 4 kW. Therefore, the total efficiency of the load leveling system is better than 42%. Fig. 6 plots the electrical efficiency, defined as the fuel cell output power measured (P_{expt}) over the theoretical power ($P_{\mathrm{theoretical}}$) of the fuel cell system as a function of the load current, for the case when air and pure oxygen are used as an oxidant. The theoretical power is defined as

$$P_{\mathrm{theoretical}} = \frac{\mathrm{HHV} \times N_{\mathrm{cells}} \times I}{2e^{-} \times F} \tag{1}$$

where HHV $= 285.8$ kJ mol^{-1}, is the high heating value of hydrogen, $N_{\mathrm{cells}} = 35$, the number of cells, I the load current, and $F = 9.6487 \times 10^{-7}$ C, the Faraday constant.

Fuel cell power as a function of temperature is plotted in Fig. 7. The stack can produce a maximum continuous power of 4 kW when its temperature is in the range of 72–77°C. The stack can generate a peak power of up to 5 kW, but only for a short period of time because of the poor water management of this specific model. The response of the stack to fast switching loads has also been measured and is plotted in Fig. 8. The observed transients actually show how the load reacts to a specific change.

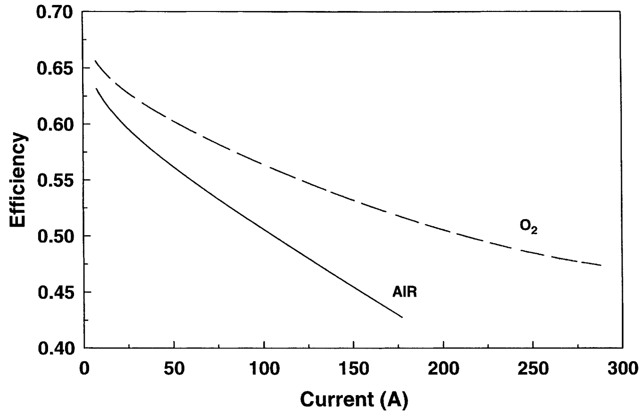

Fig. 6. Fuel cell stack efficiency curves for air and oxygen.

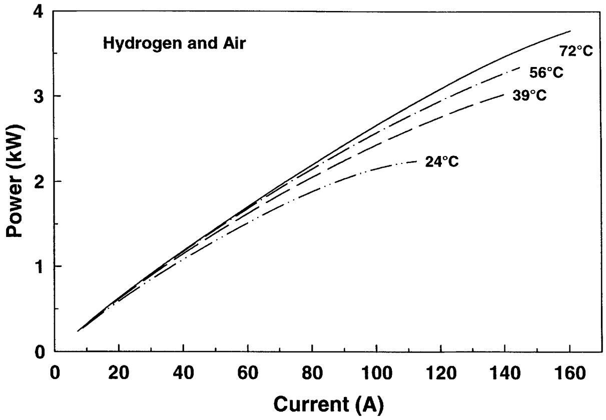

Fig. 7. Fuel cell stack power curves at different temperatures.

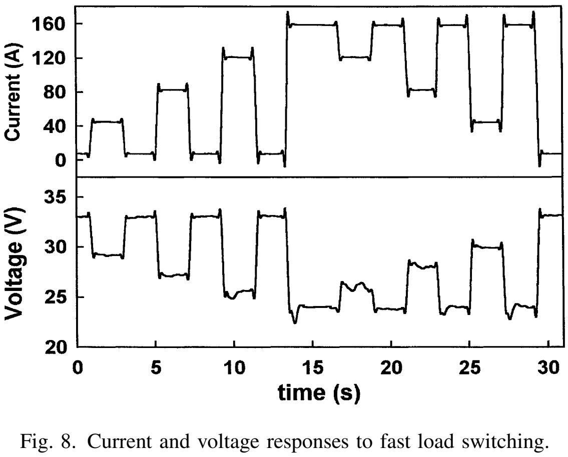

Fig. 8. Current and voltage responses to fast load switching.

6. Conclusion

The WT power available shows that excess electrical energy produced during the best wind periods can be used to produce hydrogen. When unfavorable weather conditions arise, it will then be necessary for the stand-alone site to produce electrical energy via a PEMFC. We have shown that a PEMFC stack can respond to fast load switching, through a dc/dc converter, with efficiency better than 42%. This system will also give stabilized electrical power for communication stations. Different storage techniques have also been presented and the simple technique of storing hydrogen at 10 bar in a fuel tank is retained.

Acknowledgements

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