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Human Generated Power for B9 Better Water Maker

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ABSTRACT

A local not-for profit organization, B9 Plastics, interested in providing clean drinking water to third-world environments designed and built a device to do just that. The device, called the Better Water Maker (BWM), uses a hand powered crank to generate power; enabling a pump to move water through a chamber exposing it to a ultra-violet light. The hand powered crank must be turned at a high RPM for extended periods of time which can be difficult for women and children to sustain. (Brownell, 2011)

A new seating arrangement has been designed and prototyped, which allows for the user to sit with good posture and use their legs to power the BWM. This design can be adjusted based on the different heights of its users yielding an even greater comfort level. An attempt was made to reduce the RPM's replacing the internal motors in the generator, which would allow all targeted users the ability to also sustain the water cleaning process. This paper will outline the design and manufacture of the new system with a complete Assembly Procedure, Baseline through Design Testing and Future Design Suggestions.

INTRODUCTION

The customer, B9 Plastics, is a not-for-profit organization dedicated to social and environmental improvement through the use of plastics (B9 Plastics, 2012). Their current projects aim to find solutions to the ongoing health issues associated with the lack of portable water in developing countries. B9 is striving to do this without using no chemicals, bio-systems to maintain, external electrical sources or consumables to replace. The product of these requirements is the Better Water Maker (BWM). The BWM uses ultra-violet (UV) light to kill E coli and other water-born pathogens providing safe, drinkable water. A manual crank generator provides 12-volt power to the device allowing it to pump water through a cylindrical chamber where the water is exposed to the UV light. Water flow is strictly controlled to ensure all pathogens will be eliminated.

B9 Plastics approached us with an issue they were seeing with BWM's in the field. Women and children of developing countries were having a difficult time cranking the generator and maintaining the necessary power requirements to keep the device operating long enough to generate sufficient amounts of water. They were finding that instead of going through the trouble of operating this device, individuals would just assume the risk of drinking water from other sources.

Our group was asked to develop a better way to generate the required power to operate the BWM (17 Watts). We were given a Better Water Maker to test ourselves and given free rein to design what we felt would be a better power source. A project outline was supplied to our group called a Project Readiness Package, or PRP. The contents of this document included background data on this particular B9 product as well as a list of Customer Needs for our project. These will be outlined later in this paper.

PROCESS

Preliminary design ideas required an understanding of the current state of the product. A number of tools were used giving us a better understanding of the system as a whole. The Functional Decomposition breaks down the system's functions until we reach the core function or functions. This allows us to focus our design efforts on the areas that directly affect the way the system works. It also helps us ensure that we are not focusing on the wrong areas that will delay our schedule. An accurate Project Plan is also a great way to make sure all group members are on the same page. It outlines the entire project from start to finish but allows for enough flexibility so changes can be made along the way. Deadlines and important benchmarks have detailed start and finish dates and depending on which resource is used to create the schedule a Gantt chart can be created giving a visual representation of the project. It also allows for external parties to be aware of progress that is being made week by week. Another great tool we used at this early stage in the process is a Risk Assessment. This document outlines as many problems, that the group can come up with, that could happen throughout the course of the project. Every contingency is given a severity ranking and a course of action is documented. These actions can remedy everything from group conflict to major project setbacks. These tools give the project a stable foundation as the group moves on in the system design.

Concepts

Many initial concepts must be designed, developed, and explored in order to achieve the most optimal engineering system possible. Although most of these initial concepts do not make the final cuts, they are still very useful in building and consolidating the best ideas, which leaves one suitable, reliable concept that will be utilized in the actual build. Some preliminary concepts explored include the following: Lever system similar to teeter-totter, ripcord / ratchet system spring-loaded to a neutral position, foot power, single crank arm and foot pedal with ratchet. Drawings of these preliminary concepts can be found on the teams Edge website (https://edge.rit.edu/edge/P13417/public/Home).

From these preliminary concepts, the final concept was eventually selected, and it is a combination of a few of the preliminary concepts. The concept decision is based on optimal functionality: continuous power supplied (ripcord is discontinuous power), leg power for utilization of largest muscle group, and cost constraints (too many parts will not work). From the preliminary concept list, it was evident that a leg-powered, bicycle-like product will be required for the customer's desired functionality. In addition, two concepts to decrease the rpms from 130 to 80-90 rpms were chosen: changing the gear ratio or changing the motors. These concepts are explained more below.

Gear Ratio

The current BWM generator system requires an input crankshaft speed of 130RPMs. After completing VO_2 testing and some qualitative analysis, the problem with the current design is evident. The RPM's required maintaining enough power generation is too high to maintain for any extended period of time. In order to decrease the required input RPMs, two methods can be used, one of which is a different gear ratio in the generator. By adding two gears (one large gear, one very small gear) to the current generator gearbox system, a larger gear ratio can be obtained. Obtaining a better gear ratio will allow for the same power generation at a lower input shaft speed (RPMs). The trade-off with this solution will be a higher amount of resistance to overcome in order to drive the gearbox system. In this case, the higher resistance will now be accommodated by the use of leg-power. To carry out a new gear ratio, new gears must be manufactured, and the gearbox housing must be extended. Both of these changes have a high impact on the final cost of the product; the product may be too expensive if manufactured in this fashion.

New motors

New motors are an alternative to changing the gear ratio, ultimately with the same desired goal of improving easiness of use by trading force for RPMs. Depending on the choice of motor, this would likely be less costly (preferable) than changing the whole gearbox and housing of the generator. It could also reduce losses due to friction that an additional gear would add. Another possible benefit of changing the motors is a significant increase in total lifetime of the product. The current motor being used is the Mabuchi RS-555PC (Mabuchi, 2012)**:**

MODEL		VOLTAGE		NO LOAD		AT MAXIMUM EFFICIENCY					STALL		
		OPERATING RANGE	NOMINAL	SPEED	CURRENT	SPEED	CURRENT	TORQUE		OUTPUT	TORQUE		CURRENT
			V	r/min	A	r/min	A	mN·m	g·cm	W	mN·m	g·cm	A
RS-555VC	3754(*2)	12 - 32	12	4100	0.20	3610	1.48	34.8	355	13.1	292	2977	10.9

Table 1: Specifications for Mabuchi Motors

One important shortcoming of the current motors is the short lifetime, characteristic of DC brushed motors. This is expected to likely be <6000 hours (the pessimistic estimate for bulb lifetime). With the total lifetime of the B9 BWM being a high priority, changing from brushed to brushless motors could be a large improvement, at a penalty of cost (brushless motors, while being more efficient and having a dramatically longer lifetime, can be twice the cost of brushed motors with comparable specifications). Unfortunately a brushless DC motor of the correct specifications has not yet been found. As such, we have considered other comparable brushed DC motors as replacements. The suggested new motors are the CF Motor RS-555PH-2590 or RS-987PH-4542. These motors both operate at a normal voltage of 12VDC (±10%), speed with no load is ~3000 rpms, and a max speed of ~2500 rpms.

Using four of the CF Motor RS-555PH-2590 motors in the same series configuration can yield the same desired voltage/power of 12 V/17 W at ~1650 RPMs (in the desired RPM range of ~1600–2000), while operating much closer to max efficiency than with the current motor model.

One of the RS-987PH-4542 motor is capable of replacing all four of the four motors currently used, while outputting the required amount of current of >1.6 A at +12 V and operating at ~2000 RPMs (in the desired range of ~1600–2000). Using one motor in place of four would reduce the energy lost due to friction between gears, increasing the overall efficiency of the system. Using this motor would also save on long-term costs for individual motors (when compared to the RS-555PH), while requiring initial tooling costs for modifying the generator housing slightly to accommodate its size.

Seating Arrangement

The concept generation process proves that utilizing leg-power will be optimal. In order to accommodate leg-power, a new seat must be designed. Since the product needs to be cheap, lightweight, and durable, the group decided to continue to utilize the 5-GAL plastic bucket for the main seating component. The seat is largely designed with ergonomics coupled with strength in mind. The body position of a recumbent bike-rider is mimicked in the new seat design, allowing for the user's legs to extend forward, while supporting the back with a backrest. The goal behind this new seat was to provide good strength while maintaining comfort for the user.

Experiments & Preliminary Testing

To get an idea of what the difficulties with operating the BWM generator were, it was decided that VO_2 testing should be done. The goal of this testing was to see how much a person had to work to generate water. The set-up consisted of two buckets, one filled with water and the other empty to hold the water exiting the pump, the BWM pump, the BWM generator, and the seat. The sample size consisted of three females and one male. Originally the test was to run for five minutes, during which the number of times the pump shut off would be kept track of along with how much water was pumped through. Ultimately this proved too difficult to do, so the test was changed to run as long as the user could crank the generator before getting too fatigued to continue, after which the amount of water pumped was measured to correlate how much water was actually pumped based on how much time the generator was being cranked. The key metabolic measurements taken during this testing were the individual's ability to use oxygen, the amount of carbon dioxide produced by the individual, and the heart rate of the individual during operation of the BWM generator. These results were to be taken as a baseline to compare future testing of the new design to the original design.

The second round of testing consisted of switching to the foot powered set up, but due to setbacks the first test of the prototype only consisted of changing the handles to pedals and using the new seat design. Ultimately this test was a failure due to the fact that without the new motors the resistance is the same as it was for the hand crank set-up, which means the resistance was not high enough to allow for a lower steady pedaling speed. While the pedaling position is optimal, without the higher resistance the hand crank method is better than the pedaling method.

Engineering Analysis

The engineering analysis consisted of two key components; stress analysis and motor analysis. The stress analysis for the system was done in two steps. The first step was simple hand calculations to see if the system would hold up to increased forces related to leg power. The second step was to do a Finite Element Analysis on the system.

The equation that governs the stress on the crank arms is:

$$\sigma = \frac{M * c}{I} \qquad \text{[Equation 1]}$$

Where *M* is the moment on the arm, *c* is the location of the point of measure, and *I* is the moment of inertia. The main assumption for Equation 1 was that the crank arm and handle are solid components in order to make these calculations simpler.

The deflection of the crank handle and the crank arm were also analyzed. The equation that governs deflection for this system is

$$\delta_{handle} = \frac{L^3 * F}{3 * E * I} \qquad \text{[Equation 2]}$$

Where L is the length along the axis of measure, F is the force applied to the handle while operating the generator, and E is the Young's Modulus for the material the crank arm and handle are composed of. The force was found from the torque applied to the crank arm to operate the generator, 50 in*lb, which equates to 9 lb_f. The maximum leg force for a woman was found to be 63 lb_f, where 40% of that value is acceptable to exert for an extended period of time, which equates to 25 lb_f. For these calculations the force was assumed to be completely applied to the end of the handle, which is a worst-case scenario. These preliminary calculations yielded a stress on the handle of 2548.8 psi, a stress on the arm of 462.97 psi, deflection of the handle as .1507 in and deflection of the arm as .0404 in. These values were well within the tolerance of the material of the crank arms.

For the second part of the stress analysis, the generator system was modeled in a SolidWorks due to its ability to do Finite Element Analysis simulations. FEA uses the same stress equations as were used in the hand calculations, but the part that is being analyzed is sectioned off into many tiny sections, known as a mesh. This gives a very clear picture of exactly where and to what extent stresses and deflections are being experience on the parts based on constraints implemented to the parts.

Both the original system and the new system were analyzed with the Finite Element Analysis so there would be a consistent comparison between the original and proposed design. The force with applied across the handle, which is more accurate to what force the crank arm would actually see, while the axis of rotation was constrained in all directions. From using a Finite Element Analysis on these parts, it was determined that theoretically this new proposed design would hold up to the increase in force that would come along with shifting to leg power.

Shifting to leg power requires a new seating arrangement to optimize ergonomic efficiency. When designing a new seating assembly, it is important to make sure the materials used are durable and do not corrode or weather easily. Plastic and pressure treated wood are the materials used for the new seating arrangement. Each part of the new seat has also been designed to minimize machining operations during the manufacturing process.

Once the final design is modeled using CAD software, a prototype is constructed and is then used for further feasibility analysis. The construction and assembly of the proposed design demonstrates the reliability, ease of assembly, total product weight, and functionality. Testing of this assembled prototype is carried out and the design proves to be strong and reliable, and also satisfies the necessary customer needs.

Two seat concepts were chosen to accommodate a switch from using arm power to leg power to run the generator. Both were very similar and used almost identical parts. The major difference between them is for one of them the seat surface is the bottom of the buck while the other has the top as the seat surface.

For the first concept the wooden parts can be assembled outside of the bucket, but in the second the wooden parts have to be connected inside the bucket. The difference between seat 1 and seat 2 is the seating surface area is larger on seat 2, both seats require the same amount of parts for assembly.

To test how long it would take to assemble the seats, various individuals were timed as they put the seat together. The average assembly time was 8 minutes and 30 seconds. The tool required to assemble the seat is a 10mm open-ended wrench.

Overall both seats worked very well, but Seat Concept 2 was the better of the two because of ergonomic factors. Both seat concepts satisfied functionality, so ergonomic comfort is the deciding factor.

Life Testing

To find out if the motors selected to replace the original motors in the generator will be suitable, life testing was recommended. The ideal test for these motors is to set them up so that they are driven by a secondary motor as a generator similar to how it works in the generator box. The idea with this set-up is to be able to test the output of the motor that is being run as a generator as it goes through life testing. To run this test the motors would be placed inside an environmentally controlled chamber to simulate the conditions they would be operating under. For this test the only environmental parameters in place are temperature at 120 °F and humidity at 50%.

With the original motors there was only one readily available motor that was in proper working condition, so to get some baseline tests done the motor was set up in the chamber and set to run. This test ran the motor utilizing it's standard function, not as a generator. The total testing period was set up to simulate the effect of the motor not being used continuously so on and off periods were scheduled. Due to time constraints the total test period consisted of 10 days, starting with a 72 hour on period, then a 24 hour off period, followed by a 48 hour on period, then a 24 hour off period, and finally a 72 hour on period. At the conclusion of the test the motor was still running, proving that the motors can run in the environment they are used in. If the new motors had arrived in time to complete testing they would have been tested under the conditions outlined in the previous paragraph. A test rig would have been built to accommodate driving the motors as generators to get concrete data points of where performance degradation occurs. Without the new motors these tests are inconclusive.

Analysis/Improvement Proposals

Generator Circuit

The current generator circuit design uses a shunt network to apply a negative feedback path to the regulated output voltage, V_{reg}. As the input voltage V_{in} exceeds ~14-15 V, a comparator switch turns this shunt path on, illuminating a RED indicator LED and an optical isolator LED and shunting the output voltage. In turn, the optical isolator shunts the input voltage through its phototransistor. As such this circuit configuration causes the output voltage to stabilize at approximately ~14-15 V, regardless of how high the input rises. Ultimately this protects the pump circuitry (or anything else being powered by this crank device) by preventing it from receiving excessive power. A green LED indicates sufficient voltage being generated of +14 V or higher, using a comparator with a fixed +5 V reference.

Redesigned Generator Circuit

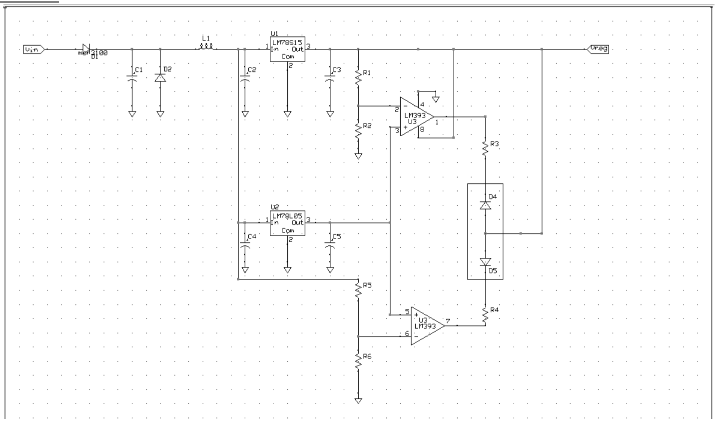

Figure 2: Proposed Generator Circuit

The newly designed generator circuit uses a much simpler approach to realize a +15 V regulator. The input voltage V_{in}, after passing through the input protection stage, is regulated using a L78S15 fixed +15 V voltage regulator. The red/green indicator dual-LED should use the same LM78L05 +5 V regulator for a reference voltage applied to both negative terminals of the LM339 comparators, and voltage dividers to illuminate at the appropriate colors at the appropriate time (the same LED behavior as in the original circuit, but combined into one LED). Additionally, a protective reverse diode is added to the inductor to protect the circuitry from the inductive kick in the event of a large change in current.

There are 2 main advantages of the newly designed generator circuit:

Cost – The revision of the generator circuit removes a significant amount of unnecessary parts, while adding the small cost of a L78S15 +15 V regulator. Overall, this redesigned circuit would cost less to fabricate than the original circuit.

Simplicity – The redesigned circuit is far easier to understand, and thus far easier to implement, test, troubleshoot, and maintain.

Pump Circuit

The original pump circuit expects as an input the 12 V/17 W required to power the ballast and pump. An input voltage greater than 12 V will turn on the UV ballast and begin to charge the 150 µF capacitor. After approximately 10 seconds of the input voltage staying high, the capacitor voltage exceeds the +5 V reference at the LM339 comparator, causing it to output high to the corresponding NAND gate. This in turn activates the pump and moves water through the device.

Proposed Changes to the Pump Circuit

There are 2 proposed changes to the current pump circuit:

Large Capacitor Between Supply Terminals – The current pump circuit deactivates the pump and resets the 10 second timer in the event that the supply voltage drops below ~12 V, even for a short amount of time. Given that the power to this device is expected to be human-generated, this can lead to a large waste of the user's energy, if he or she is unable to consistently maintain the required crank rotation speed. Placing a large capacitor between the supply terminals should smooth fluctuations in the supply voltage. This would yield a desirable trade-off – it would lead to a slightly higher 'charge-up' time, but it would also allow for small periods of insufficient voltage being generated without resetting the 10-second timer.

Reverse Zener Diode Between Supply Terminals – The current pump circuit has no protection in the event of excess power being supplied. Similar to the Zener diode in the generator circuit, a reverse Zener diode between the supply terminals with an appropriate breakdown voltage (~20 V) would protect the circuitry from being destroyed by excess power.

RESULTS AND DISCUSSION

New Seating Position

When testing the new seating position, the rpms of the current motor still exceeded the capability of the user to produce clean water. Though the leg muscle will allow the user to pedal for longer, it was not sufficient enough to keep the light on consistently. After a group test run, the average time to assemble the seat was 8 minutes and 30 seconds. The new design also allows for the user to assemble in less than ~10 minutes with the assembly instruction manual. The only tool needed is the one open ended wrench.

New Motors and New Seating Position

After applying the new motors, four of the CF Motors RS-555PH-2590 were put in the same series configuration, the rpms still proved to be too fast for a user to pedal for clean water. Though the rpms decreased by 11.54%, the user could not continuously maintain power. The new motors, did however, provide more resistance. Through observation, there is a need of further reduction in RPMs, the operation was much smoother than the last, and the pedals should be wider with a strap holding the users foot in place.

Redesigned Generator Circuit

The new generator circuit was first tested on a prototype circuit board. Power was applied directly to the circuit by a voltage source (representing V_{in} from the motors), which was swept from 0 V to +20 V DC, while the regulated output voltage V_{reg} was measured, as well as the output current through a current sense resistor. The output voltage was found to rise with the input voltage while maximizing at 15.1 V DC. As V_{in} was swept the current immediately exceeded 2 A, demonstrating that the circuit could indeed output sufficient current to power the pump circuit, while producing no more than ~15 V. Additionally, the generator circuit was then used to power the pump directly. Both the ballast and the pump motor were successfully powered using this generator circuit.

Generator Circuit PCB Layout

After verifying correct functionality of the redesigned generator circuit, a printed circuit board (PCB) was designed in order to replace the existing model inside the generator device. This PCB includes three mounting screw holes (as before) in order to be installed without additional tooling considerations. Additionally, the PCB includes the same heat sink as in the original design to be used with the L78S15 LDO voltage regulator, which uses the same package as the power MOSFET in the original design.

Pump Capacitor Results

To test the proper functionality of a large capacitor between the power terminals of the pump circuit, the pump was powered using a power supply for increasing values of capacitance between the pump terminals. More specifically, 470 µF capacitors were continually added individually in parallel and the effects were observed. Unfortunately, after adding 20 capacitors it was determined that there was no observable lag between the output power from the supply and input power to the pump for any reasonable amount of capacitance (on the order of 10 mF). While capacitors larger than 10 mF are widely available, cost and size become significant concerns. Hence, it was determined that exploring other options for temporary power storage was preferable.

CONCLUSIONS AND RECOMMENDATIONS

Better Water Maker

The new design with the new motors did produce a significant reduction in rpm's but not enough to operate with the new seating position. In addition, the motors produced an increase in resistance and did not allow users to maintain a smooth rhythm to produce water. The addition of a capacitor circuit could potentially provide enough power to produce water.

Redesigned Generator Circuit

The proposed generator circuit has been simplified significantly. From a troubleshooting perspective this is desirable, as one can more easily locate a problem with a component in the circuitry. Additionally, one can reduce cost due to parts and PCB size. Finally, malfunction is less likely due to the reduction of the number of ESD (electrostatic discharge) sensitive components.

Generator Circuit PCB Layout

The PCB layout was designed to replace the previous PCB to prevent additional tooling costs. However it may be advantageous in the long-term to minimize the board size further. While this would present the need for new screw locations, and thus retooling, one could perhaps save on the long-term production costs yielding a desirable tradeoff.

Pump Capacitor Evaluation

While the capacitor design was determined to be infeasible, additional options are available for temporary energy storage. A rechargeable battery could be used in place of such a capacitor, but one important consideration would be the battery's lifetime (hence why the capacitor design was initially chosen). Also a super capacitor could be used in place of a standard electrolytic capacitor, as in the same price range these can have much larger capacitance and are drastically smaller. However, these generally have much smaller maximum voltage ratings (far less than the 15V the pump requires). As such, this design idea would require a buck converter to reduce the voltage to the capacitor and a boost converter to increase the voltage from the capacitor to the pump circuitry.

Cost Evaluation
The original bill of material for the generator was analyzed to see what the value to cost relationship is for each part. The components were grouped into five main functions: internal protection, external protection, power generation, user interface and internal parts. The relative worth of each functional grouping was calculated by estimating the importance of each group relative to how important that function is. Then the relative cost percentage of each functional group was calculated by taking the group cost and dividing by the total product cost. The two are plotted in relation to each other with the relative cost on the y-axis and the relative worth on the x-axis. A trend line is plotted diagonally through the chart, which separates it into two segments. If the data points fall above the line the cost of the functional group is too great for the relative value the function gives the product. If the data falls below, the functional group is a good value for the price. After analyzing the generator bill of material, it can be concluded that the product as a whole is a great value for the price. Only one functional grouping falls above the trend-line and it is barely above the line.

Future Work
After working with the generator for the Better Water Maker for twenty weeks, redesigning, prototyping, testing and analyzing results there are things we observed could further be done to better this product:

Thermodynamic Analysis: A thermodynamic analysis should be performed to simulate using the generator in a hot, sunny environment. We would like to analyze how the housing of the generator acts like a greenhouse and get an output as to how the motors could perform in this environment. The black plastic housing would capture all sunlight and with no air ventilation the inside could heat up considerably

Fabricate PCB with new design : The generator PCB has been simplified and laid out in this project. We would recommend that the new design be fabricated and tested inside of a generator. We believe the cost savings would be significant

Motor Life Testing: There is still great speculation as to how long DC motors will last while being used as generators. Finding out if they have a lesser or greater life than motors used as motors would be helpful.

Redesign Crank arms: Redesigning the crank arms to be more receptive to foot power would be an important next step. The current crank arms are straight rigid; shoes often rub against the crank arms causing the user to lose his/her footing and lose their pedaling rhythm.

Research brushless motors: Brushless motors last many hours longer than brush motors. To exhaustively research brushless motors could solve many of B9's problems.

Increase the resistance of motors: By doing this changing to foot power would be a reality. The more resistance the easier it is for a user to keep their smooth rhythm. This could yield the final product B9 is looking for.

Investigate solar energy: Using solar energy is effortless, the cost could potentially increase but the device would power itself. Solar energy could also solve the problem B9 is facing attempting to reduce the effort required to power the Better Water Maker.

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