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Hybrid Fuel-Cell and Battery Power Plant Design

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Abstract

The push for more sustainable energy sources increases as energy demand increases. This paper presents the configuration of a hydrogen fuel cell and a battery to increase the efficiency of a practical power source for a sustained Direct Current (DC) load for the milestones of a senior Electrical Engineering capstone project. The goal is to design a switching schedule between a battery and the hydrogen fuel cell to run the load. The system has been prepared based on Arduino voltage and current sensors to read the inputs from the respective energy sources. The Arduino sensors utilize these readings to switch between power sources by feeding them into a solid-state relay, which acts as a gate to power the load. This automatic switching system uses computer coding to run the energy sources without human interaction based on voltage inputs. In testing, the results of the system have been promising when using voltage as a means of switching or manually switching between the sources. There is additional room to improve the switching metrics to create a more efficient system using the code currently available. Additionally, the method used to electrolyze the hydrogen was not a primary focus of this project but is essential to the sustainability of a scaled version. If adapted by other senior capstone programs, the focus on hydrogen electrolyzation would be another interesting perspective. This capstone project greatly increased student familiarity with hybrid hydrogen systems. By having the students build this project from the ground level, they gained a greater appreciation for the amount of consideration taken when there are multiple inputs to a power system. Additionally, students were able to talk knowledgeably to others about complex systems through a series of presentations and informal briefs. The students advised both nontechnical and technical stakeholders, providing insight for all levels of technical understanding.

Introduction

The issue of climate change is constantly intensifying and increasing. The global demand for energy in the past ten years has increased substantially by almost 100 quadrillion British Energy Units and is projected to continue growing based on population and standard of living [1]. In addition, a crisis has developed regarding carbon in the atmosphere, causing abnormal climate changes. The climate is not a trading card; it's our future, and climate change extends beyond any country's bounds [2]. Although many innovative solutions are being researched to independently increase our energy efficiency or decrease the amount of carbon in the atmosphere, a resounding call for sustainable energy production addresses both issues. Historically, the most significant barrier to renewable and sustainable energy has been expensive, but recent publications show that renewable energy production has decreased in cost, making it, in some cases, the more affordable option compared to fossil fuels. For example, the International Renewable Energy Agency showed that 163 gigawatts of renewable power installed in 2021 had lower costs than the cheapest coal option [3]. The barriers to renewables more often are inconsistent power supply and storage issues. Each solution to these issues must be measured in its sustainability, cost, and efficiency.

Increased natural disasters, environmental migration, and arctic thaw are all related to global carbon emissions [4]. Vessels are adapting their designs to accommodate changing emissions laws and energy production methods. One such adaptation includes the new Hydrogen Fuel Cell powered vessel fleet being launched in San Francisco, with the first 21-meter 75-passenger ferry being delivered in March 2023 [5]. New regulations are being created by the United States Coast Guard in order to safely incorporate fuel cells into the maritime world. Regulators must work to best understand how changing emission laws affect their missions and be savvy in new technologies that corporations will implement, including fuel cells.

Hydrogen is a form of energy storage with great potential in the renewable energy field due to its near-zero greenhouse gas emission and high efficiency [6]. Hydrogen can be collected using an electrolyzer to break up water molecules and isolate the hydrogen atoms. Hydrogen power uses separated hydrogen to generate electrical power through a fuel cell. The only byproducts of the reaction are energy and water vapor [7]. Hydrogen fuel cells are very similar to batteries structurally, with a positive and negative electrode surrounding an electrolyte. The hydrogen enters through the anode or negative electrode, and a catalyst separates the electron from the hydrogen atoms. The positively charged hydrogen atoms move to the cathode and combine with oxygen to produce water and heat. The electron goes through an external circuit to create electricity flow [8]. It is primarily used as a clean form of energy storage, and there are instances of it being used on vehicles, land units, and even sea-going vessels [9]. However, the energy produced using a hydrogen fuel cell is not always completely clean. The most common implementations of hydrogen technology use hydrogen, which is electrolyzed using electricity from natural gas. This technique is cleaner than just burning natural gas as it maximizes energy output. Using natural gas can enable fuel cells to be integrated into current infrastructures easier with the goal of eventually transitioning to completely renewable electrolysis, making the system fully renewable [10]. Therefore, to consider this energy storage and production method clean, the type of electricity source for electrolysis must be considered.

Low emissions, high resource availability, and high efficiency are all draws to this type of energy storage. In a world transitioning to renewable energy, there is no one instantly available solution to meet the world's energy demand. Therefore, finding ways to combine different resources and technologies is essential to meeting that demand [11]. The authors applied the ability to add a hydrogen fuel cell and battery system for an electric scooter [12]. The authors in [13] studied the simulation and implementation of Ni-MH rechargeable battery management systems.

This project aims to test ways to utilize multiple energy sources and a storage unit using computer programmable switching, explicitly looking at switching between hydrogen and battery energy storage. The fuel cell system combines a 200W, 15V Hydrogen Fuel Cell Stack and hydrogen storage tank in the form of electrolyzed hydrogen contained in the LWH22-10L-5 Hydrostick Pro. To test the outputs of the fuel cell, a series of different sensors are used, including Arduino voltage sensors, two Diymall DC 0-25V voltage sensors, and two 30A Range ACS712 Module current sensors, where all outputs are displayed in MATLAB using an Arduino UNO. This paper overviews the initial applications of hydrogen fuel cell and battery switching as well as sets up the possibility of using this switching technology to be more intelligent in the future.

Modeling Hydrogen Fuel Cell and Battery Switching

The project starts with the simulation modeling of the hydrogen fuel cell and battery switching control system in MATLAB Simulink. The simulation uses a state diagram to describe the logic used by the solid-state relays to complete the switching seen in Figure 1. The preferred state is when the fuel cell is on and can power the motor. If the fuel cell runs low on hydrogen or stops working, the relay will switch the input from the fuel cell to the battery. If there is no battery or fuel cell output, the circuit has no information, and therefore, the circuit is not powered, so the motor or load cannot be turned on.

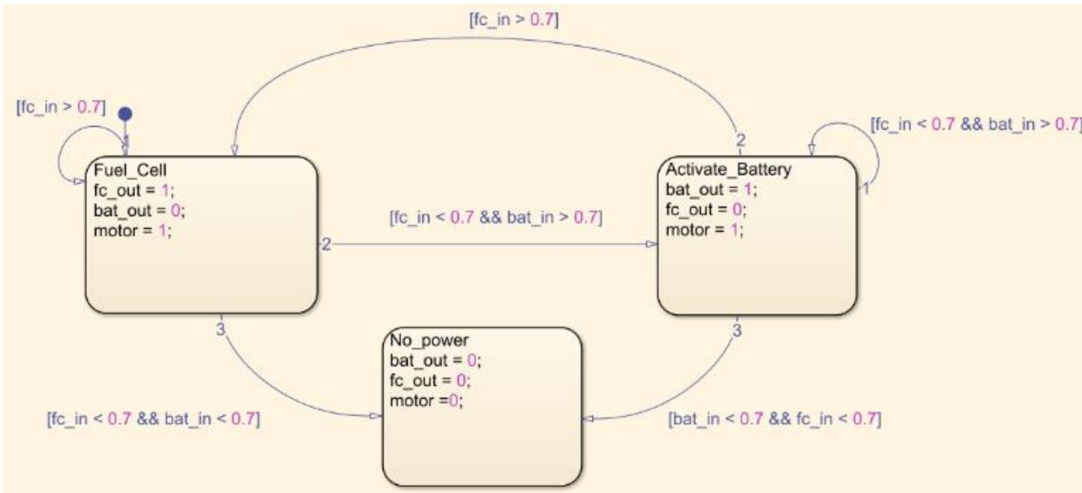

Fig. 1. Modeling State Diagram of Fuel Cell Switching

In addition to modeling the switching control system, the hardware system was also modeled using block diagrams in Figure 2. The project centers around the Arduino UNO, where all inputs and outputs occur. There are two solid-state relays that act as hardware switches. When the output of the corresponding pin to the fuel cell or battery is nonzero, that side of the circuit closes, enabling the appropriate power source to power the load. The Arduino current sensors supply inputs to determine if the activated power source is releasing any voltage and if the current is flowing. This project also considered the use of a solar panel and charge controller to charge the battery when the battery was not in use, so that aspect is included in the system.

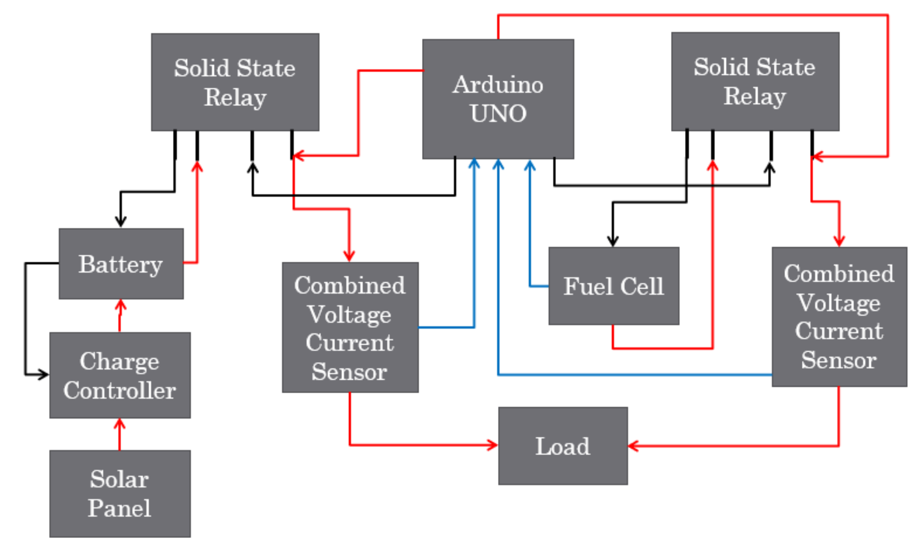

Fig. 2. Modeling Overall Hardware Setup

Building Smart Controller Switching

The inputs from the voltage of the battery and the hydrogen can be used to help a logical controller determine when to use the battery versus the fuel cell. The first iteration of switching between the power sources used a MOSFET circuit to switch between battery power and hydrogen power, which can be seen in Figure 3. When the input to the MOSFET was high for either the circuit connected to the fuel cell or the battery, that source would power the motor. To reduce complexity, the second iteration used solid-state relays similar to the original MOSFET circuit in Figure 4. The input can either be provided manually or done using the logical outputs from the Arduino UNO.

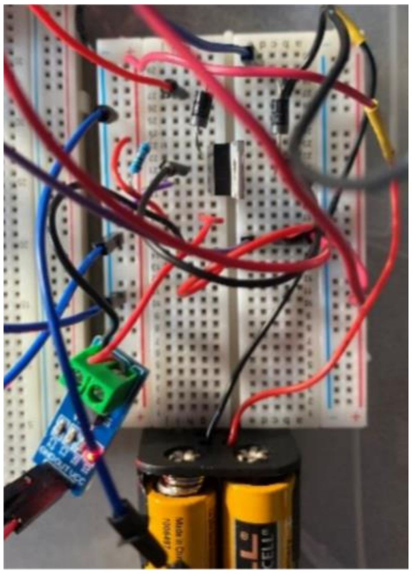

Fig. 3. One of Two Mosfet Switching Circuits

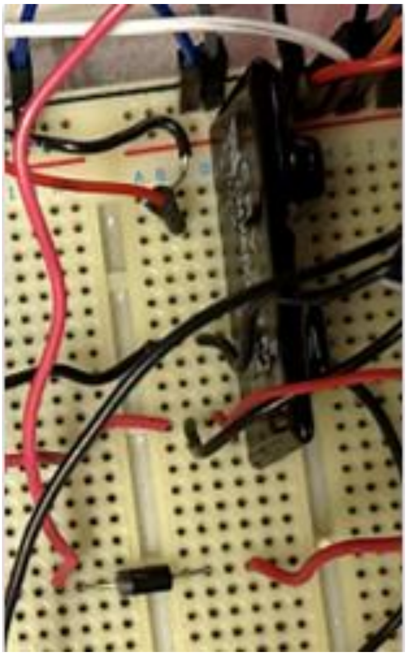

Fig. 4. One of Two Solid State Relay Circuits

The automatic aspect of the power plant is implemented to remove manual interaction when switching between energy sources. This is executed through MATLAB with the help of voltage sensor inputs, enabling the Arduino to control outputs. The code uses these inputs to determine which source to use based on the hydrogen fuel cell voltage. However, this deciding metric could be adjusted to better account for other factors. The MATLAB code is currently set up to be able to switch between sources dependent on any parameter set. Moving forward, more intelligent switching could be integrated, such as prioritizing the efficiency among sources based on a variety of factors.

Hydrogen Fuel Cell System

The system is a 200W, 15V Hydrogen Fuel Cell Stack with hydrogen provided by electrolyzed hydrogen contained in the 10L Hydrostick Pro. To test the outputs of the fuel cell, a series of different sensors are used, including built-in voltage sensors in an Arduino UNO, two Diymall DC 0-25V voltage sensors, and two 30A Range ACS712 Module current sensors with all outputs displayed in MATLAB through an Arduino UNO. The Arduino UNO can also provide logical outputs of 0 or 5 volts. All components can be seen in Figure 5.

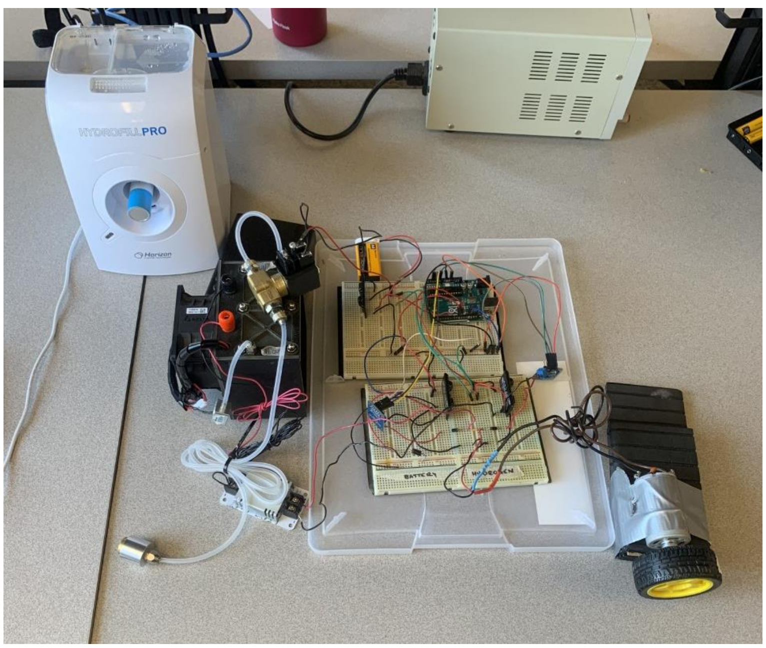

Fig. 5. Hydrogen Electrolyzer Next to Fuel Cell and Battery System

For the initial tests, a 12V DC motor shaft connected to a small wheel as the load. In Figure 6, exclusively voltage data was read from the hydrogen fuel cell after being stepped down through a transistor to 5 volts to power the 12V motor. This data shows the voltage drop-off after the hydrogen supply was removed, which helps determine the correct time to switch from one source to another. When looking at the voltage produced by the hydrogen fuel cell, one concern was the displacement in time between the fuel cell hydrogen supply being shut off and the fuel cell ceasing to produce voltage. Preliminary tests estimated the number of seconds the drop-off typically took, and the results were incorporated into switching mechanics. Additionally, the voltage measurements are used as inputs to the controller, as explained below.

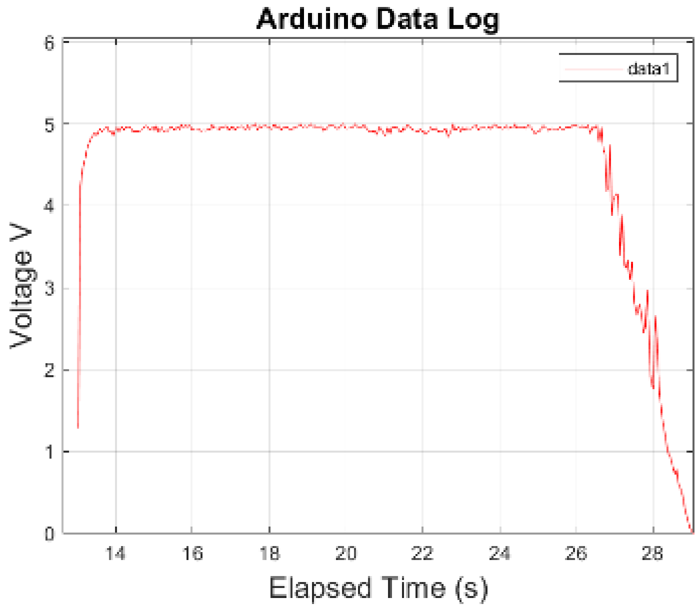

Fig. 6. Voltage Data of Hydrogen Mapped into MATLAB Graph

Battery and Solar Incorporation

In the process of upscaling the system, a battery with a larger capacity to meet higher energy demands will be used with the added goal of being more compatible with a solar power system. The LifeP04 Lithium Iron Phosphate 12V/8Ah battery is the item that was acquired to utilize in the overall system because of its large capacity, reliability, and that it is compatible with the parameters of other systems. A means of monitoring this battery will also be used with the Renogy Battery Monitor, which will provide information on the voltage, current, and power the battery is charging/discharging at as well as the relative percentage. The setup of these components is pictured below in Figure 7.

Fig. 7. LifeP04 12V/8Ah Battery with Renogy Battery Monitor

In initial testing for solar power, the voltages for the 100 W, 12V solar panels fluctuated between 11-13 V depending on the time of day. Based on the measurements shown in Figure 8, the morning period (0800-1200) voltages and currents were nominally low compared to the afternoon period. The morning had currents between 0.2 A to 0.4 A, while the afternoon had currents between 0.6-0.8A. This shows that afternoon periods of the day are optimal for charging the battery. The figure below illustrates this analysis while recording relatively constant temperature and cloud coverage. Overall, analyzing the factors for charging solar panels can be extremely beneficial when implementing this hybrid system as it directly affects how long the battery must be charging rather than supplying power to the system.

Solar Panel Readings					
Date (MM/DD)	**Time**	**Current (A)**	**Voltage (V)**	**Temperature (°F)**	**Cloud Coverage (%)**
5-Apr	900	0.2	11.3	51	99
	930	0.3	11.9	51	99
	1000	0.4	12.3	51	98
	1030	0.4	12.7	50	99
	1100	0.4	12.9	50	98
	1130	0.3	13	50	99
	1200	0.4	13.1	50	99
	Break				
	1300	0.5	13	51	100
	1330	0.7	13.2	50	100
	1400	0.5	13.2	50	100
	1430	0.6	13.3	48	100
	1500	0.5	13.2	49	98
	1530	0.7	13.2	48	100

Fig. 8. Solar Panel Output on April 5, 2023

Future Work

The next significant steps in building a hybrid power plant are to construct the higher demand load with multiple DC components and to step up the hydrogen-battery system to full voltage and current. The first aspect of building the load will entail connecting several LEDs and motors, such as the 750 GPH Motor, to create a model of a diverse set of DC loads that would power from the system. The load will be scalable so the process can be replicated in larger power systems. To ensure that the system can power the load, the load configuration specifications, including power draw and current requirements, must be measured and compared to the typical operating capabilities of the power sources. Additionally, the solar and battery system will be combined with the fuel cell and battery system. The switching logic currently used with the small-scale model fuel cell will be implemented in a similar method with the control system already in place that enables the solar cells to charge the battery. Further consideration will be made regarding how the sources are connected depending on the necessary current and voltage for the DC loads.

The goal of the future system would also be to incorporate more information to inform the switching between hydrogen and battery power. In addition, considering factors such as charge, efficiency, and demand would increase the hybrid system's performance.

Conclusion

This paper presented the functionality of a small electronics switching circuit to jointly power a load using both batteries and a hydrogen fuel cell. The small scale showed that using an Arduino UNO as both an input and output of the system has been effective and is ready to be taken to a larger scale. This project is critical to developing a deeper understanding of hybrid power systems. Best utilizing limited resources is essential to help resolve the energy demand and climate change crisis. An alternative type of energy resource increases the sustainability of the systems. Regulations must be created and implemented as emissions standards to improve the change in maritime, renewable energy capabilities. Having greater exposure to and a better understanding of renewable energy systems, specifically hybrid systems, enables those creating these regulations to be better equipped.

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