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Designing a control unit for a solar-hydrogen system for remote area power supply

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ABSTRACT

Solar-hydrogen systems for remote area power supply (RAPS) are a promising zero-emission alternative to existing diesel and battery-based systems. Considerable research and development work has been done on the main components of such systems – solar photovoltaic arrays, electrolysisers, hydrogen storages and fuel cells – but relatively little work on an overall system control unit that optimises unattended operation. The present paper therefore focuses on the design of such a control unit for a solar-hydrogen RAPS system employing a PEM electrolyser, compressed gas or metal-hydride hydrogen storage, a PEM fuel cell and inverter. The proposed system configuration includes a load splitter so that only surplus PV power over the instantaneous load is fed to the electrolyser to generate hydrogen for storage, as well as, to achieve matching the power requirement of the load. Control functions such as load splitting, power matching, switching between hydrogen production by the electrolyser and storage, water and temperature management, safety monitoring and system responses in the event of detected hydrogen leaks are identified and defined.

Keywords  Control system, solar-hydrogen system, load splitter, RAPS,

NOMENCLATURE

\[ P_i \]  instant power output of photovoltaic panels

\[ P_L \]  AC electricity power delivered to the load

\[ P_E \]  power delivered to PEM electrolyser

\[ P_{PC} \]  power output of the PEM fuel cell

\[ \Delta E \]  energy lost due to heat/conversions

MPP  maximum power point

DAQ  Data acquisition
INTRODUCTION

Solar-hydrogen systems (SHS) for remote area power supply (RAPS) applications offer a zero-emission alternative to existing diesel and battery-based systems, and with further technological development promise to become cost-competitive in the near future (Clarke et al., 2009). The application of hydrogen storage in this niche market provides an early opportunity for an initial move towards a more general sustainable hydrogen economy.

Considerable research and development work has been done on the various components of solar-hydrogen system for RAPS, namely the solar photovoltaic array, electrolyser, hydrogen storage and fuel cell (Contreras et al., 2007, Santarelli et al., 2004, Varkaraki et al., 2003, Yilanci et al., 2008, Yilanci et al., 2009). A number of experimental and demonstration systems have been reported in the literature (Shabani et al., 2010). However, there remains a need for further work on the overall control unit for such systems as well as reducing the overall cost of the system, extending the lifetime of components, and ensuring safety.

RMIT University’s School of Aerospace, Mechanical and Manufacturing Engineering has been conducting R&D into solar and wind hydrogen RAPS systems since 2005 (Doddathimmaiah and Andrews, 2006, Paul and Andrews, 2008, Shabani et al., 2010). The project reported in the present paper was commenced in 2009, and aims to develop a suitable control unit for a solar-hydrogen RAPS system than can optimise its operation on an annual basis, ensure reliable autonomous operation and oversee the safe production, storage and use of hydrogen.

The scope of this research project is limited to Proton exchange membrane (PEM) electrolysers and PEM fuel cells, compressed hydrogen gas at low pressure, and solid-state storage, rather than any other production or storage options. No work within this project is being done on improving the design and performance of PEM fuel cells or PEM electrolysers in themselves. Instead, the project is concentrating on theoretical and experimental testing of an overall control unit for a solar-hydrogen system for RAPS. The research is focusing in particular on designing and testing preferred options for splitting the PV output between final load and electrolyser as required by the instantaneous system conditions, as well as achieving high power transfer efficiency to the combined final load and electrolyser.

A key planned outcome of the project is the development and experimental testing of a control unit that can meet all the operational, reliabilities and safety requirements of a solar-hydrogen RAPS system operating autonomously for long periods. One or more devices for splitting the output of the PV array between final load and electrolyser will be designed and its performance measured in an experimental system on an annual basis. Performance data on a solar-hydrogen system incorporating the new control unit, including measures of system reliability and safety will be obtained. It is intended that the project will break new ground because no such overall control unit that enables the safe, reliable, stand-alone operation of a solar-hydrogen system currently exists.

In the following section of this paper, work to date conducted on solar/wind hydrogen RAPS systems is reviewed and the need for an overall control unit established. The functional requirements of such a unit are identified in the section of functional requirement of a control unit for a solar-hydrogen system for RAPS, and some initial design principles set out in section design approaches for the control unit. Last section summarises progress in the project to date and identifies the next steps that need to be taken.
STATE OF DEVELOPMENT OF SOLAR-HYDROGEN RAPS SYSTEMS

The Australian government has committed to reducing Australia’s total greenhouse emissions by 25% compared to 2000 levels by the year 2020 if there is global emission reduction agreement to tackle the problem of climate change (Australian Government, 2008). By reducing the emissions from diesel and petrol generators in remote and other standalone power supply applications, and offering a low emission alternative to emission-intensive centralised grids for rural electrification in developing countries, the development and application of solar-hydrogen systems for RAPS applications will contribute to the achievement of both the Australian and international greenhouse gas emission reduction targets. The present project will assist in this task by improving the economic competitiveness, reliability and safety of solar-hydrogen systems through developing a suitable control system.

The key potential advantages of solar-hydrogen systems over conventional alternatives such as diesel and petrol generators and PV systems with battery storage are the following:

- a low greenhouse gas emission system
- long-term storage, that is, season-to-season storage, for example, enabling surplus solar energy in summer to be stored with very low losses for reuse in winter, whereas batteries lose energy rapidly over time through self discharge (Paul and Andrews, 2008)
- capability of unattended operation for long periods (a year or more), and hence very low maintenance costs (Shabani et al., 2010)
- higher energy density per unit mass and per unit volume than battery storage (Bose et al., 2004, Gray et al., 2010b)
- avoided adverse environmental impacts from disposing of batteries at the end of their lifetimes, which are much greater than those for fuel cells and electrolysers
- lifecycle economic benefits compared to conventional systems due to the above features

A number of researchers have investigated solar-hydrogen systems for RAPS applications, in terms of theoretical analysis, computer modelling, experimental testing and demonstration systems. For example, theoretical and modelling work has been done by Caux et al. (2005), which made very interesting recommendations such as improving the efficiency of fuel cell by controlling the air supply; Santarelli et al. (2004) utilizing hydrogen of a stand-alone hydrogen energy system as storage and carrying medium as well as supply electricity on an annual basis; Zhou and Francois (2009) Satisfied the load requirement while maximising the benefit of renewable energy sources for an active hydrogen/wind hybrid power system (Caux et al., 2005, Santarelli et al., 2004, Zhou and Francois, 2009). Experimental systems have been developed and tested by Ipsakis et al (2008), that applied power management strategies using renewable energy sources in off grid remote areas, telecommunication stations, energy intensive desalination plant and etc; Notton et al (2009) focuses on sizing of grid-connected PV systems and studies efficiency of different combinations of PV modules and inverters under various conditions; Kaldellis et al (2009) is showing optimum sizing of autonomous PV energy systems for island electricity system (Ipsakis et al., 2008, Kaldellis et al., 2009, Notton
et al., 2009). Demonstration systems developed and deployed to date include Agbossou et al (2004), demonstrated very promising stand-alone renewable energy utilising renewable energy sources like solar, hydro and wind energy in their system; Liu et al (2009) compared the operation cost of solar-hydrogen system to grid network; Varkaraki et al (2003) particularly concentrate on hydrogen based emergency backup system and optimisation to heat exchange; Yilanci et al (2009) had reviewed issues regarding the usage of renewable energy sources and commented addition of electrolyser actually lower the overall efficiency of solar-hydrogen system (Agbossou et al., 2004, Liu et al., 2009, Varkaraki et al., 2003, Yilanci et al., 2009).

However, little work to date has been done on the overall control system for a solar-hydrogen RAPS system either experimentally nor practically (McHenry, 2009). In particular, a literature search has not revealed any detailed examination of how excess PV energy over the load can be diverted to the electrolyser on a dynamic basis as both the load and solar irradiance vary over time, and how the power transfer from the PV array to the final load and electrolyser can be optimised over an annual period. Finding practical and cost effective solutions to this key function of load splitting will therefore be a prime focus of the present research project.

Thus, this project will contribute to the advancement of scientific and technical knowledge in the field of solar-hydrogen systems by developing and testing experimentally a novel control unit for such systems. In addition, the project outcomes will potentially benefit rural and remote communities and facilities in both Australia and overseas, including island communities and remote industrial and agricultural facilities, by assisting in the development of more cost-effective, low emission, and reliable remote area power supply systems. All the R&D outcomes mentioned above may also create opportunities for commercialisation of solar-hydrogen RAPS systems, and individual components (in particular a control unit), by Australian companies, as well as advanced educational demonstration systems.

**FUNCTIONAL REQUIREMENTS OF A CONTROL UNIT FOR A SOLAR-HYDROGEN SYSTEM FOR REMOTE AREA POWER SUPPLY**

The standard solar-hydrogen for RAPS applications is a standalone system comprising a photovoltaic array, PEM electrolyser, PEM fuel cell, hydrogen storage at low pressure (metal-hydride storage) and DC-AC inverter (Figure 1).
Solar energy is converted to electrical energy by the PV panels and directly connected to the load. When there is excess PV power over the load, the system will send the excess power to the electrolyser for producing hydrogen for storage. Later, when there is not sufficient solar energy to meet the load, hydrogen is drawn from the storage canister and fed into the fuel cell for producing electricity to meet the supply deficit.

The advantages of using hydrogen for energy storage is that it can stored at high pressure or in metal hydrides which have a high energy per unit mass on a system basis (Gray et al., 2010a), and does not self-discharge unlike battery. Of particular benefit to standalone solar RAPS systems, hydrogen can retain its energy content over long periods, from summer to winter, for example, allowing surplus solar energy in the summer to be stored for reuse during the less sunny winter period. Hydrogen can be stored in solid-state form at relatively low pressures in certain metal hydrides, which have safety advantages over high-pressure gas storage (Gray et al., 2010a). Ideally the photovoltaic array should operate as close as possible to its maximum power point (MPP) at all times whether it is supplying just the final load, or the load plus the electrolyser. This function, along with load splitting, is critical functions that a control unit for a solar-hydrogen system (SHS) should perform. Overall the control unit must ensure the system operates efficiently, continuously, reliably, safely, and in an environmental friendly manner at all times without additional intervention, that is, autonomously. Specifically the main control functions that need to be performed are the following:

1. **Mode switching**

   The system must be switched between the following modes depending on the instantaneous solar radiation and load to be supplied:
Control mode 1:

If $P_i > P_L$, where $P_i$ is the output of PV panels and $P_L$ is AC electrical loads. The system is set to operate in control mode 1, where the load is supplied directly and wholly by the PV array, and the excess PV power over the load, after taking into account energy losses in the control circuits, $\Delta E$, is fed to the PEM electrolyser for hydrogen production. Hence the power fed to the electrolyser $P_E$ is given by:

$$P_E = P_i - P_L - \Delta E$$

The on/off conditions of the electrical components, and key valves in the system, for mode 1 are summarised in Table 1.

Control mode 2:

If $P_i \leq P_L$, the system is set to operate in control mode 2, where the load is supplied only partially by the PV array, and the supply deficit is supplied by the fuel cell. The amount of load that must be met by the fuel cell by drawing hydrogen from the storage canister is given by:

$$P_{FC} = P_L - P_i + \Delta E$$

The on/off conditions of the electrical components, and key valves in the system, corresponding to mode 2 are summarised in Table 2.

<table>
<thead>
<tr>
<th>ELECTRICAL COMPONENTS</th>
<th>ON</th>
<th>OFF</th>
<th>VALVES</th>
<th>ON</th>
<th>OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV arrays</td>
<td>●</td>
<td></td>
<td>Deionised water</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>PEM electrolyser</td>
<td>●</td>
<td></td>
<td>Hydrogen canister</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>PEM fuel cell</td>
<td>●</td>
<td></td>
<td>Hydrogen check valve (inlet)</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>DC-DC converter</td>
<td>●</td>
<td></td>
<td>Hydrogen supply valve (outlet)</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>DC-AC inverter</td>
<td>●</td>
<td></td>
<td>Air supply</td>
<td>●</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: The on/off conditions of the electrical components, and key valves in the system, for mode 1
Table 2: The on/off conditions of the electrical components, and key valves in the system, corresponding to mode 2

2. Load splitting and maximum power point tracking for the PV array

When $P_i > P_L$ during the day time and the system operates in mode 1, the PV power will be split between the load and electrolyser, with the surplus PV power over the load going to the electrolyser for producing hydrogen.

The control unit should also either be pre-programmed with the voltage-current characteristic curve of the PV array, or make rapid adjustments to the effective impedance across the output terminals of the array, so that the PV array operates close to its maximum power point at all times [see Figure 2 and Paul and Andrews (2008)].

The control unit therefore also has to ensure that the voltage across the electrolyser is set at just the right level so that the power drawn by the electrolyser is equal to the difference between the PV power and the load, minus any energy conversion losses.

If $P_i < P_L$, the system must operate in mode 2 so all the PV power is fed to the load, and the fuel cell is switched on in order to supply the power supply gap.

All these optimal matchings must be performed over each discrete small time interval in order to obtain the most Hence it would lead to a more energy efficient and cost effective solar-hydrogen system. The most appropriate basic small interval to be employed in the control unit is still being investigated and is a matter of some complexity since it depends, among other factors, on:

- the rate of change of incident solar irradiance
- the rate of change of the load
- the response time of the control unit in finding the optimal settings for a given solar irradiance and load.

Figure 2: V-I characteristics of a photovoltaic panel and its maximum power point

3. Control of the PEM electrolyser
It is important to ensure that there is always enough de-ionised water being fed to the PEM electrolyser on its oxygen-side electrode. Water supply pressure also should be regulated so it does not damage the membrane electrode assembly of the electrolyser.

The applied voltage and current drawn by the electrolyser must be kept within preset maximum limits to ensure the electrolyser stack is not damaged. It is also prudent to monitor the temperature of electrolyser stack to make sure it does not get over heated. If the electrolyser is operated in a confined space, a hydrogen sensor needs to be installed to keep a constant watch for any hydrogen leaks.

If the monitoring system detects that any of these preset limits or conditions are exceeded, the control unit should shut off power to the electrolyser, close the hydrogen outlet valve, and sound an alarm.

The hydrogen produced by the electrolyser should be dried and get as near as possible to a purity grade of 4.0 (99.99%) to avoid damage to metal hydride storage, and poisoning of the catalysts of the fuel cell.

4. Control of hydrogen storage

The hydrogen production will be stored in a hermetically-sealed canister either in solid state or low-pressure gas state. The flow rate of hydrogen into and out of the storage canister should be continuously monitored so that the integrated input and output masses of hydrogen can be calculated by the control unit. The pressure at the inlet/outlet valve of the canister and also the canister temperature must also be continuously monitored.

The amount of hydrogen stored in a compressed gas cylinder can be readily calculated from its pressure, temperature and the known volume of the cylinder. But the measurement of how much hydrogen is stored in a metal hydride canister is not so straightforward. In the latter case, the calculation of the cumulative flows in and out of the canister over a period provide one of the best means of estimating the hydrogen actually in the canister at a particular time.

The control unit must also ensure the pressure of the hydrogen is reduced before feeding to the fuel cell module. The shut off valve for the storage canister should always be closed if not charging/discharging hydrogen.

5. Control of PEM fuel cell

A solenoid valve would normally control the hydrogen supply to the fuel cell depending on what mode the overall system was operating in; at the same time the pressure at the inlet would be continually monitored to check whether it is within the acceptable range. The oxygen supply is controlled by the pressure and flow rate of the incoming air to ensure the stoichiometry of the main reactants is within the requisite range for the hydrogen and oxygen to be fully reacted within the cell.

The temperature of the fuel cell’s membranes should be maintained so that they are neither over-moisturised (flooded) or become dried out, because either way it would degrade the performance and lifetime of membrane. Hence water management for cooling the cell needs to be controlled so that appropriate water flow is allocated at right time for cooling the membrane. On the other hand, oversupply of hydrogen to the fuel cell might decrease its performance of the component and further reduce the overall efficiency of the SHS.
6. Monitoring of component and system performance

For system monitoring and control, data acquisition (DAQ) must be undertaken in each small discrete time interval, and on the basis of this input data stream the control unit must make physical and electrical adjustments (C) to the system as quickly as possible within each interval.

List of system components to monitor/measure (DAQ) and control/regulate (C):

- Pyranometer
  
  *Solar irradiance (DAQ)*

- PV panels
  
  *Voltage (DAQ)*
  
  *Current (DAQ)*

- PEM electrolyser
  
  *Temperature (DAQ)*
  
  *Deionised water (DAQ & C)*
  
  *Hydrogen production (pressure) (DAQ & C)*
  
  *Voltage (C)*
  
  *Current (C)*

- Hydrogen storage
  
  *Hydrogen inlet (charge) pressure (DAQ & C)*
  
  *Solenoid valve (C)*
  
  *Check valve (C)*
  
  *Relief valve (C)*
  
  *Hydrogen flow rate (DAQ&C)*
  
  *Hydrogen supply (discharge) pressure (DAQ & C)*

- PEM fuel cell
  
  *Temperature (DAQ)*
  
  *Hydrogen supply (pressure and flow rate) (DAQ & C)*
  
  *Air supply (C)*
  
  *Water flow rate (DAQ & C)*
  
  *Voltage (DAQ & C)*
  
  *Current (DAQ & C)*

- DC - AC inverter
  
  *DC-AC conversion (C)*

7. Safety system
Measured variables such as temperature, voltage and current of the electrolyser can lead to determine how the electrolyser performs. For example, if the temperature of electrolyser suddenly becomes very high, it could indicate that the electrolyser is operating at very high current input and the control unit should responded to cease the operation. Other variables such as the measured output of fuel cell can indicate how well the fuel cell operates. For instance, if there is a sudden voltage drop, it could be that the fuel cell is flooded and the system should stop supplying hydrogen to the fuel cell.

Within this system, if it is detected that there is any hydrogen detection by sensors at above the acceptable safe levels, there must be some hydrogen leakage taking place. In this event, the control unit must immediately shut down all power supply to the electrolyser to stop hydrogen production, as well as shut off the main valve of the hydrogen storage canister, and the input valve to the fuel cell.

**DESIGN APPROACH**

The prime focus in the present research project is to develop an electronic system with the appropriate software and hardware to perform the system mode switching (function 1 above); and load splitting, maximum power point tracking for the PV array, and supply of the correct power to the electrolyser (function 2). The direct output from the PV array will thus need to be allocated to the final load and electrolyser dynamically and continuously in a manner that keeps as close to the MPP of the PV array as possible.

A central control module will constantly acquire digital data on the values of all the key components and system variables, and make relevant control adjustments to individual subcomponents on the basis of these inputs. For example, when there is excess energy from the PV after satisfying all electrical loads, the central control module would need to provide the right voltage to electrolyser in order to maximise energy transfer as well as hydrogen production.

**CONCLUSION**

The design for an integrated control unit for a solar-hydrogen system for RAPS applications has been outlined. Research work is continuing towards developing an integrating control unit with appropriate use of Programmable Logic Control and the special electronic circuits needed to effect load splitting, and voltage and current regulation according to prevailing conditions throughout the system. The SHS control system will be modelled using Simulink (Matlab), where all components would be simulated using visual based blocks with according algorithms. All functional requirements mentioned before will be implemented into the simulation to establish the optimal control algorithms and procedures. Once an optimal control unit design has been developed and tested through such computer modelling, a small experimental system will be constructed to measure the actual performance of the control unit. Later all theoretical modelling data can be compare with the actual experimental data to further verify the accuracy and precision of control unit for solar-hydrogen system for RAPS.

**REFERENCES**

X. Dou, J. Andrews, M. Simic


**BRIEF BIOGRAPHY OF PRESENTER**

Xin Xu Dou completed his Bachelor of Engineering (Manufacturing and engineering management) with honours from RMIT in 2008. Xin Xu started his PhD (Mechanical Engineering) on a control unit for a solar-hydrogen system in 2009 under the guidance of Associate Professor John Andrews and Dr Milan Simic. Xin Xu is interested in the area of mechatronics, control engineering as well as advanced manufacturing.