Residential Electrolyzer Optimized with Pulse Width Modulation and Magnetism

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I. Introduction

Fuel-cell electric vehicles (FCEVs) have the potential to replace the internal combustion engine. FCEVs are more efficient than gasoline and produce no harmful emissions. FCEVs are similar to electric vehicles; however, in FCEVs, energy is stored as hydrogen and converted to electricity by the fuel cell. In spite of the benefits that FCEVs could provide, the infrastructure that is required to provide these vehicles with the necessary fuel is still in its early stages of development [1].

Electrolysis can be simply described as the process of separating water into hydrogen and oxygen gas. The process of electrolysis can be utilized to supply systems such as FCEVs with the necessary hydrogen gas. A system that performs electrolysis is known as an electrolyzer. For an electrolyzer to be used in this manner it must be highly efficient.

Pulse width modulation (PWM) is the process of controlling an analog circuit with a digital microprocessor. PWM can be implemented to control the power draw of a system and, by using this process, power consumption can be reduced significantly [2]. By utilizing PWM, this project seeks to measure and maximize the efficiency of an electrolyzer system.

II. The Problem

Transportation continues to contribute to poor air quality which has lasting effects on everyone [3]. More effective energy solutions will be helpful to combat the long-term effects of oil and gasoline. The project consists of multiple subsystems including a safety subsystem, a PWM system, an electrolyzer, and the electrical and mechanical design. An immediate challenge that arises from the project will be the challenge of successfully measuring power draw and accurately defining and measuring efficiency.

A. Background

1) Basic Principles of Electrolysis: Electrolysis is the process by which an electric current is passed through a substance to trigger a chemical change [4]. Water electrolysis occurs when a power source is connected to two electrodes. One electrode is positively charged (anode) and the other is negatively charged (cathode). While submerged in water, electrons flow from the anode to the cathode. An oxidation reaction occurs at the anode that is represented by the chemical equation:

$$4OH^- \rightarrow O_2 + 2H_2O + 4e^- \quad (1)$$

The reduction reaction at the cathode is represented by the chemical equation:

$$4H_2O + 4e^- \rightarrow 2H_2 + 4OH^- \quad (2)$$

The overall reaction of the cell is represented as:

$$2H_2O + electrical \quad energy + heat \rightarrow 2H_2 + O_2[5] \quad (3)$$

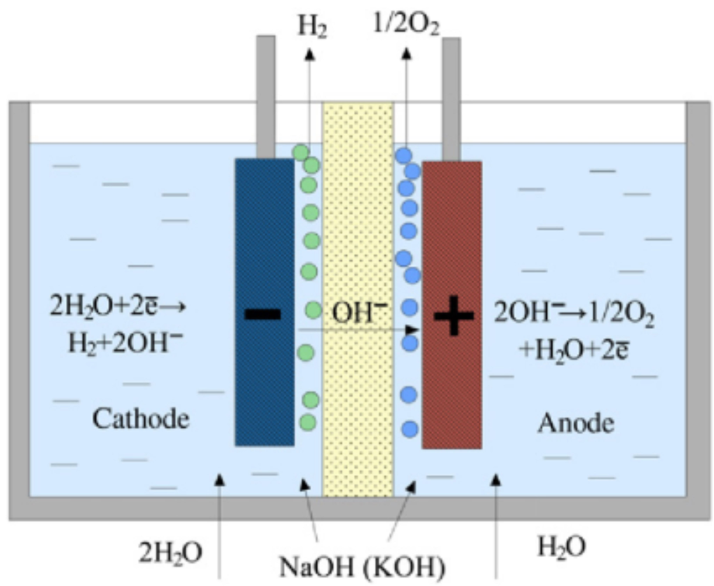

Fig. 1. Diagram of a basic electrolysis device [6]

The theoretical energy required to produce hydrogen gas from water electrolysis (ΔH(T)) is the sum of thermal energy demand (Q(T)) and electrical energy demand (ΔG(T)).

$$\Delta H(T) = Q(T) + \Delta G(T) \quad (4)$$

Where:

$$Q(T) = T\Delta S(T) \quad (5)$$

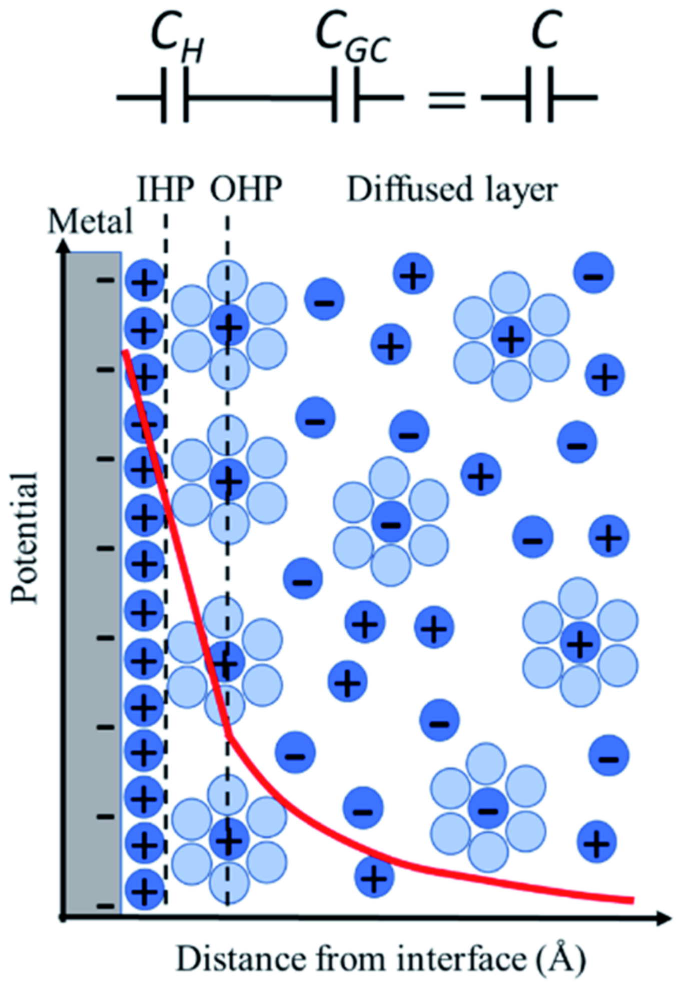

Fig. 2. Gouy-Chapman-Stern Model of EDL during steady state of electrolysis[9]

and ΔG(T) is the change in the Gibbs free energy. T is the temperature of the cell and Δ S(T) is the change in entropy of the cell [7].

2) Using Pulsating Current to Enhance Efficiency of Electrolysis: Electrolysis is typically used with a constant current source applied to the electrolyte. As current is applied, free electrons are injected into the solution. Some of these free electrons will start to build on the surface of the electrodes, making the electron double layer (EDL) as shown in Figure 2. This EDL forms the diffusion layer, and this formation will create a capacitance between the electrode and the electrolyte [8].

Full formation of the EDL will take setup time. Pulsing the current at the right frequency will help prevent the EDL from fully forming. During the off period, the EDL will disperse into the local electrolyte continuing the reaction while there is no applied current [10]. Besides the electrochemical effect from the pulsing current, there is inherent energy efficiency that comes from the duty cycle as we are allowed to pulse higher currents as long as the average current meets current standards.

3) Calculating Efficiency of the System: Every reaction has energy cost associated with it known in terms of Gibbs Free energy. Since our system will be closed, the volume and temperature of the energy cell (EC) will be constant. This means that the EC will have Helmholtz free energy [11]. The standard equation for the energy to start electrolysis with constant current is:

$$E^{\circ}{}_{cell} = \frac{-\Delta G^{\circ}}{nF} \tag{6}$$

where n would be the number of moles of electrons being transferred. By using the Helmholtz energy, the equation changes to:

$$E^{\circ}{}_{cell} = \frac{-\Delta A^{\circ}}{nF} \tag{7}$$

Finally, Helmholtz free energy can be calculated:

$$\Delta A^{\circ} = \Delta H^{\circ} - TR\Delta n - T\Delta S^{\circ} \tag{8}$$

The standard reaction enthalpy for the electrolysis of water is ΔS° = 285.8 (kJ/mol), so ΔA° = 233.1 (kJ/mol). With this, the minimum voltage needed to start the EC would be 1.21 V. The maximum efficiency of an electrochemical cell in a real-world application is:

$$\epsilon_{real} = \frac{\mathbf{\Delta H}}{nE_{elec}} \tag{9}$$

$$\Delta E_{elec} = \Delta A + IR + \Sigma\eta \tag{10}$$

The electrical energy takes into consideration the Helmholtz free energy, the transient current in the system, and the resistance of the cell. The resistance of the cell includes the resistance of the electrolyte, the electrodes, and the external circuit. $\Sigma\eta$ refers to the sum of over potential due to the diffusion layer and the lack of water on the electrode as the gas leaves the cell. The simplest way to keep the over potential low is by increasing the surface area of the electrode [11].

4) Using Magnetic Fields to Enhance Gas Production: The hydrogen production efficiency can be increased and energy consumption can be reduced by external magnetic fields. The magnitude of the magnetic field affects hydrogen production in the electrolysis process, but the most influential factor is the gradient magnetic field that is used. A magnetic field that is normal to the surface of the horizontal electrode causes bubbles to revolve and spread between the electrodes, which will increase the electrolysis efficiency [12].

B. Goal of the Project

The goal of this project is to use electrolysis for electrical power generation in an efficient manner that also takes into consideration safety concerns regarding gas production and containment. The final product should have an energy efficiency of greater than 70%.

C. Stakeholders

During this project, the stakeholders will have two different categories, interior and exterior. Our interior stakeholders will have a direct interaction with the team and the progress. This includes access to the GitHub repository. Weekly meetings will occur with the project supervisor and the team. For our external stakeholders, we have Jesse Roberts and will meet with him bi-weekly. Another stakeholder is the Tennessee Technological University ECE department which will provide funding. Any and all requests for funding will have to be signed off by the project supervisor.

Interior Stakeholders

- Project Team
- Project Supervisor - Dr. Van Neste
- Funding - ECE Department

External Stakeholders

- Jesse Roberts

D. Specifications

- Shall be simple to use, requiring little manual control. This way, it will not require users to be experienced or familiar with its components and how they operate.
- Shall measure the efficiency of power output. This will be a key metric of the system's functionality that can also be used for comparison between the electrolyzer and similar systems.
- Shall operate in a way that is safe for the operator.
- Shall measure the volume of gas that is output (or make measurements from which these values can be calculated). This will be useful for measuring expected values.

E. Constraints

- Shall have a safety shut-off because of the possible hazards created by the gases that are being produced and created by excessive pressure.
- Shall have a safe process for adding sodium hydroxide to the electrolyzer. Sodium hydroxide can be a dangerous substance, so there should be a safe and documented process when it needs to be added to the system.

F. Standards

1910.103 OSHA - Storage, handling, and transportation - This standard set involves the proper etiquette when operating with hydrogen, specifically paragraph gaseous hydrogen, which is referenced in paragraph b. This set specifies storage location based on container size, which in this case will be inside a well-ventilated room, ensuring that all potential leaks of hydrogen will cause a minimal amount of damage. This set also specifies that the piping, fitting, and tubing cannot be cast iron, as cast iron is known to be susceptible to corrosion from hydrogen. The final major note of this set is the specification that all mobile units (RVs, food trucks, ambulances, etc....) must be electrically bonded to the system to ensure the electrical potential energy is equalized between the two systems. This is to ensure that unique systems will all behave predictably and safely [13].

NFPA 2 - Hydrogen Technologies Code - This standard set is similar to OSHA standards 1910.103, as it describes the proper handling, transportation, and storage of hydrogen. However, it also describes the use of hydrogen for research purposes and appliances. Of note for the project's scope, the device using the hydrogen must have a manual emergency shutoff valve. It also notes the use of hydrogen inside vehicles, and, should the project ever progress to such a stage, this would be necessary for a reference [14].

NFPA 54 - National Fuel Gas Code - This standard set applies to the installation and location of household gas ranges. Chapter 10 references specific installation practices that must be upheld in household settings, including but not limited to, ensuring combustible material is not within 12 inches of the range, and all above-mounted fixtures must be no less than 30 inches from the burner top [15].

NFPA 70 - National Electrical Code - This standard set describes the required procedures for electrical systems. For the purposes of this project, the wiring sizes table **310.15(b)(16)** will be the most common point of reference. Other standards that happen to become relevant will also be followed [16].

ANSI Z21.1 - American National Standards Institute - This sets out a guideline for safety standards that set out the general safety requirements for household gas cooking appliances, such as gas stoves and ovens. This standard outlines specifications and testing procedures to ensure the safe design, construction, and operation of these appliances. It covers aspects such as gas supply, burner design, ignition systems, temperature controls, and safety features to protect users from potential hazards associated with gas cooking appliances. This standard set was designated for residential application of a gas stove [17].

G. Survey of Possible Solutions

1) Possible solutions to designing Electrolysis system: People have studied water electrolysis as a means of hydrogen production for hundreds of years. Since pure water is a poor conductor of electricity, the efficiency of hydrogen production using water electrolysis has been a major challenge. In the past 100 years, three main solutions to this problem have been developed [18].

Alkaline water electrolysis is a process by which an acid or base, such as KOH, is added to the water. The KOH/water solution splits into positive and negative ions, which makes the solution more conductive than pure water. This increases efficiency because less electricity is required to produce hydrogen. The group will use alkaline water electrolysis because it is the easiest and most cost-effective electrolyzer [19].

Polymer electrolyte membrane electrolysis (PEM) uses an acidic solid polymer as the electrolyte [19]. The solid polymer membrane splits the cell in half between the anode and cathode. The conductive membrane allows electrons to flow away from the oxidation reaction on the anode into the reduction reaction on the cathode. It is possible to get better results out of PEM water electrolysis [20]. However, due to the complexity and cost of electrolyte membranes, PEM water electrolysis is not a viable solution for the project.

High-temperature water electrolysis follows the same general structure as alkaline water electrolysis, but it runs at 800-1000 °C. The additional thermal energy causes the system to require less electricity for hydrogen production. This is advantageous for certain cases in which excessive heat is a byproduct of a different process that is not directly related to the water electrolysis [19]. The team does not have access to a method of expelling high levels of heat, so this method will not be used for the project.

2) Possible ways to detect gas output of the system: There is no shortage of available options for hydrogen gas detection. Hydrogen gas detection is well researched and documented [21].

The problem with many detection methods is that, while they are very precise, they are also very expensive. There are much simpler methods that can be used to detect the hydrogen gas output of the system. Using a container with a defined volume that is completely submerged in water and a timer, the flow rate of the system can be found. If the system is set up to feed gas into the container, a timer can provide the time it takes for the container to "overflow" with gas. This will provide enough information for the flow rate of the system to be calculated.

3) Different ways to generate pulsating current: Currently, there are a few ways to generate a pulsating current for the PWM. The three options that are able to be applied to this project, within reason, are RC Circuit Pulse Generation, using a 555 Timer IC Circuit, or using a Digital Pulse Generator. The RC Circuit would be the most straightforward approach to making a pulse; however, it would be difficult to modify or make perfect. An example circuit for an RC pulse generator is shown in figure 3.

Using a 555 Timer IC would be similarly easy when compared to the RC Circuit approach, but the 555 chip has known issues regarding stability and ease of use. An example circuit of the 555 Timer IC method is shown in Figure 4.

The final approach is to use a Digital Pulse Generator. The benefit of this approach is the increased modifiability and stability of the system. However, this system is generally more difficult to create.

H. Challenges

Foreseen challenges right now would be: lack of mechanical and chemical experience on the team, limited time, and budget. System-dependant challenges include: the pressure out of the electrolysis generator, the flashback prevention on the outlet of the gas tank, and keeping overall power consumption to a minimum.

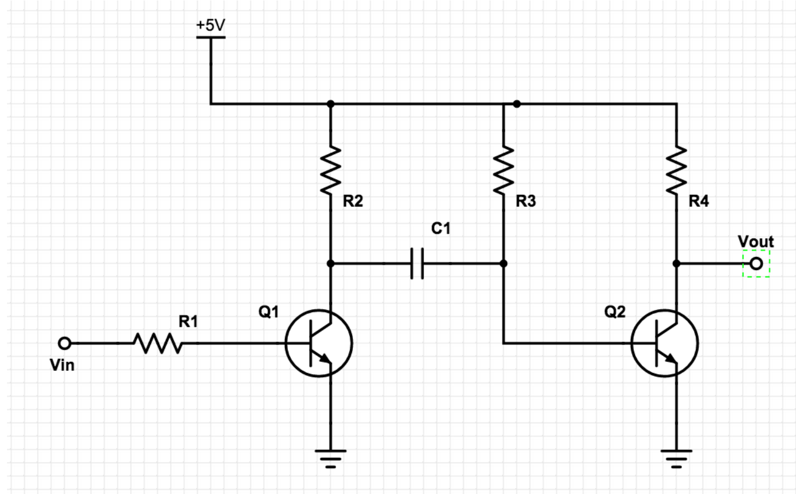

Fig. 3. RC Pulse Generator [22]

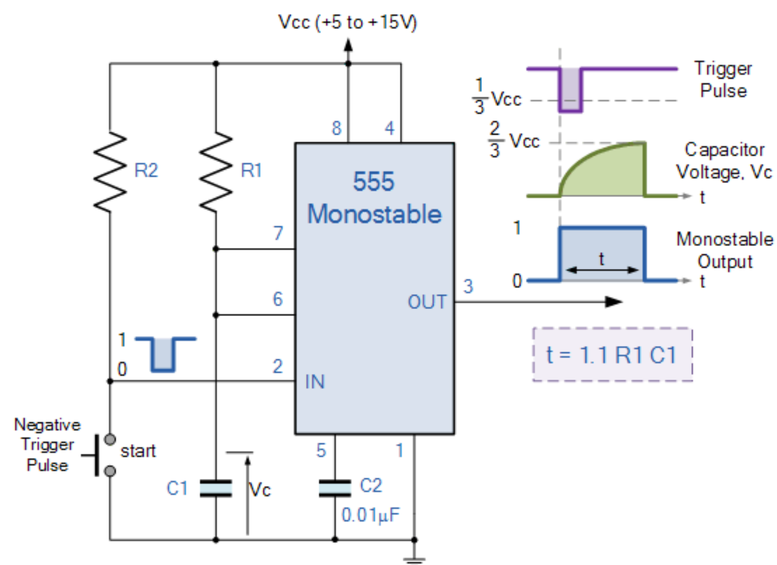

Fig. 4. 555 Timer IC Pulse Generator [23]

I. Summary

Overall, the system's main focus will be efficiency and safety. The system will need to meet all standards related to issues including power used by the system and the control of potentially hazardous gases and chemicals. The use of permanent magnets and PWM will potentially contribute to the efficiency of the system, and a control system will be used for safety.

III. Looking Toward a Solution

A. Unknowns

There are a few unknowns that may contribute largely to possible unintended consequences of this system, the main one being how the consumer could mishandle the product. For example, substances other than water could be used, whether by accident or on purpose, and this would cause mostly unpredictable outcomes. There is also no way to ensure that all households are getting the same quality of water. This makes finding a general testing environment quite difficult, as testing for some possible points of failure would be ideal, but it is impossible to cover all scenarios. There are also concerns about how long the system would last. It is unknown how well the system will perform in the long term, which is very important as this would presumably be a device that lasts a comparable amount of time to that of the standard consumer stove.

B. Existing Solutions

Hydrogen generators that utilize electrolysis are being used to prolong gasoline use. These generators already perform electrolysis so the project could focus on measurement and improvement. The product could be an excellent starting point for this project [24].

C. Measure of Success

A measure of success for the system would be a working electrolysis machine with an efficiency above 70 percent. By measuring the system's energy input and then using the theoretical value for energy in a kilogram of brown's gas an efficiency rating can be determined between the chemical output and the electrical input. Any calculations that are based on burning the brown's gas are subjected to a compounding efficiency loss and would not speak to the proposed system itself.

Another measure of success would be the accuracy of the gas output. The gas output can be measured using either oxygen or hydrogen sensors that calculate the throughput of the gas in a specified area. Using the calculations and chemical equation it is possible to determine the gas amount and overall energy output. Experiments could be conducted on known concentrations of either oxygen or hydrogen gas to verify that the sensors are reading correctly.

The final measure of success is the accuracy of the pulse generator output's frequency and voltage. The team will be implementing a pulsating current for the electrolyzer to increase gas production and decrease power consumption. A test can be done to verify that the pulse generator is operating on the right frequency and also outputting the correct voltages.

D. Broader Implications, Ethics, and Responsibility as Engineers

Electrolysis has lots of applications including industrial plants and automotive power. The Department of Energy has launched an initiative to design a way to generate hydrogen within a certain price per kilogram. It is being made to launch a more green energy source than the standard fossil fuel systems that are in use now. The system being proposed could be a great stepping stone to solving the impending environmental crisis associated with the use of fossil fuels. Another application to consider is the potential shift in the automotive industry to hydrogen cars. The potential shift will cause strain on the current hydrogen production infrastructure leading to demand for more hydrogen production in residential areas.

The potential of damage to consumers' property or injury to themselves is a high risk meaning that the safety subsystem needs to be a high priority. Alkaline electrolysis process uses sodium hydroxide which makes a caustic solution, and as a solid can cause serious chemical burns. Extra precautions need to be taken when designing the tank as leaks could cause serious damage to property.

IV. Resources

A. Personnel and Skills

This project will be a challenge that will require several skills. The list below shows each team member's skills before starting this project.

- Brennan Angus
  - Mathematics
  - C++
  - Telecommunications
- Matthew Beausoleil
  - Telecommunications
  - Electronics Design
  - Machining
- Jacob Cooper
  - C++
  - Microcomputer Systems
  - Electronics
  - Assembly
- Wyatt Groves
  - Signal Processing
  - Power Systems
  - 3D Printing
- Austin Jerrolds
  - Python
  - Digital System Design
  - AutoCAD Electrical
  - Soldering
- Conner Sanders
  - C/C++
  - Pneumatic Systems
  - Embedded Systems

Brennan Angus has taken the role to relearn chemistry to get a better understanding of the chemical side of the project as the team is comprised of ECE students. As new skills are required throughout the project they will be acquired by the team members as needed.

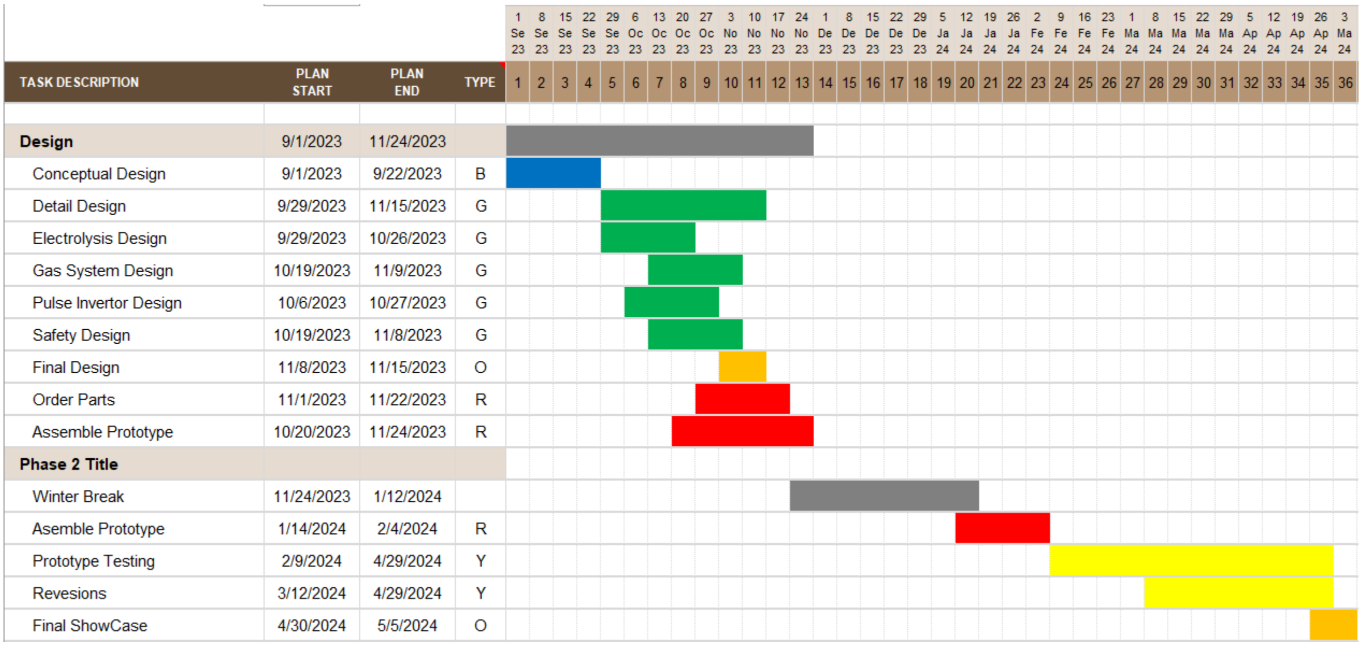

Fig. 5. Proposed Timeline

B. Budget

Components	Price($)
Electrodes	180
Pulse Generator	90
Mini Compressor	400
Hydrogen Sensor	65
Housing System	80
Gas System	260
Micro-controller	30
Total	925

Fig. 6. Proposed Budget

The expenses should not exceed $1500. Expenses could vary based on unforeseen complications and expenses specific to different approaches and specific subsystems. Figure 6 shows a detailed list of the items expected at this time.

C. Timeline

The group expectation for completing this project is 9 months. Figure 5 shows the projected timeline of the system. The group will go through design phases for the various subsystems that lead intermediate builds. The final product should be completed in May.

V. Conclusion

The proposed project is to develop an electrolyzer using PWM and permanent magnets as well as calculating the overall power efficiency. The electrolyzer is to be an easy-to-use Brown's gas generator that could function as an alternative energy source. The primary goal can be achieved using an alkaline electrolysis process, gas sensors, pulse generators, and magnets.

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