Solar Water Filtration and Vending System

Team 29
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ECE 445 Project Proposal — Spring 2018
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February 2018

1. Introduction

1.1 Objective

Our objective is to create an effective solar-powered water purification and dispensing system to be deployed in remote rural environments. Our system will be powered using solar energy due to lack of electrified infrastructures. Solar energy will be converted to electric energy and stored in a battery. The battery will be used to power a series of water pumps that will channel feed water through filtration membranes. Purified water will then be stored and dispensed based on button inputs. A system of sensors will monitor and control water purity, water levels in the tanks, and the correct dispensing.

1.2 Background

Many people in rural areas in developing countries don't have access to clean water. They have to walk several miles a day to obtain it from the closest water source. In addition, this water can't be consumed without further treatment. Without electrified infrastructure, they burn wood to heat water. As result, considerable amount of smoke is inhaled, causing long-term lung issues.

One of our member's non-profit organization is building solar water pumps, allowing people in rural areas to have an easier access to untreated water. To complement the water pumps, we have decided to design a water filtration system using solar energy to power the pumps required to push water through the filtration membranes.

A first approach using solar radiation to distill the water was considered. However, this method produces low amount of drinkable water, which required supporting heating mechanisms to increase the production rate. Nonetheless, to heat a considerable amount of water to the boiling temperature requires fair amount of power, which is not feasible considering the available solar panel.

1.3 High-Level Requirements

1. The solar charging should be able to maintain output within range of 13.5 - 13.8 V.
2. Both water tank should never go below 5 % and surpass 90% of its capacity.
3. End user will get the amount of water from the input value with 2% uncertainty.

2. Design

2.1 Block Diagram

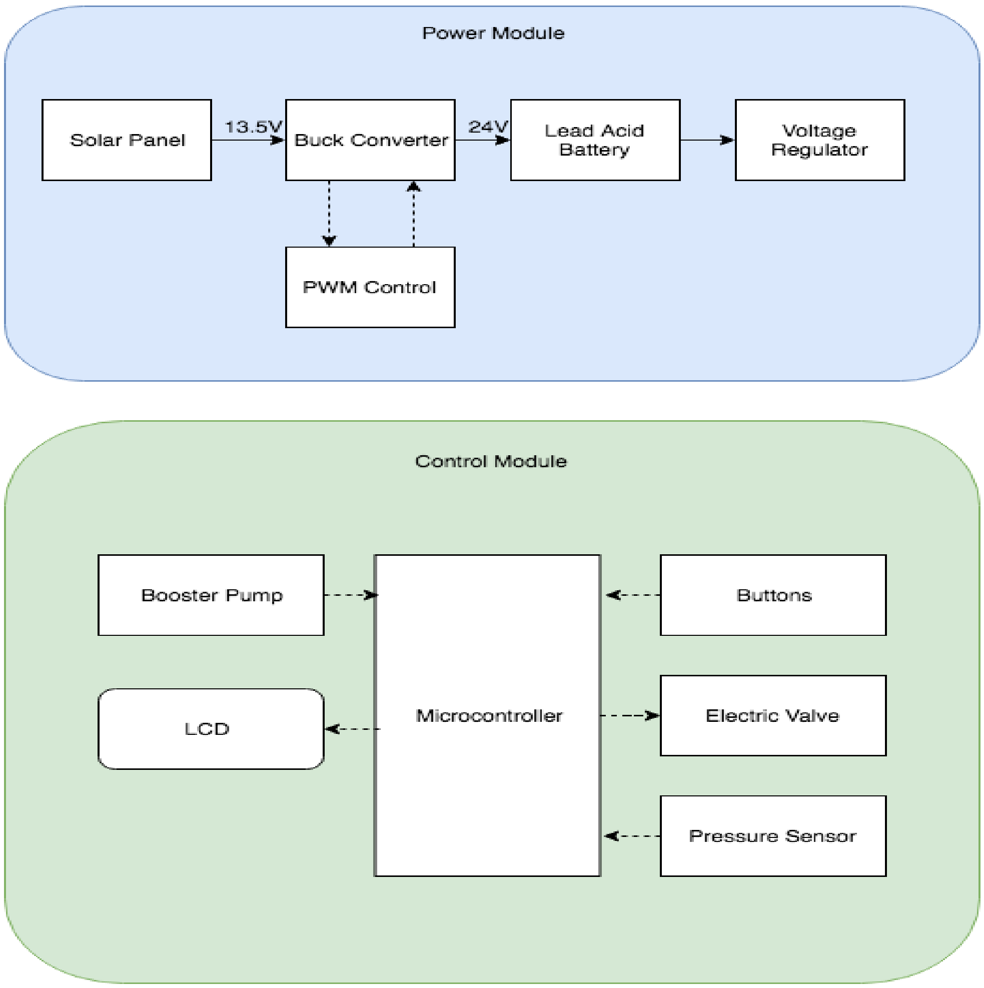

Figure 1. Block Diagram

Our system is composed of two modules; power and control. The power module consists of a lead-acid battery charged using solar panels. It will provide the energy required to power the whole system whenever the solar panels are not generating enough power. Since the output voltage of solar panels is unsteady, a dc-dc converter is required to maintain a desirable charging voltage.

The control module will manage the input and output of water flow in the filtration/dispensing system. Pressure sensors will signal the microcontroller the level of water in the containers. With this information, the microcontroller can turn on/off the electric valves to allow the flow of water in or out of the system. Input button will allow end user to indicate output water to be dispensed. A display screen will show the data obtained from the sensors, as well as user input values.

2.2 Physical Design

Our design is consisted of one clean water tank under the filtration unit. The filtration unit will have three pre-filtration tanks before going to the reverse osmosis membranes. They are Polypropylene (PP) sediment, Granular activated charcoal (GAC), Carbon block (CTO) filter. The dirty water will be pumped through the filtration unit using booster pump that is powered by PV system.

The water tank and the filtration unit will be inside a box made of wood for the vending machine. There will be three buttons for dispensing the water, water tube for the end user getting the clean water, and LCD to display the current status of the clean water tank. Our solar panel will be mounted right beside the wood box

2.3 Functional Overview

2.3.1 Power Module

Solar Panel

Since our project is concentrated in rural areas, we need to use solar energy as our main energy source. In these areas, electricity is not stable. Sometimes, there may not be electricity at all. Therefore, we will use PV to power our system. We will use a 100W solar panel to power the water pump as well as the control units.

12V Lead-Acid Battery

We will use lead-acid batteries because they are relatively cheaper compared to its counterparts. It will power the water pump as well as the control unit that will monitor and manage the flow of water in and out of the filtration system.

To improve lifespan of the battery, it must be charged at the floating charge point. A 12V lead-acid battery floating point ranges from 13.5-13.8V [1]. This is because it is composed of six cells, where each cell measures on average 2.25V during float charge.

Buck Converter

The output from the solar panel is dependent of weather and positioning of the solar panels relative to the sun. Therefore, a dc-dc converter is required to maintain a suitable voltage to charge the batteries. Since the output voltage from the solar panel is greater than battery voltage, a buck converter is required.

The dc-dc conversion should be as efficient as possible, so we can obtain the most from the solar panel. We have decided that our buck converter must have an efficient greater than 80%.

PWM controller & Voltage Regulator

The PWM controller will adjust the duty ratio required for the buck converter to keep the desired output. It will be an analog implementation. It consists of an error generator, PI control, comparator, triangular wave generator. Moreover, A voltage regulator IC will be used to step down the battery voltage to 5V to power the control module.

Requirement and Verification for Power Module (20 Points)

Requirements	Verifications
● The solar panel must be able to provide a voltage of 13.5V and above to charge 12V battery	**Equipment:** Solar panel, Voltmeter, Ammeter. **Procedure:** 1. Expose the Solar Panel under direct the sunlight. 2. Measure open circuit voltage with voltmeter. **Expected Output:** ● Output voltage must be above 13.5V when exposed to enough sunlight.
● Charging voltage of a 12V lead-acid battery ranges from 13.5-13.8V.	**Equipment:** Battery, Buck converter, Oscilloscope, Ammeter, Power supply. **Procedure:** 1. Connect the Lead-Acid battery to the buck converter. Supply voltage ranging from 15-20V. 2. Use oscilloscope to measure the voltage of the output. **Expected Output:** ● Measured output voltage should be within range 13.65V ± 0.15V
● Maintains the component thermal stability below 125°C	**Equipment:** Buck, PWM, IR Thermometer **Procedure:** 1. During all verifications, use IR thermometer to check the thermal stability across the component of the

	circuit **Expected Output:** ● All the component should be below 125°C
● PWM generator must provide square wave what goes from 0.5±0.5V to 4.5±0.5V	**Equipment:** PWM generator, Oscilloscope **Procedure:** 1. Measure PWM output with oscilloscope. **Expected Output:** ● Square output signal ranging from 0.5±0.5V to 4.5±0.5V
● Buck Converter must keep an average output voltage between 13.5-13.8 V ● Voltage ripple must be less than 1% of the average output voltage.	**Equipment:** Power Supply, Buck Converter, PWM Generator, Oscilloscope. **Procedure:** 1. Connect resistive load of 1Ω to buck converter output. 2. Supply 15 to 20 V to buck converter 3. Measure output with oscilloscope **Expected Output:** ● Average voltage within 13.5-13.8V range. ● Ripple voltage <1% average output voltage.

2.3.2 Control Module

Pressure Sensors

One pressure sensor each will be placed in the distillation tank and the clean water tank. These will serve as measurement devices to calculate the amount of water in each tank based on the reading. This in turn will be fed to the microcontroller to control the valves and feed the values to the data panel.

Over the past week we were asked to consider other options for measuring water levels, including flow meters. This was in an effort to eliminate any other data required for operation besides the reading from the meters. We determined that pressure sensors were still the most viable option, because flow meters would not be able to provide an accurate reading for distilled water, which often flows in small quantities. Moreover, we would still require the volume of the container for the second high-level requirement. Lastly, we believe this product would be shipped as a coherent package, including standardized water container sizes.

Input Buttons

There will be 3 different input buttons, each corresponding to 3 different outputs. Each input will trigger a “dispense” signal, asking the system to dispense a required discrete amount of water. The microcontroller will receive the signal, which will then trigger the valves while monitoring the quantity of water from the pressure sensors until the requisite quantity of water is dispensed.

Microcontroller

This will serve as the primary control unit. It will take inputs from the sensors as depicted in the diagram, and send outputs to the electric valves, heating elements and the data panel. This will require a relatively simple microcontroller, but one that can take around 40 bits of input (providing for 8 bits output from each sensor). It must check the values provided against programmed minimums for water level and temperature, while performing logic operations to determine the output signals to each valve.

Electric Valves

We will have at least 2 electric valves - between the distillation tank and the clean water tank and between the clean tank and the dispense pipe. We may also add another valve to allow for input into the distillation tank; we are defining this as a reach project. These will consist of simple sluice gates that slide in and out to open or close a pipe based on microcontroller input. This will help moderate the amount of flowing water and fulfill the second high-level requirement.

Requirement and Verification for Control Module (20 Points)

Requirements	Verifications
● Accuracy of pressure sensor to within 100 ml of water	**Equipment:** Tank, Measuring cup, Water Pressure sensor, Arduino **Procedure:** 1. Connect Pressure sensor to Arduino 2. Pour water into tank and measure reading 3. Add incremental measured amounts of water to change the amount **Expected Output:** The reading is accurate to within equivalent pressure to 100ml of water
● Less than 1s between consecutive pressure sensor and temperature sensor readings	**Equipment:** Tank, Measuring cup, Water Pressure sensor, Arduino **Procedure:** 1. Connect Pressure sensor to Arduino 2. Pour water into tank and measure reading

<table>
<tr><td></td><td>3. Add incremental measured amounts of water to change the amount
Expected Output:
The reading changes within 1s</td></tr>
<tr><td>● Microcontroller data must be processed within 0.25s for each set of inputs.</td><td>Equipment: Microcontroller, Pressure Sensor, Input Buttons, Temperature Sensor, Oscilloscope
Procedure:
1. Connect Sensors and Input Buttons to Oscilloscope through Microcontroller
2. Perform any combination of operations expected during operation of project, routing outputs through Oscilloscope
Expected Output:
● Each cycle of outputs is displayed every 0.25s</td></tr>
<tr><td>● Low power requirement for efficient operation, ideally within 1W</td><td>Equipment: Microcontroller, Pressure Sensor, Input Buttons, Temperature Sensor, Multimeter, electric valve
Procedure:
1. Connect Sensors and Input Buttons to Microcontroller
2. Measure voltage and current across pin that powered the chip
Expected Output: Total power is below 1W</td></tr>
<tr><td>● Must close the valve within 1s with a reliable constant open/close time.</td><td>Equipment: Microcontroller, Electric Valve, stopwatch
Procedure:
1. Connect Valve to Microcontroller
2. Turn the valve on and off repeatedly, for at least 10 times
Expected Output: Valve closes each time within 1s, and deviations between times are less than 0.2s</td></tr>
<tr><td>● Electric Valve between the distillation tank and clean water tank should be closed if the tank has 90% of its capacity volume
● Electric Valve for dispensing the water should be closed if the tank only</td><td>Equipment: Microcontroller, Electric Valves, Pressure Sensors, Tank
Procedure:
● Connect Valve to Microcontroller, and Microcontroller to pressure sensor as in final setup</td></tr>
</table>

has 5% of its capacity volume	● Pour the water to the tank lower than 5 % and greater than 90 % of its capacity respectively **Expected Output:** Electric Valves should be closed based on the conditions in the high-level requirements

2.3.4 Display Module (5 points)

This will be a simple data panel, consisting of a LED display depicting how much water is available, what the purity of the water is, and some other operation statistics. This will provide a simple external measure of the operation of the system. This data can be transmitted by RF signals if necessary, if we proceed with our reach goal of data transmission and analysis

Requirements	Verifications
● Low power requirement for efficient operation ideally within 1W.	**Equipment:** Microcontroller, LED Display, Multimeter **Procedure:** 1. Connect LED Display to Microcontroller 2. Measure voltage and current across Display during operation **Expected Output:** Total power is below 1W
● Error Display	**Equipment:** Microcontroller, Electric Valve, Pressure Sensors, Tank **Procedure:** 1. Connect Valve to Microcontroller, and Microcontroller to Sensors as in final setup 2. Vary water level in tank, testing minimum bound as in high-level requirements. **Expected Output:** Display error message if there is too little water to dispense.

2.4 Calculations

We decided that the converter must have an efficiency greater than 80%. The losses produced in the converter are due to the switching and conduction of MOSFET and diode.

The MOSFET losses can be calculated as:

$$P_{sw} = \frac{1}{2} \cdot V_{in} \cdot I_L \cdot (t_f + t_r) \cdot f_{sw} \quad \text{eq. 2[2]}$$

$$P_{c1} = I_L^2 \cdot D \cdot R_{ds,\,on} \quad \text{eq. 3[2]}$$

While the diode losses are:

$$P_{rr} = f_{sw} \cdot V_{in} \cdot Q_{rr} \quad \text{eq. 4[2]}$$

$$P_{c2} = V_F \cdot I_d \quad \text{eq. 5[2]}$$

Where P_{sw} is the switching loss, P_c the conduction loss, and P_{rr} the reverse recovery loss.

To obtain these values, it is necessary to specify some initial assumptions:

- V_{in} must be the highest possible voltage our solar panel can supply to find the highest loss when all other parameters are kept constant. Hence, V_{in}=20V.
- I_L is the average voltage through the inductor. This value is equal to the current flowing into the battery. Assuming our battery has an internal resistance of 0.1Ω and 12.6V of emf; $I_L \approx (V_{out} - 12.6)/\,0.1$. Considering our lead-acid battery will be charged between 13.5-13.8V; I_L should range between 9-12 A.
- t_f and t_r are specifications of the MOSFET. Assuming IRF540, $t_f + t_r = 87ns$[3].
- f_{sw} is the switching frequency. Higher f_{sw} allows us to use smaller inductance and capacitor in our circuit. Bigger components will result in smaller ripples. Let's assume $f_{sw} = 50kHz$.
- D is the duty ratio. In a buck converter, $D = V_{out}/V_{in}$. A bigger duty ratio would incur bigger losses. The biggest D possible is 0.69.
- For IRF510, $R_{ds,\,on} = 0.077\Omega$ [3].
- If we use Schottky diode, $P_{rr} = 0$, since it doesn't have reverse recovery. It also has small forward voltage. This diode has to withstand at least 12A of forward current. DSSK has $I_F = 40A$ per diode, with $V_F = 0.39V$ [4].

With these assumptions, we obtain:

$P_{sw} = 1.044W$

$P_{c1} = 7.65W$

$P_{rr} = 0$

$P_{c2} = 4.68W$

We can see that the most significant losses come from the conduction loss. Hence, the efficiency can be further improved by choosing MOSFET with lower $R_{ds,on}$ value, and diode with smaller forward voltage.

The total power loss must account for the copper loss from the inductor. The ESR loss from the capacitor is negligible considering how small the ripple current is.

The size of inductor and capacitor will depend on the switching frequency of the MOSFET and the current and voltage ripple.

Assuming our buck converter is working at 50 kHz with a ripple of 1% of the average output current and voltage, we can determine their values with the following equations:

$$v_L = L\frac{di_L}{dt} \qquad \text{eq. 6[2]}$$

$$V_L = L\frac{\Delta i_L}{\Delta t} \qquad \text{eq. 7[2]}$$

When Mosfet is on; $V_L = V_{in} - V_{out}$, $\Delta t = DT$. Considering that ripple must be within 1%, $\Delta i_L = 0.01 I_L$. Hence, $L > 0.75mH$.

$$i_c = C\frac{dv_c}{dt} \qquad \text{eq. 8[2]}$$

$$i_{cmax} = C\frac{\Delta v_c}{\Delta t} \qquad \text{eq. 9[2]}$$

When Mosfet is on; $i_{cmax} = \frac{\Delta i_L}{2}$, $\Delta t = DT$. Considering that ripple must be within 1%, $\Delta v_c = 0.01 V_{out}$. Hence $C > 6\mu F$. This value of capacitor does not take into account the ESR resistance of the component, which increases the voltage ripple.

In order to ensure that our buck converter will work within the proposed specifications, we will select a 1.5mH inductor and 10μF capacitor.

Considering that the inductor must withstand at least a current of 12A, we will be using T60405-R6166-X033. It has a resistance of 46mΩ, which will result in loss of 6.75W.

Considering all the calculated losses, the approximate power loss in the dc-dc conversion is 20W, which gives us an efficiency of 90%.

2.5 Circuit Schematic

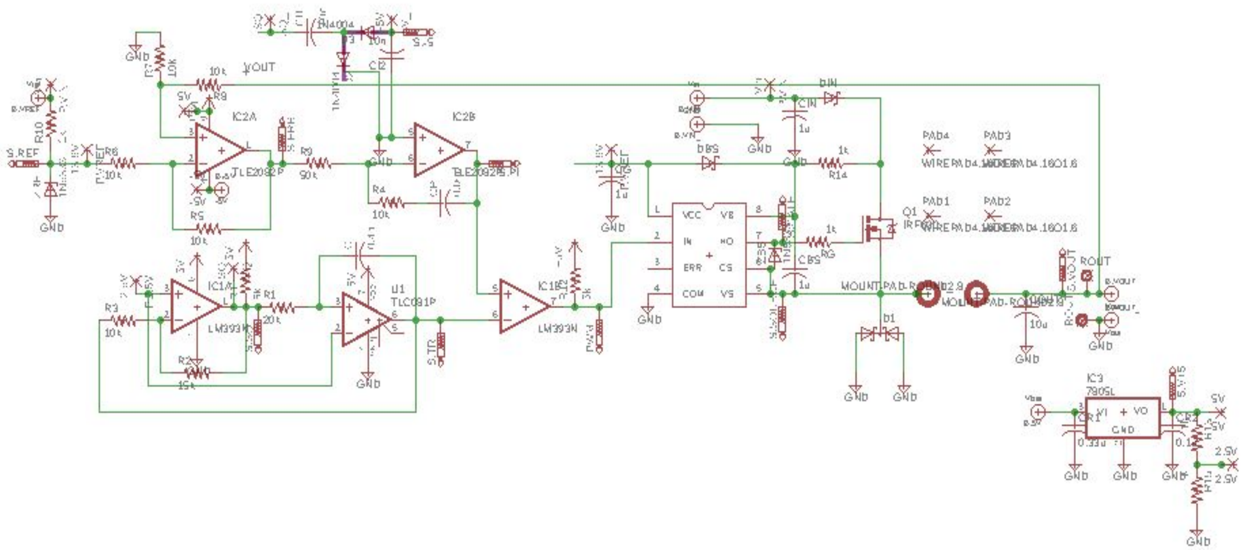

Figure 3. Power Module Schematic

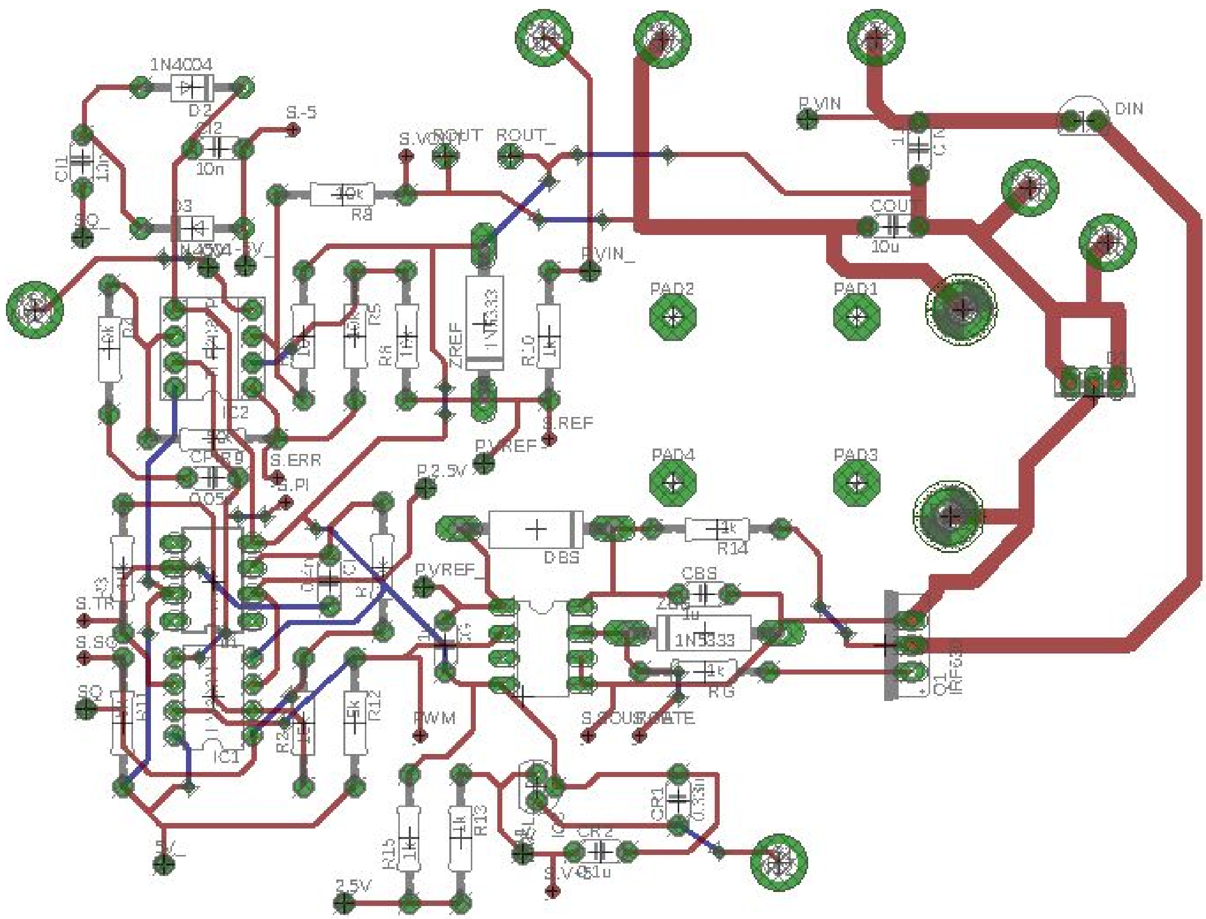

Figure 4. PCB layout

2.6 Simulations

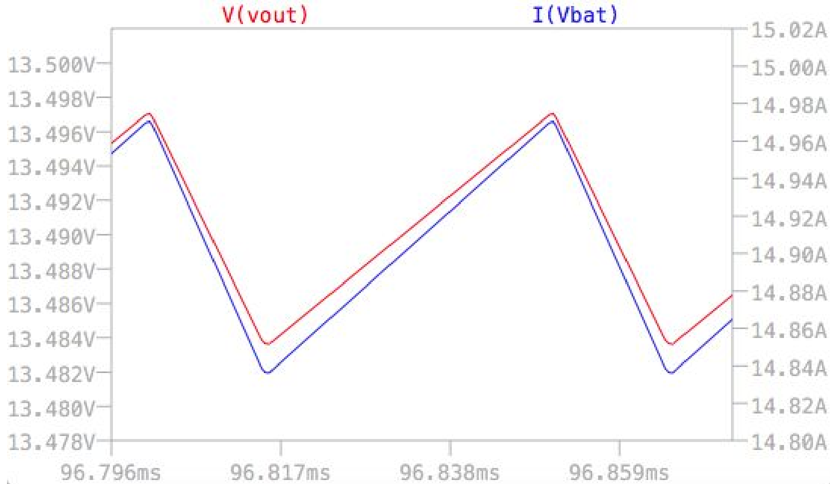

Figure 4. Voltage and current ripple for L=1.5mH, C=2μF, f=50kHz

Figure 5. PWM signal

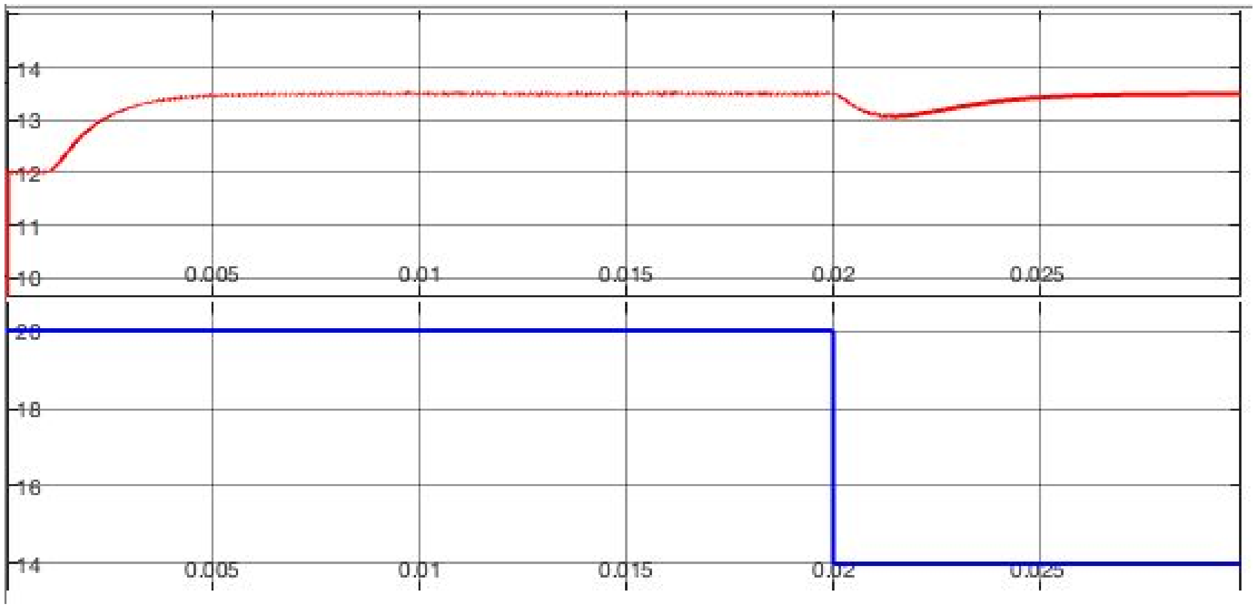

Figure 6. Output voltage response to step from 20 to 14V with 13.5V reference

2.7 Tolerance Analysis

The Buck converter is designed by considering a switching frequency of 50kHz. This frequency is set by the PWM generator (Figure 6) and can be determined by the following equation:

$$F = \frac{R_1}{R_2} \frac{1}{R_3 C_1} \frac{V_1(V - V_1)}{V_1^2} \qquad \text{eq. 10[2]}$$

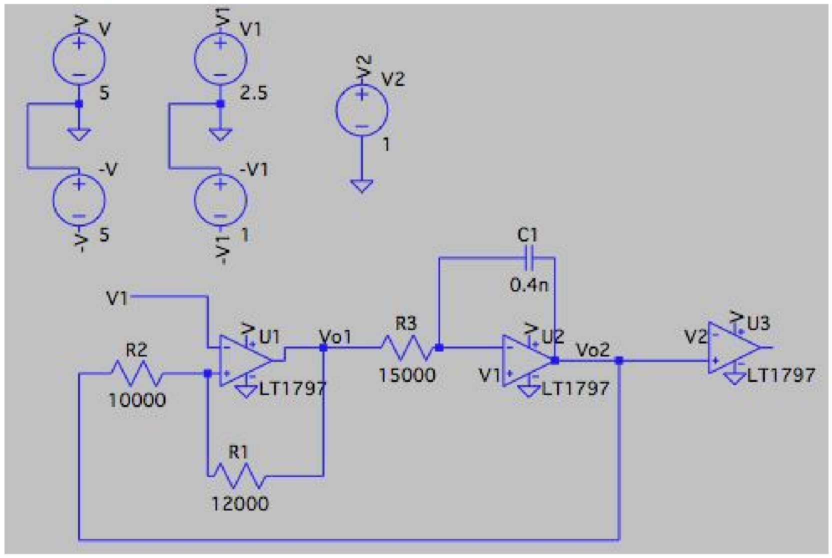

Figure 6. PWM circuit

The 0.4nF capacitor and resistors have 5% tolerance. Therefore, the resulting frequency from these components will result in a range of possible frequencies:

$$F_{max} = \frac{1.05R_1}{0.95^3 R_2} \frac{1}{R_3 C_1} \frac{V_1(V - V_1)}{V_1^2} = 61.233kHz$$

$$F_{min} = \frac{0.95R_1}{1.05^3 R_2} \frac{1}{R_3 C_1} \frac{V_1(V - V_1)}{V_1^2} = 41.032kHz$$

A lower frequency will result in higher ripple. If we chose the minimum required values of capacitor and inductor, the ripple will be greater than what we specified. Therefore, we must choose the components to account for possible margins of error to due tolerances.

3. Cost and Schedule

3.1 Labor

By researching annual average salary for entry level electrical and computer engineer based, it comes out to be around $40/ hour. We decided to choose $40/hour for hour labor cost. Our team consists of three people, we estimate to work around 7 hours/week for each member. We also assume that we work start from week 4 to week 14 because the first four weeks are about the introduction of the course. Therefore, using the labor cost calculation formula, the labor cost for our project comes out to be:

40$/hr * 3 people/week * 7hr/week * 10 week*2.5 = $21,000

After discussing our design with the machine shop, we come up the idea to buy the water tanks. Therefore, the machine shop only needs to create the pyramid, case for the clean water bottle, and connect everything together. It will take them one week which is around 40 hours. Moreover, the average salary for machinists is 20.25/hour. Therefore, the machine shop cost comes out to be:

20.25$/hr * 40 hr * 2.5 = $ 2,025

3.2 Material

	Part	Quantity	Unit Cost
Power Module	100 W Solar Panel	2	$109.95
	LM7805 Voltage Regulator	1	$0.70
	DSSK 48-0025B Schottky Diode	1	$2.56
	B82726S2163N0	1	$9.80

	1.5mH Inductor		
	Various Capacitors	x	Free
	Various Resistors	x	Free
	12V 12AH Lead-Acid Battery Power Sonic	1	$28.99
	IRF2125 Gate driver	1	$6.24
	TLC081 Op-Amp	3	$1.60
	TLE2082 Op-Amp	2	$3.35
	IRF630 Mosfet	1	$0.94
Control Module	ATMega 328p Microcontroller	1	$2.01
	Plastic Water Solenoid Valve	2	$6.95
	Pressure Sensor	2	$10.56
Filtration Unit	iSpring RCC7 High Capacity Under Sink 5-Stage Reverse Osmosis with booster pump	1	$249.99
I/O	16x2 LCD display	1	$6.48
	Input Buttons	3	$0.20
		Total Cost	$574.33

Grand Total: Labor Cost + Parts Cost = $23,599.33

3.3 Schedule

Table 3.3 Schedule for the Rest of the Semester

Week	Objectives	Mustika	Rahul	Lixiang
2/12	**Design Document**	Measurement, cost & schedule, fix CAD, Tolerance analysis R&V for power module	Schematics and R&V for control module	Schematics, calculations, simulations
2/19	**Finish Ordering Parts, PCB layout**	Pick parts and Order parts for design and input/output unit	Pick parts and Order parts for control module	Pick parts and Order parts for simulations
2/26	**Finish PCB design**	Assemble the design with Machine Shop	PCB design for control module	PCB design for power module
3/5	**Hardware Assembling**	Assemble the Control module, heating module	Assemble the control module	Assemble the power module
3/12	**Continue Assembling**	Finalize PCB design	Coding for control module, display module	Assemble the power module
3/19	**Spring Break (Finalize PCB Design)**			
3/26	**Performance Analysis**	Modular Testing for charging modules	Modular Testing for control module	Modular Testing for Power modules
4/2	**Improve the Prototype**	Connect the prototype all together	Improve coding based on the testing data	Improve the power module based on the testing data
4/9	**Prepare for Demo**	Prepare for the demo	Prepare for the demo	Prepare for the demo
4/16	**Write Final Report**	Write the final paper	Write Final Paper	Make sure the Demo works
4/23	**Final Presentation**	Finalize Final Paper	Create PowerPoint for presentation	Prepare for final presentation
4/30	**Final Presentation**	Prepare for final	Prepare for final	Finalize

		presentation	presentation	PowerPoint

4. Ethics and Safety

There are several potential safety hazards that we need to consider with our project since we are working with rechargeable batteries and water. In order not to violate IEEE Code of Ethics #1 (“: “To hold paramount the safety...”) [6], we have made changes to our design and created rules for this project. The main hazards associated with lead-acid batteries are chemical hazards, electrical hazards, and fire hazards. Lead acid batteries are usually filled with an electrolyte solution containing sulphuric acid. This is a very corrosive chemical (pH<2) which can permanently damage the eyes and produce serious chemical burns to the skin [5]. Electrical hazard can be triggered by extreme temperature. Lastly, when the battery is being charged, hydrogen can be produced. The mixture of two parts hydrogen to one part oxygen produced is perfect for an explosion, creating a fire hazard [5]. To prevent these hazards, we will use gloves while dealing with lead-acid batteries.

Another safety issue we need to consider is how water leaks can create short circuits and potentially lead to fires. For that reason, our water circulation should be insulated and use reliable seals. Additionally, pressure sensors will be placed in both tanks to make sure that water will not overflow. Our solar charging system is also placed outside the vending machine so that it will never be in contact with water.

In order not to violates IEEE Code of Ethics #3, our system will include data panel so that all the data and values from the system are factually verifiable. We believe that our project demonstrates good environmental stewardship through green and sustainable energy. We also believe that this system will allow more time for villagers in developing countries to engage in other activities, thereby implementing IEEE Code of Ethics #5 (“To improve the understanding by individuals and society….”)[6] .

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