Integrated Stand-alone Renewable Energy System Based On Energy Storage In The Form Of Hydrogen

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Abstract

Electrolytic hydrogen offers a promising alternative for long-term energy storage of renewable energies (RE). A stand-alone RE system based on hydrogen production has been developed at the Hydrogen Research Institute and successfully tested for automatic operation with designed control devices. The system is composed of a wind turbine, a photovoltaic array, an electrolyser, batteries for buffer energy storage, hydrogen and oxygen storage tanks, a fuel cell, AC and DC loads, power conditioning devices and different sensors. The long-term excess energy with respect to load demand has been sent to the electrolyser for hydrogen production and then the fuel cell has utilised this stored hydrogen to produce electricity when there were insufficient wind and solar energies with respect to load requirements. The RE system components have substantially different voltage-current characteristics and they are integrated on the DC bus through power conditioning devices for autonomous operation by using the developed control system. The experimental results clearly indicate that a stand-alone RE system based on hydrogen production is quite safe and reliable.

Sommaire

L'hydrogène électrolytique offre une alternative prometteuse pour le stockage à long terme des énergies renouvelables (ER). Un système à ER autonome basé sur la production d'hydrogène a été développé et testé avec succès, à l'Institut de Recherche sur l'Hydrogène. Le système est composé d'une éolienne, de panneaux solaires, de batteries comme mode de stockage énergétique tampon, de charges CC et CA, d'un électrolyseur, de réservoirs d'hydrogène et d'oxygène pour le stockage, d'une pile à combustible, d'un module de contrôle, d'appareils d'interface de puissance et de plusieurs capteurs. L'excès d'énergie à long terme, par rapport aux besoins de la charge, est dirigé vers l'électrolyseur pour la convertir sous forme d'hydrogène stocké sous pression. Cet hydrogène est ensuite utilisé pour alimenter la pile à combustible afin de produire de l'électricité lorsque les énergies éoliennes et solaires sont insuffisantes pour satisfaire les besoins de la charge. Les composantes du système à ER ont des caractéristiques tension-courant substantiellement différentes et elles sont intégrées au bus CC via des interfaces de puissance, pour une opération autonome en utilisant le système de contrôle développé. Les résultats expérimentaux indiquent clairement qu'un système à ER autonome basé sur la production d'hydrogène est sécuritaire et fiable.

1.0 Introduction

Energy storage can play an important role in the development and operation of an environment friendly renewable energy (RE) system. The integrated wind and solar energy system, based on long-term seasonal storage as electrolytic hydrogen (H_2), is considered a promising alternative to overcome the intermittence of the RE sources [1-2]. In comparison to commonly used battery storage, H_2 is well suited for seasonal storage applications, because of its inherent high mass energy density. A typical self-sufficient RE system must include both short-term and long-term energy storage. A battery bank is used for short-term energy storage due to its high charging-discharging efficiency, and also to take care of the effects caused by instantaneous load ripples / spikes, electrolyser transients, wind energy peaks. However, batteries alone are not appropriate for long-term storage because of their low energy density, self-discharge and leakage. The combination of a battery bank with long-term energy storage in the form of H_2 can significantly improve the performance of stand-alone RE systems. In such a RE system, electricity production in excess of demand is converted to H_2, using an electrolyser; electricity requirement in excess of production is met by converting H_2 to electricity through a fuel cell. The intent is to demonstrate that H_2 is a practical energy storage medium for RE and that it is safe and reliable.

The overall RE system performance is very sensitive to local weather conditions, and to achieve an adequate performance from such a system requires appropriate components and well-designed control system [3-5]. The control system for proper energy management in a stand-alone RE plant was a real challenge. We have designed and developed a control system with power conditioning devices to integrate the different components of the RE system and to manage the energy flow in the system to assure continuous supply of the load demand. The system parameters are monitored continuously for real time operation and control. The system operation has been tested for autonomous operation and technical feasibility of the stand-alone RE system based on hydrogen production. Our integrated RE system has been in operation for the last 2 years.

2.0 System Description

The stand-alone RE system based on hydrogen production has been tested successfully at the Hydrogen Research Institute (HRI). The system consists of a 10 kW wind turbine generator (WTG) and a 1 kW (peak) solar photo voltaic (PV) array as primary energy sources. The excess energy with respect to load demand has been stored as electrolytic hydrogen through a 5 kW electrolyser and utilized to produce electricity as per energy demand through a 5 kW fuel cell system. The RE system components have substantially different voltage-current characteristics and are integrated through the developed power conditioning devices on a 48V DC bus, which allows power to be managed between input power, energy storage and load. The DC-DC buck and boost converters are connected for power conditioning between the electrolyser and the DC bus, and between the fuel cell and the DC bus, respectively. The schematic of the RE system is shown in Figure 1 and the system components' specifications are given in Table 1.

Current from the DC bus bar keeps batteries (short-term energy storage) charged, feeds power to the load bank via an inverter and also supplies power to electrolyser via power-conditioning device. To simulate any type of electrical load profile, we have used DC and AC programmable loads. Our developed RE system has also a programmable power source at DC bus and can be used to test the system, when there is no power available from wind and solar energy system. The programmable power source can simulate any type of intermittent power output. The electrolyser and the fuel cell are major components of the RE system. We have also studied the polarization characteristics of them, which depend mainly on voltage, current and temperature. The different sensors are used to record real time voltages and currents of WTG, PV array, DC bus / battery, electrolyser, fuel cell, load, H_2 detectors, electrolytic H_2 flow rate from the electrolyser, H_2 consumption rate in the fuel cell, oxidant consumption rate in the fuel cell, H2 and oxidant pressure in the fuel cell, fuel cell stack temperature, electrolyzer cell temperature, DC-DC converter (boost and buck) duty ratio. There are also some sensors in the electrolyzer and the fuel cell system that provide the secondary information.

3.0 RE System Operation and Control

A control system is required for efficient energy management and autonomous operation of the RE plant. The control system is a challenge because the sensor data is required for continuous real time operation and the same control algorithm is needed to send signals to

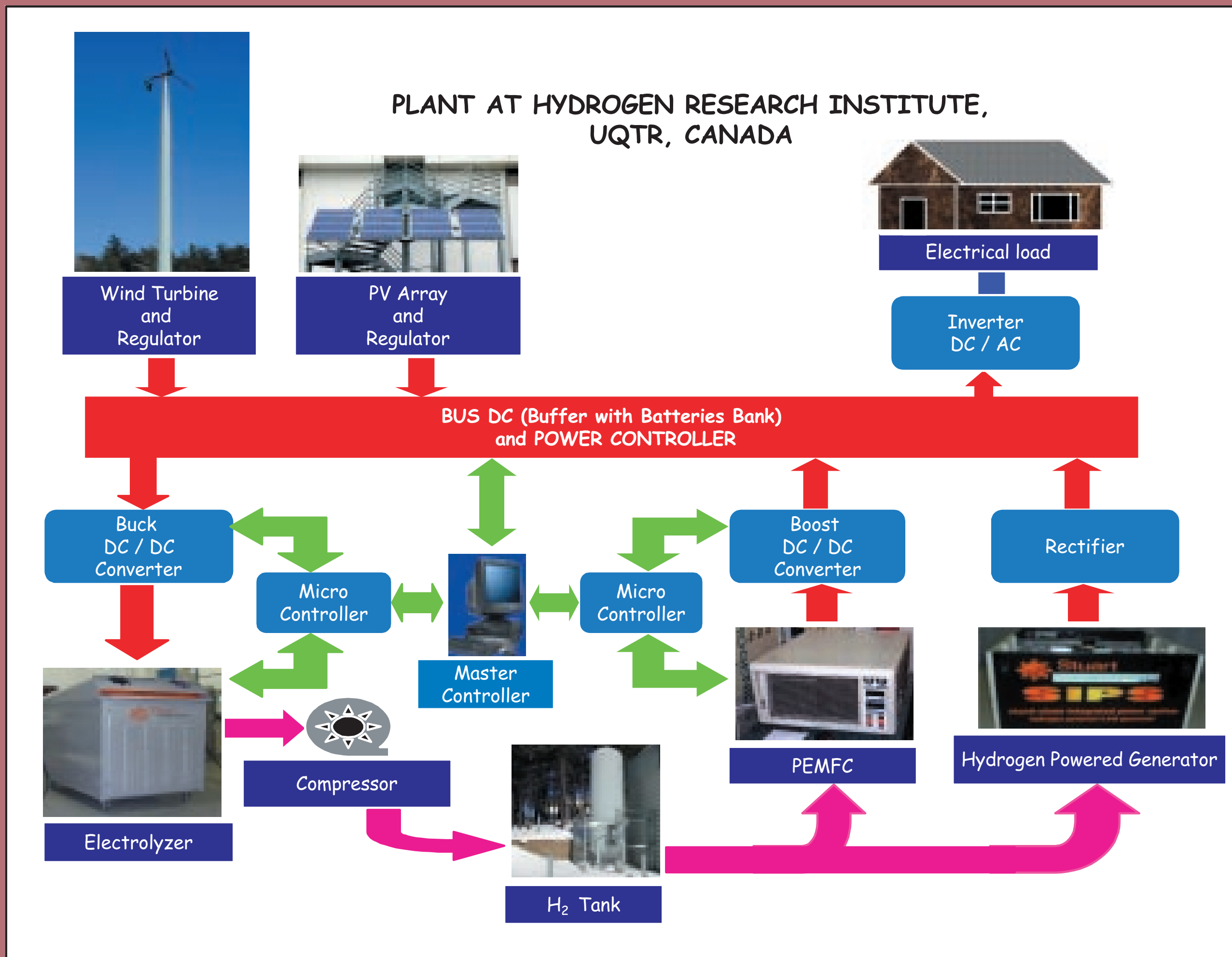


Figure 1: Stand-alone Renewable System of Hydrogen Research Institute

Table 1: Specifications of the RE system components

Component	Specifications
Wind Turbine Generator	10 kW, 3f Permanent Magnet Alternator, VCS-10 - 48 V DC, Bergey - BWC Excel
Photovoltaic Array	1 kW (peak) PV array, Golden Genesis GP 64 PV Modules (4S*4P) with Charge Controller
Electrolyser	5 kW, Alkaline Electrolyser with Compressor, Stuart Energy System
Buck Converter	5 kW, Multiphase PWM, 36-48 Volt, HRI System
Fuel Cell System	5 kW, Proton Exchange Membrane Fuel Cell Stack (MK5-E), 19-35 Volt, Ballard Power System
Boost Converter	5 kW, Multiphase PWM, 24-48 Volt, HRI System
Controller	Energy Management Control System, HRI System
DC Load	12 kW (programmable), Water Cooled, Dynaload
AC Load	3 kW (programmable), California Instruments
Inverter	5 kW, Trace Engineering
Battery	42.240 kWh
Power Source	10 kW (programmable), Elgar
H2 Storage	10 bar, 3.8 m3 represents 125 kWh of stored energy [2]

the power conditioning devices on a real time basis for effective operation of the electrolyser and the fuel cell. The developed control system has the capability to perform the autonomous operation even with intermittent RE sources. The control system has been designed to maximize the direct energy flow from the RE sources to the electrolyser and the load in order to avoid losses in the batteries [6]. The energy level at the DC bus plays an important role for the operation and control of the RE plant. It allows effective energy management among the primary power sources, the electrolyzer input, the fuel cell output and the load. The control system consists of a master controller and two secondary micro controllers (Figure1). The real time data of the RE system has been recorded and used for decision-making in the control algorithm. With respect to energy level at DC bus and pre-defined limits of energy levels in the control algorithm, the master controller sends the conditioned signal (duty ratio) to the secondary controllers for on / off operation of the electrolyser and the fuel cell. The secondary micro controllers manage the power flow with respect to the energy availability at DC bus through the digitally controlled DC-DC converters. The DC-DC converters use multiphase technique to generate pulse width modulation signals to control the power flow. The limits of energy levels in the control algorithm have been managed through double hysteresis strategy. The DC-DC (i.e. buck and boost) converters are important components in the system for effective operation and power flow control of the electrolyser and the fuel cell. The control algorithm has been developed in such a way that the fuel cell and the electrolyser do not operate simultaneously. The limits of energy level in the control algorithm and the load profile have been varied from time to time to check the reliability and the technical feasibility of the control system for autonomous operation. The major parts of the power in the system are intermittent in nature, even though the integrated RE system has operated automatically and effectively by using the developed control algorithm and power conditioning devices.

The excess energy storage in the form of H2 is done through the H2 production system, which consists of a 5 kW electrolyser with a control unit, a compressor, purification and drying process. The electrolyser input energy has been controlled, with respect to energy available at DC bus, through the duty ratio of DC-DC converter. The H2 produced by the electrolyser is temporarily stored in a water-sealed tank of the electrolyser system, and when this tank is full, the electrolyser compressor starts automatically and sends the H2 at high pressure, through the purification and drying process, to the main storage tank of 3.8 m3 water capacity. The time cycle period, corresponding to the filling and compression of the H2 in the water-sealed tank, depends on the electrolyser input power. The stored electrolytic H2 has been utilized to produce electrical energy as per load requirement through a 5 kW fuel cell. The fuel cell power output has also been managed as per energy requirement via the DC-DC converter. The electrolyser and fuel cell on / off operations have been controlled automatically as per pre-defined limits of energy levels in the control algorithm.

4.0 RE System Performance

The performance of RE system is given for a typical day as well as for long-term operation. The energy available from the WTG and the PV array for a typical day (i.e. Dec. 10th, 2001) is given in Figure 2. On that day of operation, the limits of energy levels in the control algorithm were set to start the electrolyser at 99% of energy level at DC bus or above and to stop the electrolyser at 84%. The fuel cell on and off operation was set to 83% and 85%, respectively. During this operation, the RE source power, the load profile, the electrolyser input power, the hydrogen flow rate, the fuel cell output power, the hydrogen consumption rate are shown in Figure 3. The ripples / peaks in the electrolyser power are due to the cyclic operation of the compressor. The H2 flow rate is measured, when it is sent to main storage tank. The power flow of batteries (i.e. charging / discharging) is also carefully monitored. It has been observed that the power supplied to the electrolyser is mainly from the short-term energy storage (i.e. batteries) due to the non-availability of sufficient energy from the RE sources during the operation. The electrolyser and the fuel cell operation were started and stopped automatically as per pre-defined energy levels in the control algorithm. In the control algorithm, the proper selection of energy levels should be done for the most effective operation of the electrolyser and the fuel cell. However, the choice is a complicated problem, and may be studied only by trial and error, as we have done. The energy levels are chosen in such a way so as to keep the batteries at a near full charge and only allow them to be discharged for a short-term and then recharged. This allows the batteries to act as a buffer for the RE system, when components such as electrolyser or load bank are suddenly turned on. The performances of electrolyser and fuel cell were judged by different efficiencies. It has been found that the electrolyser utilization factor (i.e. current efficiency) was about 85%, and the energy efficiency with the compressor running was about 60% and without the compressor running it was 65%. The fuel cell utilization factor was about 90% and the energy efficiency was more than 45%.

The RE system performance was recorded for long-term operation from Dec. 3rd, 2001 to April 17th, 2002 for daily operation of 6 hours, during working hours. Frequently, no energy was available from the RE sources at our location because of climatic conditions. Therefore, a 10 kW programmable power source was used to simulate the typical RE patterns for those days when no RE power was available. During that period, the power available from primary energy sources is shown in Figure 4. The electrolyser input power, the fuel cell output power, the batteries charging / discharging power at the DC bus, and the load profile are shown in Figure 5 (a) and 5(b). The corresponding hydrogen flow rate is linear to the electrolyser input energy. The electrolyser and the fuel cell operation and power flow have been automatically managed through the digitally controlled DC-DC converters. The master controller has made this entire autonomous operation, with the required decisions and controls by obtaining the information through the sensors. The load profile, the programmed output energy pattern of the DC power source and the energy levels in the control algorithm have been changed from time to time to check the reliability of the system and the validity of the developed control algorithm. The performance analysis shows that an autonomous RE system based on electrolytic hydrogen is safe and reliable.

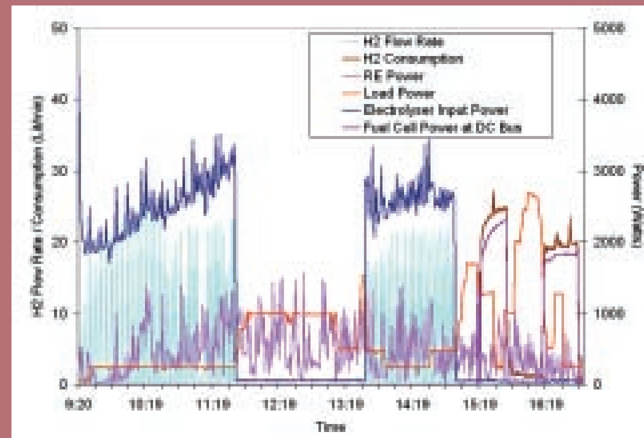


Figure 3: Power, and H_2 flow rate and consumption rate in RE system on 10th Dec 2001.

5.0 Conclusions

The successful long-term autonomous operation and performance show that a stand-alone RE system based on H2 production can be used through a developed control system and power conditioning devices. The components of the RE system, which have substantially different voltage-current characteristics, are integrated through power conditioning devices on the DC bus for effective operation and the system has been tested successfully for autonomous operation. The sensors collect the real time data and utilize this information in the control algorithm for effective energy management in the system. The buffer energy storage, i.e. batteries, were efficient to manage the load transients,

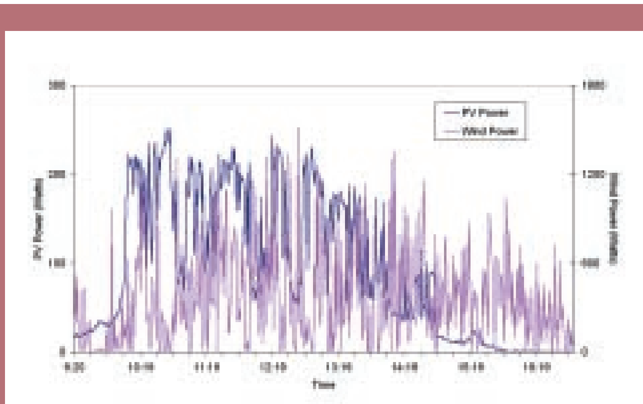


Figure 2: Power available from WTG and PV array on Dec 10th, 2001.

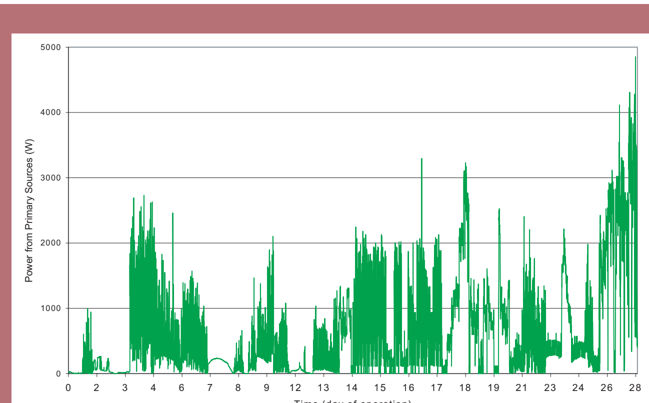
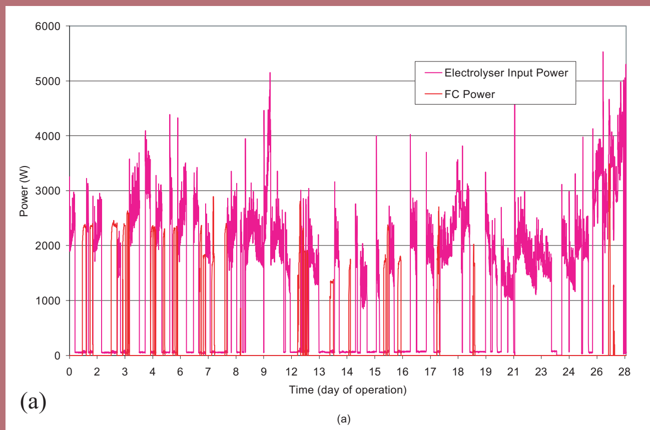
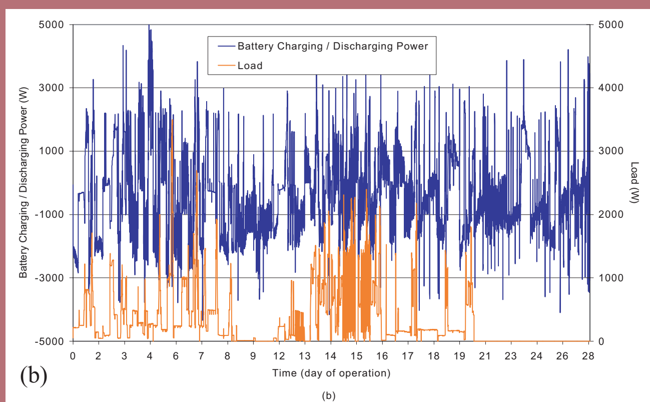


Figure 4: Power available from primary energy sources.





Figures 5a and b: Electrolyser input, fuel cell output, battery charging /discharging and load power

electrolyser ripples and the intermittent power peaks from the RE sources. The developed control system and power conditioning devices have been tested for different load profiles and for various intermittent input power patterns, which were also generated through the programmable DC power source.

We have also used a programmable power source as input to our RE system, which can simulate any type of intermittent power output by using the wind or solar energy profile of any region. The different load profiles are generated through the programmable load to test the system operation and performance. The developed stand-alone RE system of the HRI can be utilized to test the operation and performance of stand-alone RE system based on electrolytic hydrogen.

6.0 Acknowledgement:

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