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Optimal power management of final load and electrolyser in a solar hydrogen power generation system

Xin Xu Dou^{1, a}, John Andrews¹, Milan Simic¹, Reza Hoseinnezhad¹, John Mo¹

¹School of Aerospace Mechanical and Manufacturing Engineering, RMIT University, Bundoora 3083, Victoria, Australia

^axin.x.dou@gmail.com

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Abstract

This paper describes a control unit for a solar-hydrogen power generation system that is capable of supplying an electrical load simultaneously with diverting excess power to an electrolyser to produce hydrogen gas for storage as backup energy. The functional requirements of such a control unit are defined. The transient response time for the PEM electrolyser is studied and analyzed through experimental testing. A design of load splitting device that also performs maximum power point tracking is proposed and its performance measured experimentally. Initial results suggest that the device can accomplish both the load splitting and maximum power point tracking functions satisfactorily.

1. Introduction

Renewable solar sources are widely used in many applications such as battery charging, telecommunication, water pumping, remote house power supply and solar heating. Solar energy is virtually free and solar systems benefit from low maintenance and being pollution free. A solar-hydrogen power generation system typically consists of photovoltaic array, proton exchange membrane (PEM) electrolyser and PEM fuel cell. However, the initial cost of installation can be still high. In most applications, such system would require a maximum power point tracker to draw maximum power from the photovoltaic (PV) array, and an electrical device to split the load between final load and electrolyser to generate hydrogen for storage [1].

A computer simulation of a grid interactive solar-hydrogen system has been conducted by Contreras[2]. In Wang [3] reported the results of a comprehensive system simulation in Matlab, on the power management side, of a standalone system. Miland and Ulleberg [4] studied a small-scale standalone solar-hydrogen system experimentally. However, their hydrogen stand-alone power system uses a parallel approach which lacks of freedom of altering output voltage. Based on the idea of tracking methods presented in [1], Xiao [5] discussed and simulated an adaptive version algorithm. Schmilovitz and Tafticht [6, 7] presented detailed approach of maximum power point tracking methodology. Liu [8] investigated a grid interacted solar-hydrogen demonstration system with battery bank and hybrid hydrogen generation in China. His work presented and discussed the technical and economical feasibility of such solar system. An application of switch mode power supply topology in the automotive field was presented by Zhang [9]. His method of regulating low voltage but high current outputs is very similar to the methodology used in this research.

The knowledge of the transient response of electrolyser leads to more precise control system design but, has not been investigated yet. This paper is going to cover the functionality design of a solar-hydrogen system; response time measurement to pulse signals at different frequencies and some results of a load splitting device in solar-hydrogen system.

2. Functional requirement for standalone solar-hydrogen power generation application

2.1 Typical solar-hydrogen system configuration

The proposed solar-hydrogen system for standalone applications is comprised of photovoltaic array, DC-DC converter(s), PEM electrolyser, hydrogen storage at low pressure or solid state, PEM fuel cell and DC-AC inverter (Fig 1).

Figure 1 Proposed solar-hydrogen power generation system for standalone applications

Solar insolation is captured and converted into electrical energy via photovoltaic array and connected in line with electrical load. When the system is operating in surplus mode, we have a surplus PV power over the main load $P_{PV} - P_L > 0$ [10], the electrolyser is switched on for absorbing the excess energy and produce hydrogen for backup storage. The power input to the electrolyser is thus the surplus power from PV array over the load minus any losses in conversion and load splitting.

The design approach to load splitting between final load and electrolyser adopted here is to progressively step up the voltage input to the electrolyser until the maximum surplus power available is reached. At the same time the final load is fully met. As the voltage applied to the electrolyser is increased stepwise, eventually a saturated point is reached when there is insufficient power from the PV array to supply both loads. Moving back one step from this voltage thus allows an operating close to the maximum power point of the PV array to be found.

Otherwise, when the PV array power generated is just enough to meet the load or in a power deficit condition, that is $P_{PV} - P_L \leq 0$, the electrolyser is switched off. The fuel cell is switched on to meet the final electrical load, drawing upon the already stored hydrogen [4].

Hence the system requirement is for a specific power electronic equipment that can split the available PV power between the final load and the electrolyser. At the same time, the system will try to get very close to the maximum power point of PV array.

2.2 Response time of electrolyser

There is little work reported in the literature on the transient response of PEM electrolyzers, in terms of current, to rapid changes in applied voltage. As researcher Itaya et al indicated that the current response time to a change in applied potential was around 100 ms [11]. In order to maximise the absorption of surplus power from PV over the main load, the dynamic characteristics of electrolyser need to be well understood [10], since the applied voltage to the electrolyser will need to be varied rapidly depending on changes over time both PV power and the final load. In addition, if a stepping method for electrolyser voltage is adopted to find the optimal voltage to supply at any time, the electrolyser will need to settle to a near steady state after each step change. Once found, a dynamic tracking and self-tuning system can be designed to match the requirements of the control unit, achieve control of power inputs and outputs, determine which power electronic technique to be implemented, perform load splitting, power tracking.

In the experiments conducted to date, the solar-hydrogen system has been considered to have two main loads for testing purposes. One of them is a resistive (linear) DC electrical load, to simulate some typical variation and stepping conditions [10]. The second is PEM electrolyser, which has a unique voltage-current characteristic and its impedance varies as voltage-current increase, as show in Fig 2. In Fig 2, $V_{E,ci}$ is the activation voltage also known as the cut in voltage of the PEM electrolyser, V_E and I_E is the unique voltage and current pairs along the curve and $V_{E,max}$, $I_{E,max}$ is the maximum allowable voltage and current of the PEM electrolyser respectively.

Figure 2 Measured voltage-current characteristics curve of a PEM electrolyser

3. Experimental results

3.1 Dynamic response time of PEM electrolyser

Figure 3 Experimental configuration of response time test for electrolyser in Renewable Energy Laboratory, RMIT University

An experimental test bed was constructed in the Renewable Energy Laboratory at RMIT University. The testing equipment includes a signal generator, DC power supply, multimeter, a modified bipolar junction transistor constant current source circuit, PEM electrolyser and digital cathode ray oscilloscope (CRO), as shown in Fig 3.

Test results, obtained in our lab for the response time of electrolyser at different input pulse frequencies, are shown in Fig 4 to Fig 9. On Fig 4 and Fig 5, rising and falling edges are captured.

Figure 4 50 Hz Rising edge

Figure 5 50 Hz Falling edge

Figure 6 100 Hz Rising edge

Figure 7 100 Hz Falling edge

Figure 8 500 Hz Rising edge

Figure 9 500 Hz Falling edge

During the test, input pulse signals are stepped from 50 Hz up to 100 kHz to verify the performance of electrolyser. From the result, it is very clear that the more rapid input signal is and the longer response time is required for electrolyser to reach the steady state. The teal blue colour line represents the pulse signal from the signal generator. The yellow line represents the voltage response from the electrolyser, typically in the range between 400 mV up to about 700 mV. Each of the divisions, or dotted boxes, represent an increment of 100 mV on the vertical axis, and either 2.5 μ s or 500 ns on the horizontal axis (Fig 5 to Fig 9).

Figure 10 A divider experimental setup for measuring voltage as a surrogate of current

Fig 10 shows a model of equivalent circuit used for experimental testing. The electrolyser is in line with the resistor (R_{FIX}). This is a testing configuration for the electrolyser response time. The voltage, captured by the C.R.O. (V_{CRO}) is shown in between Fig 4 and Fig 9. Applying straight Ohm's law we have $I_E = \frac{V_{CRO}}{R_{FIX}}$, i.e. the current passing through the electrolyser (I_E) can be calculated. Typically in the testing, this current is calculated to be approximately 0.6 amp based on a voltage drop of 300 mV across a 0.5 ohm resistor.

3.2 Load-splitting MPPT system

Another experimental test rig of MPPT load-splitting system was designed and constructed as shown in Fig 11. The system comprised a custom made dual buck module circuit on a printed circuit board, PV array, multimeter, electronic load and PEM electrolyser. A manual voltage stepping test was conducted to find out the performance of the system. In order to find the optimal applied voltage for the electrolyser, the voltage input to the electrolyser is progressively step up until the maximum surplus power available is reached.

Experimental tests were performed and initial results were successfully obtained and shown in Fig 12 and Fig 13. Such test is designated to allow the electronic load to pull a reasonable amount of power. By altering the voltage input to the electrolyser we are able to exploit the excess energy, and at the same time we ensure the output voltages are maintained at a desirable and stable level for both loads. From the results, we can see that the total output power of the combine load is closely tracking the input power from PV. However, there is about 10 watts power loss between the two curves, such

losses is mainly due to ohmic losses of the buck converter, large area of ground plain of the PCB and voltage protection circuits.

Figure 11 Solar-hydrogen experiment test bed setup with combined loads (electrolyser and electronic load) for manual testing

Figure 12 Performance of solar-hydrogen system with combined loads (electrolyser and electronic load) with an increasing voltage trend

Figure 13 Performance of solar-hydrogen system performance with combined loads (electrolyser and electronic load) with an increasing current trend

The output of the solar-hydrogen demonstration system is about 50 watts to the combined load at a solar radiation of 1077 W/m^2 on a voltage ascending cycle, as shown in Fig 12. On the other hand, the system is providing about 48 watts power at a radiation of 1052 W/m^2 on a current ascending cycle with very stable output voltage for both loads, as shown in Fig 13. The system is inherently absorbing all energy from PV array at the same time maintained the output voltage steady and as desired.

4. Conclusion

We have presented a standalone solar-hydrogen power generation system. Key components of the system were selected, tested and integrated in the whole system. The response time of PEM electrolyser was successfully obtained. The reaction periods for PEM electrolyser are found in the range of $150 \mu\text{s}$ (67 Hz) and $7.5 \mu\text{s}$ (133 kHz) respectively. Having that in mind, a feasibility of a real time optimal control was investigated. Common microcontroller found off shelf can have clock speed of 16 MHz, therefore, building a control system to control and self-adjust the voltage supply to electrolyser while maintain it at a stabilised level is highly achievable.

Demonstration systems were setup to evaluate the load splitting concept of hybrid solar powered system with energy storage via PEM electrolyser. Stability of the system is furthermore investigated and results are presented in Fig 12 and Fig 13. We can see that the combined loads can fully utilise the power generated from PV array with minor losses. These initial test results are a first step towards developing a comprehensive control unit for a standalone solar-hydrogen system, where parameter sensing and calculations can be automatically and promptly performed by microcontroller. We planned to develop a comprehensive control unit with more sophisticated controls and optimizations.

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