Regenerative Braking in Electric Bike Conversion Kit

ECE 445 Project Proposal

Team 38

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March 3, 2023

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1. Introduction

1.1 Problem

Though electric bikes are a greener alternative to gas-powered cars and faster than traditional bikes, electric bikes' limited range can discourage some to make the switch. An average electric bike has a range of 20-40 miles [1]. For some, this range is simply too low to justify purchasing something on the order of $1000 to $2000, especially when that price tag reflects that of an entry-level electric bike [2].

Conventional electric bikes also suffer from the same brake wear as a traditional bike. It is suggested that traditional cyclists replace their brake pads every 500-1000 miles [3]. Since electric bikes use the same braking system as manual bikes, the same advice more or less applies. For those who cycle frequently, brake maintenance may be seen as an undesirable chore.

1.2 Solution

To solve these problems, we would like to create a kit that transforms a traditional bike into an electric bike that is capable of regenerative braking. The regenerative braking aspect would both provide a range boost to the user, as well as preserve the manual brakes such that brake maintenance would not need to be conducted as often as with both a traditional bike and more conventional electric bikes.

This kit would contain all of the components of a traditional electric bike, including motor, battery, and user controls. Completing the assembly would result in a friction drive, throttle-assist electric bike. The kit would also include the necessary control unit to not only provide the traditional function of supplying power to the motor, but also to supply power to the battery during regenerative braking. The end result is that the user would be able to convert their bike into an electric bike capable of regenerative braking. Riders will be able to use a regenerative braking control that is separate from the manual brake lever, slowing them down. The use of this system will both recharge the battery and reduce manual brake wear.

1.3 Visual Aid

The regenerative braking feature will be best utilized when coming to a stop for traffic signs, or when trying to slow down while biking down a hill. It will help recapture kinetic energy that would otherwise be lost to friction due to traditional brakes.

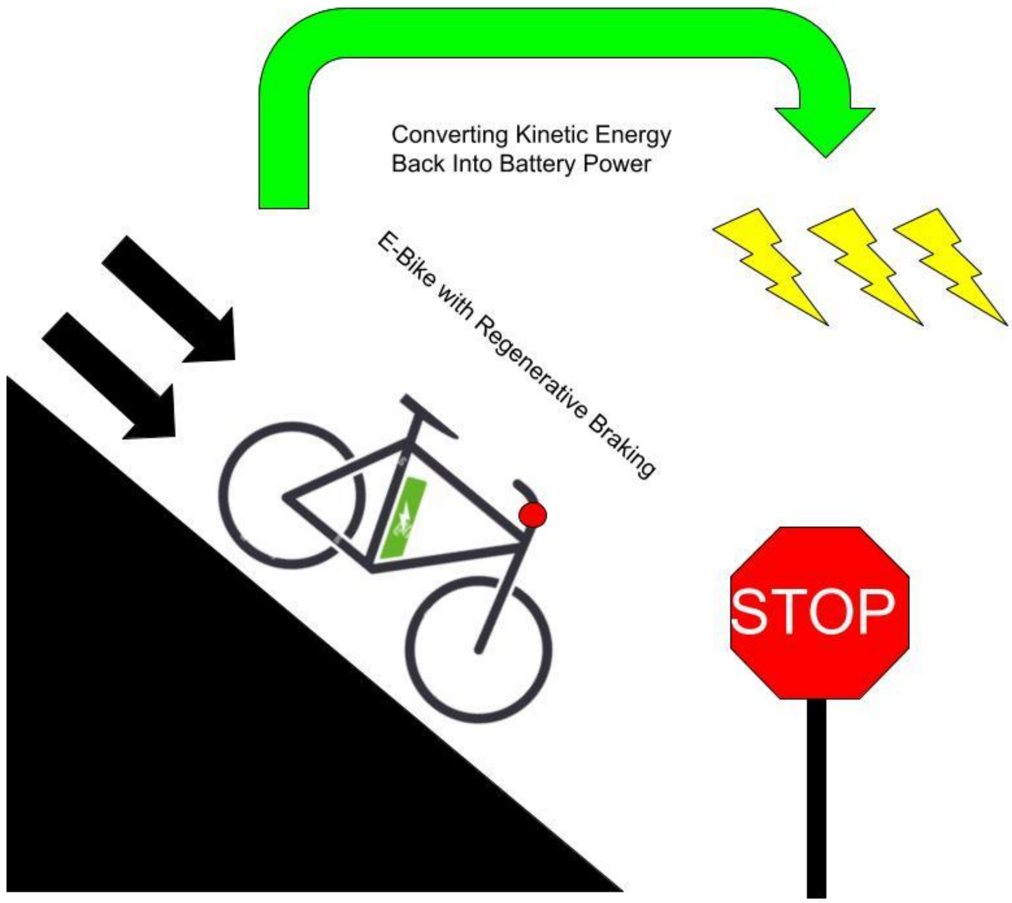

Fig 1: Example of Regenerative Braking Application

1.4 High-Level Requirements

- Pressing a button or switch on the bike must initiate regenerative braking. The braking should be strong enough to stop the bike at 15 mph within 100 yards. Regenerative braking should not be relied on for emergency stops.
- Using regenerative braking during city driving should result in a range boost of at least 1-10% compared to not using regenerative braking over the same ride.
- The electric bike will be limited to 20 miles per hour as per Class 2 E-bike definition [6].

2. Design

2.1 Block Diagram

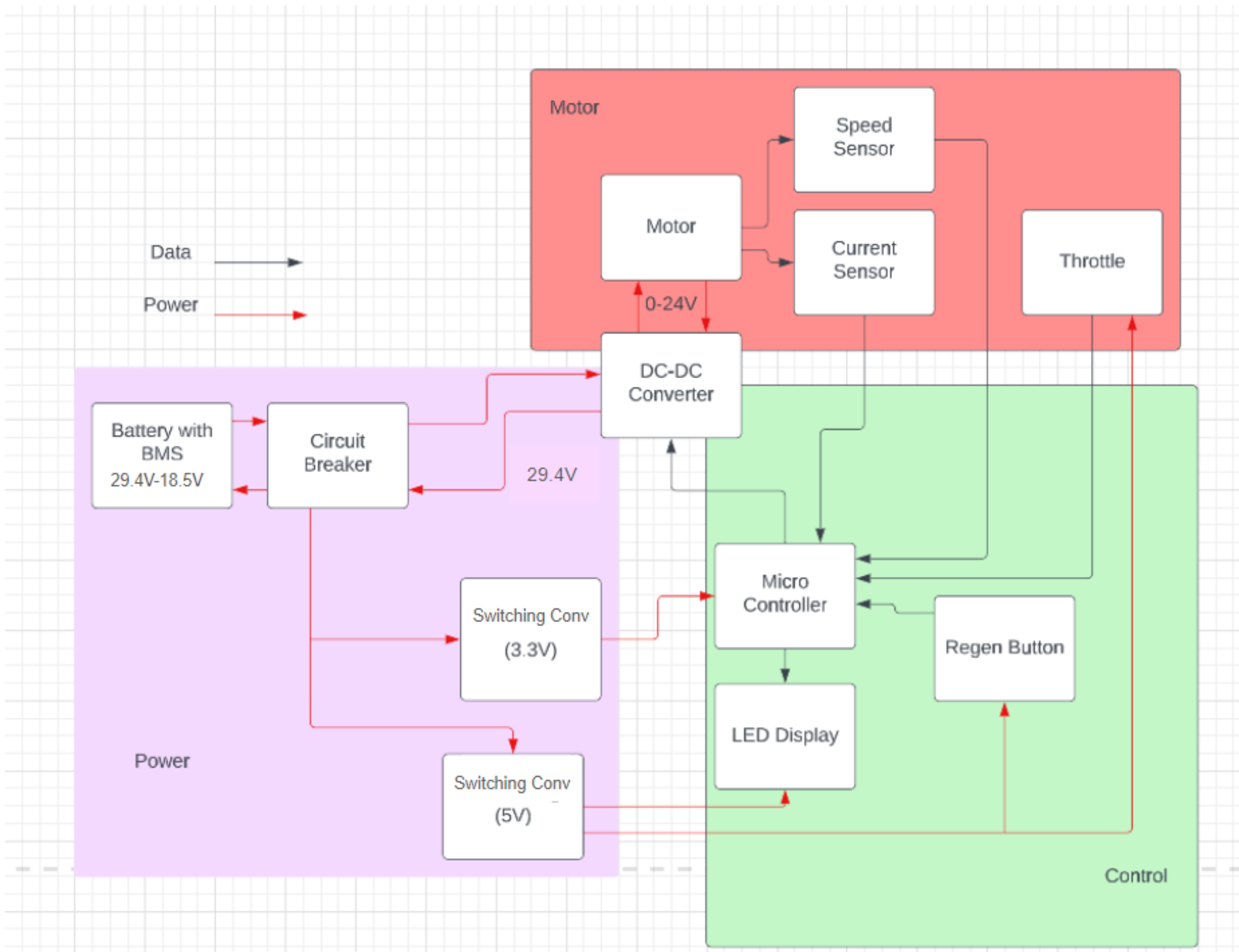

Figure 2: Block Diagram

2.2 Subsystem Overview

2.2.1 Motor Subsystem Overview

The motor subsystem is responsible for the input and output to accelerate the motor. It will also be responsible for taking in torque and converting the kinetic energy into electrical energy to be stored in the battery. The motor controller will take input from the control subsystem and apply power or allow the motor to regen depending on the signal. This will allow the user to safely and easily switch between braking and accelerating without any overlap. The motor itself will draw power from the battery.

The microcontroller will receive the throttle signal from the twist throttle. The magnitude of the twist throttle signal will be used to determine the duty cycle of the switching signals generated in the control unit. Low throttle signal will correspond to low motor voltage, while the max throttle signal will correspond to the full 24V motor voltage. However, if the speed sensor measures a speed of 20mph, the microcontroller will stop sending signals to increase the voltage at the motor.

In short, the motor controller receives a throttle signal and uses that information to determine the duty cycle of the switching signals generated by the control unit. The duty cycle of these signals determine the voltage at the motor when the BDC is in buck mode. Thus, the voltage at the motor can be varied depending on the duty cycle of the switching signals.

It is important that the voltage at the motor can be varied, as this will control the rpm of the motor, and therefore the speed of the bike. Through the motor controller, the twist throttle input can be used to control the overall speed of the bike.

2.2.2 Power Subsystem Overview

The power subsystem is responsible for taking power from the battery and regulating output for all the other subsystems. It will receive the power generated by the motor during regenerative braking, and convert into it to charge the battery. Because we are not using the wall charger designed to work with the BMS, we must also have additional protections in place in order to ensure that the battery is not damaged by charging it. There will be a circuit breaker in between the battery and all other systems in order to allow emergency shutoff and to prevent current spikes.

Power output to the control subsystem will be fairly straightforward. This can be done with switching converters to conserve power. Battery output to the motor, along with motor output to the battery, is the main challenge in this regenerative braking project.

To do this, we will be using a bidirectional DC/DC converter along with an error circuit. These can and will be purchased in a combined package. Switching signals from the control subsystem (discussed in a later section) are used to control the switching action of the MOSFETs in the BDC converter. Depending on the duty cycle of these pulse signals, or lack thereof, to each of the MOSFETs, voltage can be boosted from the motor to the battery, or bucked from the battery to the motor. The BDC converter will allow us to both achieve normal operation, where the battery is powering the motor, and regenerative braking operation, where the motor is recharging the battery.

Because the bidirectional converter and the circuitry for voltage ripple correction can be bought as a package, the majority of our design considerations will be focused on which resistors, capacitors, and inductors to use to achieve the desired buck-boost operation. A sample of this can be found in our Tolerance Analysis section.

2.2.3 Control Subsystem Overview

The control subsystem is primarily used to regulate the switching signals used in our BDC converter. By varying the duty cycle on these signals, the battery output can be bucked to the appropriate motor voltage, between 0 and 24V, and the motor output can be boosted to the 29.4V battery charging voltage. Duty cycle variation will become important as the motor voltage drops during regenerative braking action.

The control subsystem will make use of the microcontroller. For our project, we have decided to use a TI F280xx microcontroller with automotive specification to ensure that it can continue operation at higher temperatures. The maximum operating temperature of this device is 125 C, which should be sufficient for an electric bicycle application [7]. Both operating temperature testing and verification of microcontroller functionality will take place during the assembly and testing phase of our design project.

Another function of the control subsystem is to route the twist throttle signal directly to the motor controller. The twist throttle will give an analog output between 0V and 5V, which can be directly used by the motor controller to regulate bike speed. The control subsystem must also provide the power supply to the twist throttle.

Similarly to the twist throttle, the control subsystem also handles the regenerative braking signal. Our regenerative braking function will be controlled by a button (or a switch with the same functionality) mounted on the handlebars of our bike. 5V should be supplied to it from the control unit. When the button is pressed, it will send a regenerative braking signal to the control unit. This signal will be used to override the normal operation switching signals with regenerative braking operation switching signals, allowing the motor to recharge the battery.

The last main function of the control unit is to collect and store data related to battery recharging. Data on current from the motor will be collected via current shunt. This data will be used to determine how much the battery has been recharged.

2.3 Subsystem Requirements

2.3.1 Motor Subsystem Requirements

The motor control subsystem must reliably measure the speed of the bike within 0.5 mph. This will be necessary for ensuring that the speed of the bike does not exceed 20mph, as per Class 2 E-bike definition. It may also be useful in determining regenerative braking efficiency as the project progresses.

The motor control subsystem must also measure current output from the motor during regeneration. Accuracy must be within ± 5% of a multimeter reading. This data will be necessary for testing. It reflects how much the battery has recharged over the course of a ride, as well as the range boost gained from using regenerative braking.

The motor voltage must change reliably with throttle input. Voltage at the motor should be within ± 5% of the expected motor voltage based on the duty cycle. Changing the motor voltage will be necessary for changing the motor speed. Thus, is it necessary that throttle input reliably leads to a set motor rpm.

The motor must not activate without throttle activation. If the twist throttle input is within 0.5V of the resting throttle position, the motor should be off.

2.3.2 Power Subsystem Requirements

The power subsystem must convert the battery voltage, 24V into the desired voltage for the motor. The motor voltage should be between 0V to 24V, depending on the throttle input. The battery voltage is also allowed to vary within tolerances. 29.4V is the battery charging voltage. The battery voltage can also be expected to dip slightly as the charge drops. This drop will likely just result in a slightly reduced maximum bike speed. Boosting battery voltage to the motor is not desired, meaning battery voltage during normal operation will be the highest voltage the motor can reach. Our tolerance for the motor voltage is 24V ± 2.5V when the motor is meant to operate at 24V.

The power subsystem must also convert the motor voltage, ideally between 24V and 0V, to 29.4V ± 1.5V for successful battery recharging during regenerative braking. It is not expected or possible for the motor to supply this to the battery at all points during regenerative braking operation. It is expected that once the motor voltage dips below a certain threshold, the voltage will be too low to boost to the desired charging voltage. What exactly this threshold is will depend on our switching converter operation.

The power subsystem must also convert the 24V battery voltage into 3.3 ± .5V for the microcontroller to operate. This will likely be done using a switching converter.

2.3.3 Control Subsystem Requirements

The microcontroller must recognize the regenerative braking “ON” signal and change from normal switching mode to regenerative braking switching mode within 1s.

The microcontroller must also recognize the regenerative braking “OFF” signal and change from regenerative braking switching mode to normal switching mode within 1s.

To elaborate slightly on the above requirements, the regenerative braking signal, whether it is off or on, must be monitored closely by the microcontroller. These switching modes are what allow the bike to accelerate and maintain speed in normal mode and to regenerate in regenerative braking mode.

The control subsystem must be consistently below 125 C throughout the duration of bike operation. Exceeding this temperature threshold would result in the microcontroller exceeding its temperature rating. Microcontroller failure would make it impossible for the bike to operate in either mode.

Finally, the control subsystem must also supply 5V ± 0.3V to both the twist throttle and the regenerative braking button. The twist throttle must have a voltage supply at least during normal bike operation. The regenerative braking button must have a voltage supply in both operation modes.

2.4 Tolerance Analysis

One aspect of our design that poses the risk to the successful completion of this project is our bidirectional DC/DC converter. If this component does not function reliably or successfully, then the motor cannot receive voltage from the battery and the battery cannot be recharged by the motor. The converter's operation is crucial to the success of this project.

For our Tolerance Analysis section, we decided to model a simple bidirectional DC/DC converter in boost mode. More details on the model can be found by seeing reference [9]. We firstly wanted to see if it was possible to boost a motor voltage of 24V up to the required 29.4V. To accomplish this, the bidirectional DC/DC converter was drawn in LTSpice. Because we are still waiting to test the parts, a few reasonable assumptions about the battery internal resistance and the load resistance and inductance of the motor were made. These will be modified as more tests are run. The battery was modeled as a DC voltage source with an internal resistance of 0.7R. The motor was modeled as a DC voltage source with series resistance and inductance. See Figure 3 for more details.

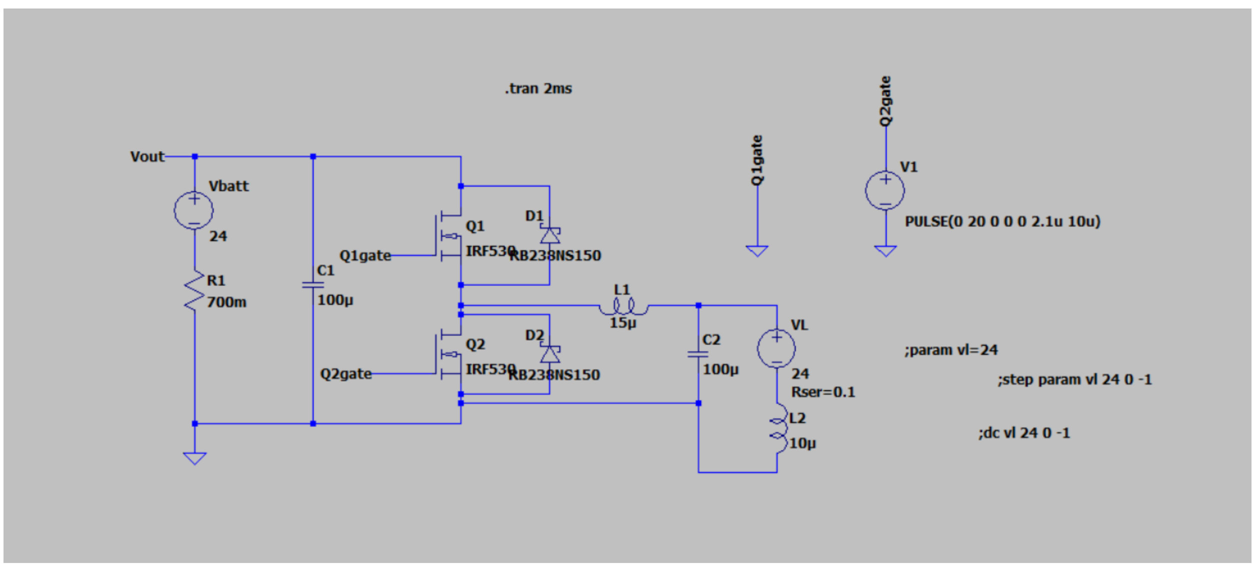

Figure 3: Bidirectional DC/DC Converter Schematic in Boost Mode

The next steps for implementing this converter were to decide on the duty cycle and values for the inductors and capacitors seen in Figure 3. The duty cycle calculation can be seen in Figure 4. It typically contains an efficiency term, but this was set to 1 due to this being an ideal model.

$$a = \left(1 - \frac{24}{29.7}\right)$$

Figure 4: Duty Cycle Calculation for 24V Motor Voltage

The inductor and capacitor calculations are done separately for buck and boost modes. These equations can be found in the figures below.

$$L_c = \frac{a(1-a)^2 R}{2f}$$

Figure 5: Minimum Inductance Calculation for Boost Mode

$$L_c = \frac{(1-a) R}{2f}$$

Figure 6: Minimum Inductance Calculation for Buck Mode

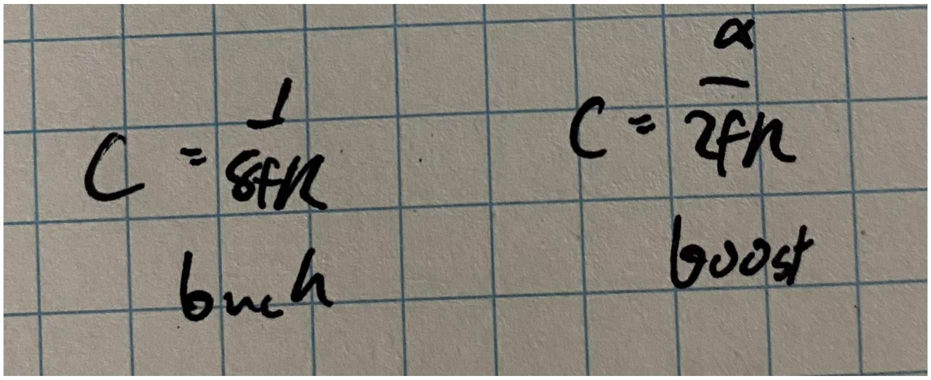

Figure 7: Minimum Capacitance Calculations for Buck and Boost Mode

In the boost mode equations, R represents the internal resistance of the battery. In the buck mode equations, it represents the motor resistance. F in all equations represents the switching frequency. For this test, it was set to 100 kHz. There are different tradeoffs when considering switching frequency. At some point speed is sacrificed for efficiency. As a result, switching frequency will likely change to meet the demands of our bidirectional DC/DC converter. This frequency was chosen because it fit within the parameters of some of our considered bidirectional DC/DC converter components.

For this particular test, we calculated an ideal duty cycle of 0.1837. The inductance was chosen to be 15uH to fall outside of possible minimums, and capacitances of 100uF were chosen to help mitigate the ripple seen in the output voltage. The duty cycle was adjusted slightly to 0.21 for the simulation. The end result can be seen in Figure 8.

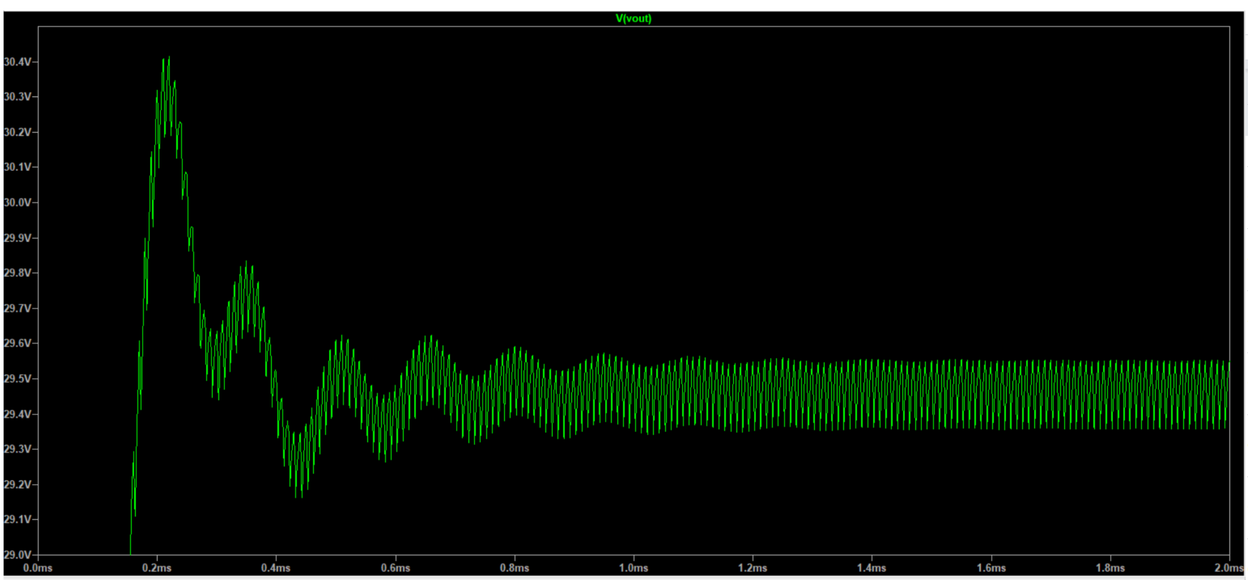

Figure 8: Initial Simulation Results

Though the initial peak and voltage ripple will have to be mitigated somehow, one can see that our bidirectional DC/DC converter is perfectly capable of supplying 29.4V ± 1.5V to the battery. Though this design will need to be tweaked as more testing is done, it shows promise as it is. The issues that we can see with it now will need to be mitigated by an error circuit to prevent systemwide ripples. This will be another consideration we must make with our design.

The next step in this analysis was attempting to decide approximately at what motor voltage regeneration becomes unsustainable. We wanted to know approximately how low the motor voltage could drop while still producing a voltage output that could charge the battery. The motor voltage was dropped to 18V. The duty cycle was recalculated to be 0.387, then adjusted to 0.415. The inductor and capacitor values were left unchanged, as a varying duty cycle was accounted for in the initial calculations. The results of this new simulation can be seen in Figure 9.

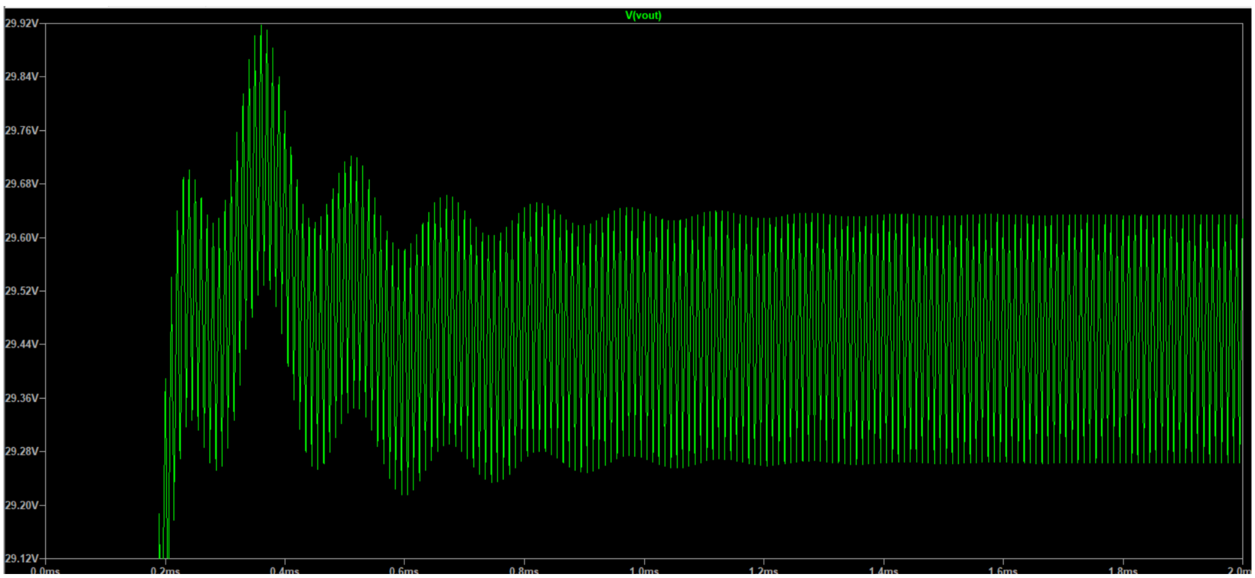

Figure 9: Boosted Battery Voltage when Motor Voltage is 18V

Figure 10 shows the results obtained at 14V. The calculated duty cycle was 0.5238, but was adjusted to 0.595. 29.4V was also obtainable here.

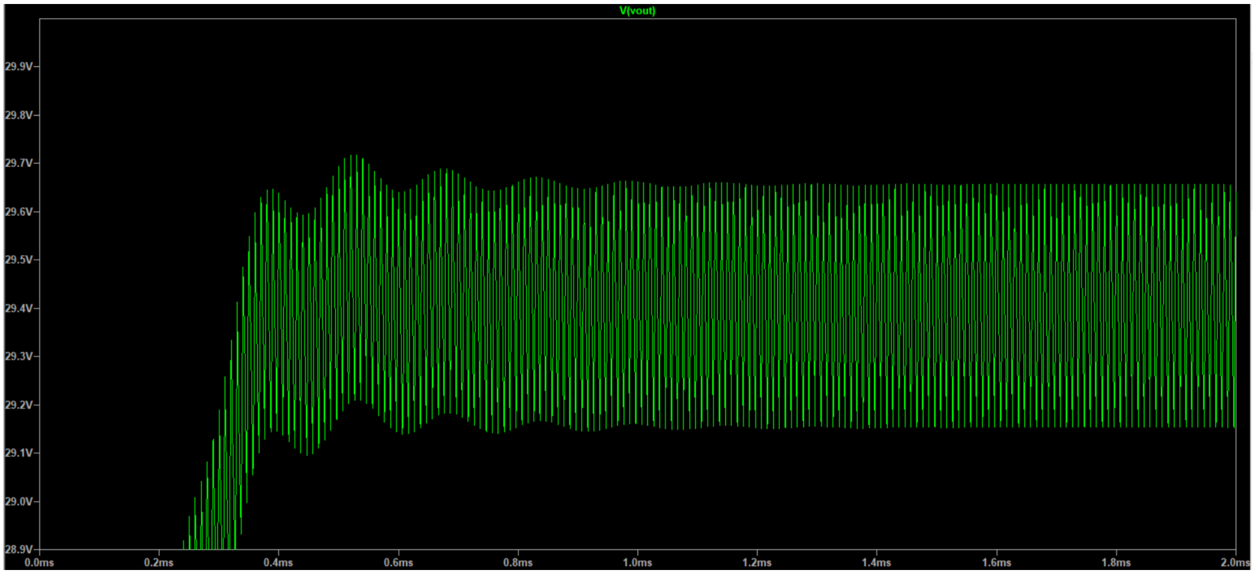

Figure 10: Boosted Battery Voltage when Motor Voltage is 14V

Favorable results could also be obtained with 13V. The duty cycle was calculated to be 0.5578, but was adjusted to 0.68. This is noted to be a large adjustment, much larger than the other adjustments. The results of this simulation can be seen in Figure 11.

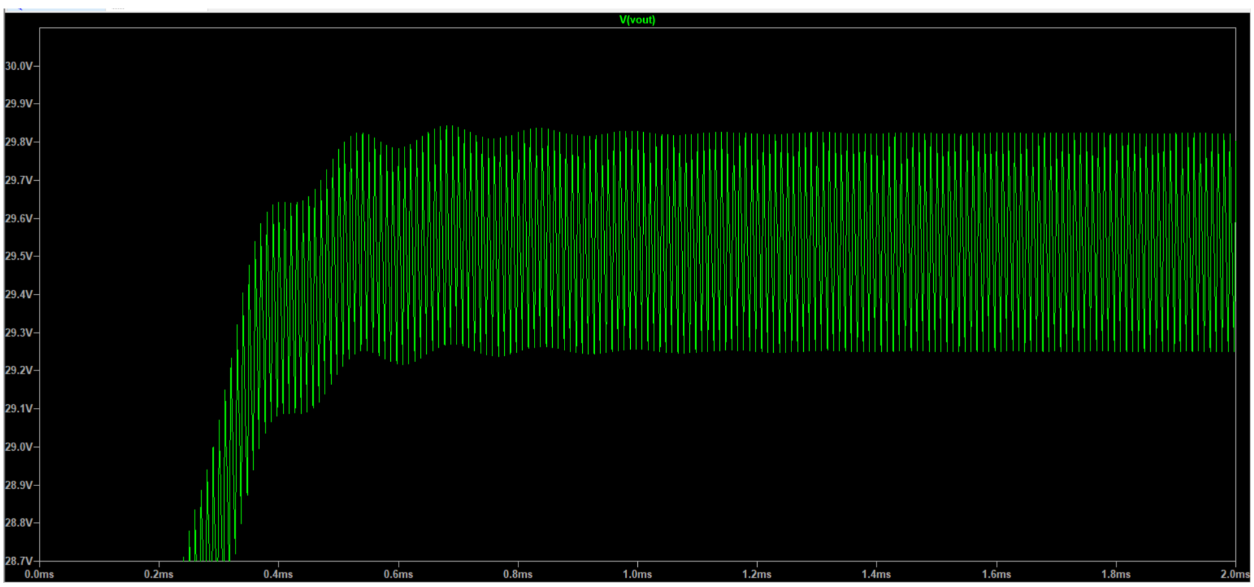

Figure 11: Boosted Battery Voltage when Motor Voltage is 13V

Unfortunately, the 12V motor voltage simulation did not work out quite as well as expected. The best results obtained were at a duty cycle of 0.77 at an average voltage of 29.1V. The results can be seen in Figure 12.

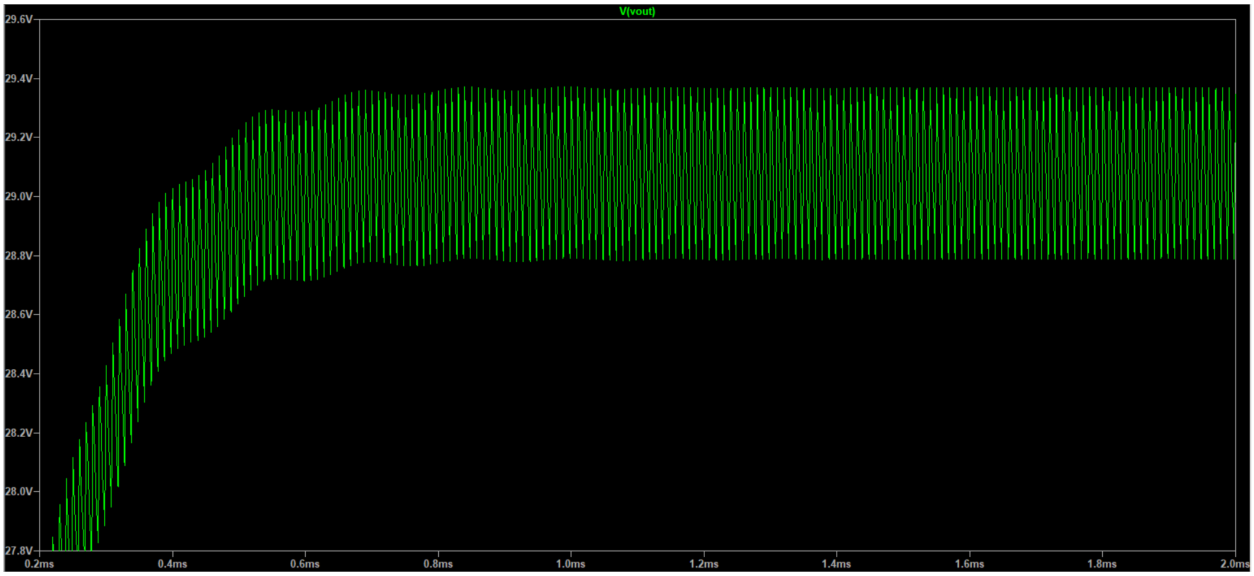

Figure 12: Boosted Battery Voltage when Motor Voltage is 12V

We stop reliably seeing 29.4V at the output when the motor voltage hits 12V. This is not to say that the battery will not recharge at 29.1V, or that this cannot be improved upon as the design of the bidirectional DC/DC converter improves. Adjusting internal resistances can also produce different results. This will be something to consider when the physical motor and battery are tested.

This tolerance analysis was conducted to give us a baseline for when regeneration no longer becomes possible. As of now, we have shown that half of the motor voltage range can produce the 29.4V required at the battery. A 12V motor voltage comes close, but falls short at 29.1V. Improvements should be made upon the circuit to increase the range of input voltages it can reliably operate under. Despite this, regeneration is certainly possible with our motor and battery combination.

3. Ethics and Safety

Due to the potential risks associated with the battery being used for this project, we as a team must take care to minimize those risks, as stated in Section I.1 of the IEEE Code of Ethics [4]. We will take care to ensure that the batteries do not receive more charge than they can hold. We will also make protections against any unsafe battery conditions, such as overcurrent, overvoltage, short circuiting. During assembly, we must also take care not to drop or damage the battery in any way, as this can be unsafe to users. Charging at cold temperatures and ensuring that the battery does not operate above its rated temperature will also be important considerations. Charging below 0C will also be a consideration for the end user [5]. There will also be an emergency shutoff switch to prevent any unsafe conditions with the battery.

Another important consideration for our project is that our regenerative braking system must function to a satisfactory degree. The user must be able to slow the bike to a stop during typical use using our braking system. Design considerations will be made to have the bike slow to a stop in a reasonable distance. A manual braking system will also be included in the final design to ensure that the user can stop the bike at all times, especially during emergency situations.

We are not responsible for the user riding the finished project in any way that is not in accordance with the traffic laws in their area. Safe riding practices must be determined and followed by the user. Helmets and protective eyewear are recommended while riding an electric bike.

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