BikeBike Revolution: Energy Efficient E-Bike

ECE 445 Final Report

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Abstract

For our project, we designed and implemented an E-bike which can be converted from an indoor stationary bike to a pedal-assist outdoor bike. Our project's purpose is to help conserve energy so that after the user utilizes the bike for indoor exercise, they can use the energy generated from pedaling for transportation outside. Our bike has a motor / generator which, in generator mode, can charge the bike's battery from the user pedaling, as well as from the wall outlet. In motor mode, the bike functions as a pedal-assist E-bike which is supported by a PWM controller. For the user features, our design includes a battery life indicator, a switch to differentiate between motor and generator mode, and a switch relay as a safety feature that disconnects the circuit when current is too high.

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1. Introduction

1.1 Background and Objectives

Biking is a longtime hobby and top choice of exercise with a broad audience. Indoor cycling in particular has been a great form of activity that is currently on the rise in popularity [1]. The amount of energy generated after pedaling for an hour is about 80 Wh including losses, while the average fully electric E-bike is rated between 300-1000 Wh [2], [3]. The amount of power generated is feasible in an electrically-assisted bike, which can be rated as low as 144 Wh.

Our solution allows a pedal-assist E-bike to convert into an indoor stationary bike, and to use the energy generated from pedaling indoors to power the E-Bike for use outdoors. Our design includes an indoor stand to support the bike for safe use indoors with the motor / generator, battery, and power electronics mounted on the bike frame itself. The power electronics system consists of DC-DC and AC-DC power conversion, as well as a PWM control circuit. Furthermore, the multi-input system of our design allows the battery to adapt to the grid to ensure a reliable energy source if needed.

1.2 High-Level Requirements List

1. From full charge, the bike must be able to travel with electric-assisted power with an average of 150W and travel with a rate of at least 10mph.
2. In generator mode at a maximum input, the bike should be able to generate at least 100W of power by the user pedaling the bike. In this mode, the bike must also be able to switch to using power from the grid in order to get charged.
3. The DC-DC Boost converter must be able to exhibit at least 75% efficiency when taking in varying values of voltage output from the generator.

1.3 Block Diagram

Our block diagram consists of four interconnected subsystems: the power electronics, control module, sensing module, and motor / generator. The power electronics module consists of power transmission to and from the motor / generator and from the grid. The control module is involved with sending power to the motor using the PWM controller and determining when the system should be in motor or generator mode, and the sensing module takes in information for the controls or for user interface. Lastly, the motor / generator can be used as either a generator to charge the battery or a motor to support E-bike functionality.

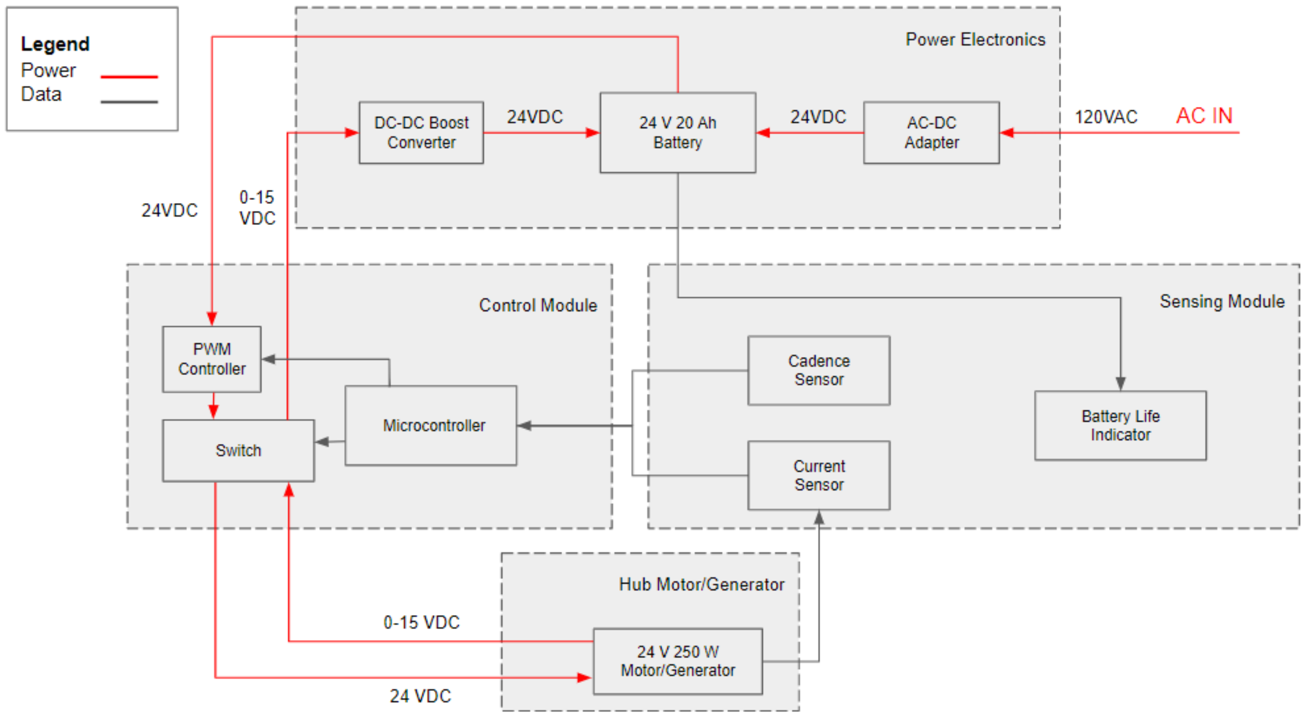

Figure 1. Block Diagram for BikeBike Revolution.

2. Design Procedures and Details

2.1 Power Electronics

2.1.1 Battery:

The 24 V, 10 Ah battery is where the power used in the system is stored. The battery will be connected in parallel so that the Ah will double and the rating will be then 24 V 20 Ah to have better longevity. Depending on if it is in generator, motor, or grid power mode, the battery will take charge from the AC-DC adapter, boost converter, or 120 V outlet, respectively. From full charge, the battery must be able to power the motor for at least 1 hour at 50-250 W range.

2.1.2 Grid Power:

The 120 V AC power supply coming from the standard American outlet will be also utilized in this system as a way of providing a powerful and reliable energy source to the E-Bike if necessary. This source will be directly charging the DC battery on the bike when in grid power mode, and output constant 120±0.5 V AC power

2.1.3 AC-DC Adapter:

An AC to DC power conversion needs to be made in order to connect the 120 V AC grid power to the 24 V battery. We decided to use a 100-240 V AC to 24 V DC adapter for this step as it is the simplest and has easy accessibility for implementation to the rest of the system. The leads of the adapter will also be connected to alligator clips so that the sealed lead-acid (SLA) batteries can be charged safely. It takes in 120±0.5VAC from the outlet and outputs 24 ±1 V DC through the port to the battery.

2.1.4 DC-DC Boost Converter:

DC to DC power conversion will be integral to safely and successfully transfer different voltage ratings between the generator and battery. More specifically, it will convert input voltage from 1-15±1 V DC from the generator and output 24±1 V DC to the battery. A boost converter will be used in order to step up the varying input voltage from the generator to the 24 V that is needed for the battery. The converter includes the LM3478 operational amplifiers and the IRF7807 for the switching element and frequency. We chose a converter over a transformer as it is lighter and more cost effective. Since the output voltage of the converter needs to be at a constant 24 ±1 V, the feedback resistors in the converter should be changed in order for the right value to be outputted. The equation used to find this is shown in the equations below, with out design choosing an 18 Ω resistor to have a 24 V output. The equations and reference design in Figure 3 are from [4].

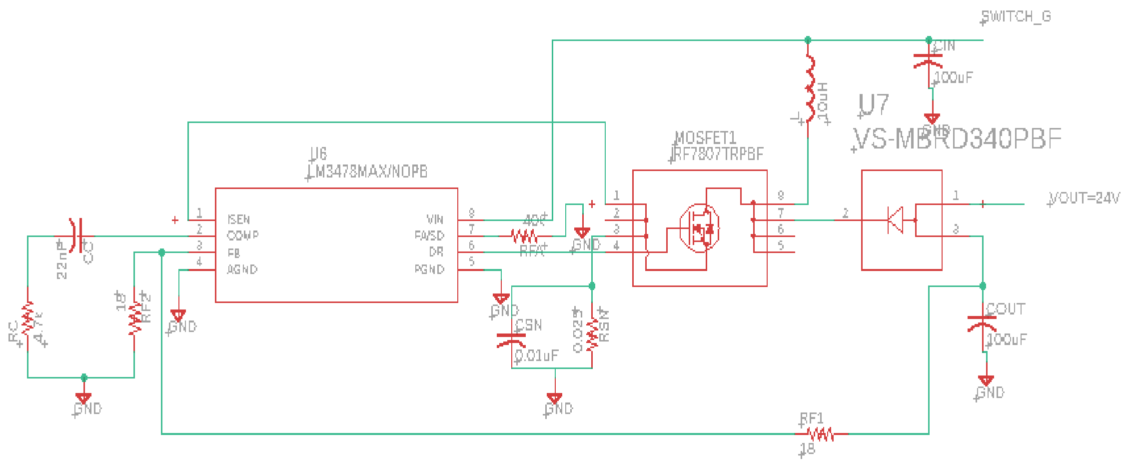

Figure 2. 10-40V to 24 V DC-DC Boost Circuit Schematic.

2.2 Motor / Generator

2.2.1 Motor / Generator:

The motor / generator is a single component determined by the switch to run as a motor or as a generator. We decided to use a 24 V 250 W Brushed DC Electric Motor for this project. In the motor mode, the motor draws power from the battery to drive the rear wheel of the bike. In the generator mode, current is generated as the user pedals and spins the generator. This current is sent out to the DC-DC converter to be stored in the battery.

2.3 Control Module

2.3.1 Microcontroller:

The microcontroller takes in data from the switch, cadence sensor, PWM controller, and current sensor to determine how much power should be supplied to and from the battery. If the switch is in motor mode, the microcontroller allows the battery to supply power to the motor and depending on the frequency output of the cadence sensor, the microcontroller allows more or less power to be supplied by controlling the PWM controller. When the switch is in the generator mode, the microcontroller allows the DC-DC converter to supply power from the generator to the battery. The microcontroller also takes in data from the current sensor as a safety feature to stop the system with a switch if the current goes over the determined threshold for boost converter operation. [5] was also used to help make the pin layout and schematic build of the microcontroller in Figure 4.

The microcontroller with the cadence sensor and PWM controller utilized open-loop feedback control. An alternative was to implement a PI or PID controller, but due to time constraints and priority placed on the hardware components of our design, we decided to stick with open-loop feedback for simplicity.

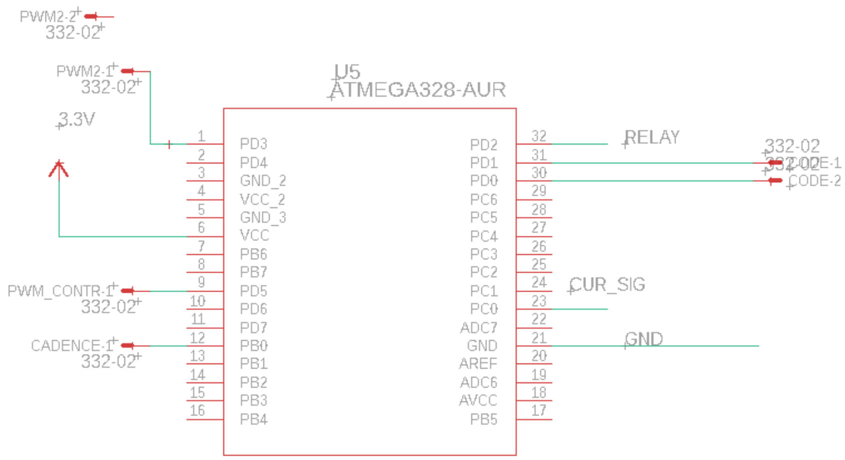

Figure 3. ATMEGA328 Microcontroller Schematic.

2.3.2 Switch:

The switch will consist of one relay and a physical switch to control whether the motor-generator should be functioning as a motor, a generator, or in the off position. In the motor mode, the switch connects the battery to the motor through the PWM controller. While in the generator mode, the switch connects the generator to the battery through the DC-DC converter. In the off position, it does not connect anything and the user can charge the battery directly from the grid. The relay's purpose is to direct electrical signals coming from the microcontroller so that it may safely switch off the system in case the current coming from the motor / generator is beyond the ratings. When the current at the motor / generator is above 10.5 A, the microcontroller sends a low signal to the MOSFET which turns the relay off and disconnects the motor / generator from the circuit. Figure 5 shows the relay schematic inspired by the reference design in [6].

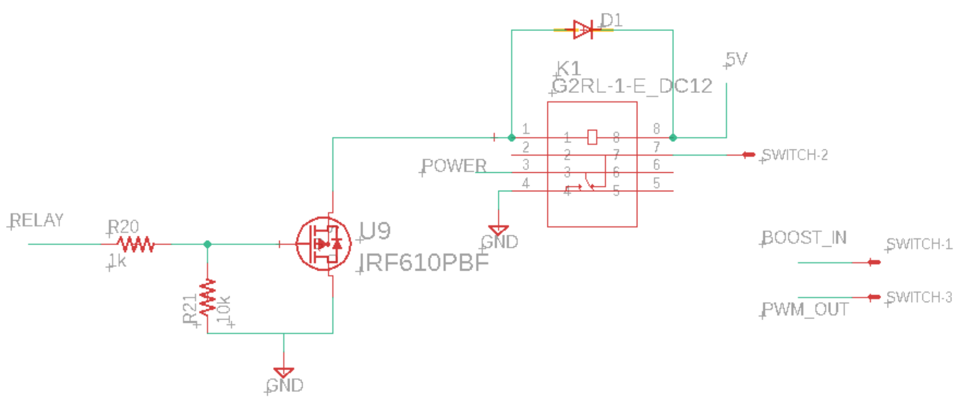

Figure 4. Relay / Switch Circuit Schematic.

2.3.3 PWM Controller:

The PWM Controller is used to control the speed of the motor. The microcontroller generates a PWM signal, which is then taken by the Cytron MD10C which uses an H-bridge to drive the motor. It supports motor voltage range from 5 V to 30 V DC and has maximum current up to 13 A continuous and 30 A peak (for 10 seconds). A simple flowchart is displayed in Figure 6 and seen in [7].

2.4 Sensing Module

2.4.1 Cadence Sensor:

The cadence sensor we will be using is to measure how fast the user is pedaling the bike. This sensor will be mounted on the pedals of the bike. The data from the sensor will be input to our microcontroller to direct the motor in pedal-assist mode, specifically to supply more power when pedaling speed decreases and less power when pedaling speed increases. The sensor outputs frequency, where faster pedal speed corresponds with higher frequency.

2.4.2 Current Sensor:

The current sensor is used as a safety measure in the system and regulates how much current is going in and out of the battery and the motor to make sure the correct amount is being transferred. If the amount of current is greater than 10.5 A, the current sensor will notify the microcontroller to turn off the system through the relays and switch. The current sensor uses the ACS725LLCTR-20AB-T current sensor chip rated for at least 20 A for the battery and generator outputs. It also uses a conductive resistor for low power loss and better capability for higher accuracy of measurement from [9]. Figure 8 shows the given schematic provided by the reference design slightly altered to have higher current rating.

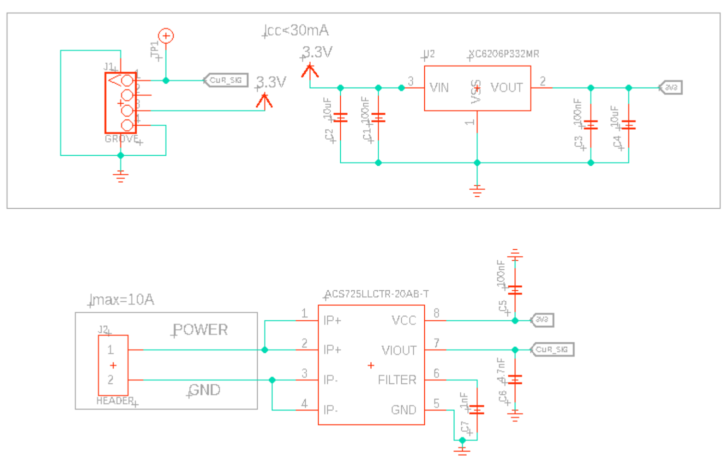

Figure 5. Current Sensor Circuit Schematic.

2.4.3 Battery Life Indicator:

This component includes a voltage sensor which checks the voltage of the battery through a voltage divider and uses four LEDs to show how much charge the battery has left. As the battery life decreases, the voltage also decreases following the battery's voltage curve. The number of LEDs lit up is proportional to the voltage detected. One lit LED corresponds to 25% charge, so all four LEDs lit up means the battery is fully charged. Figure 9 depicts the voltage regulator circuit schematic from [10].

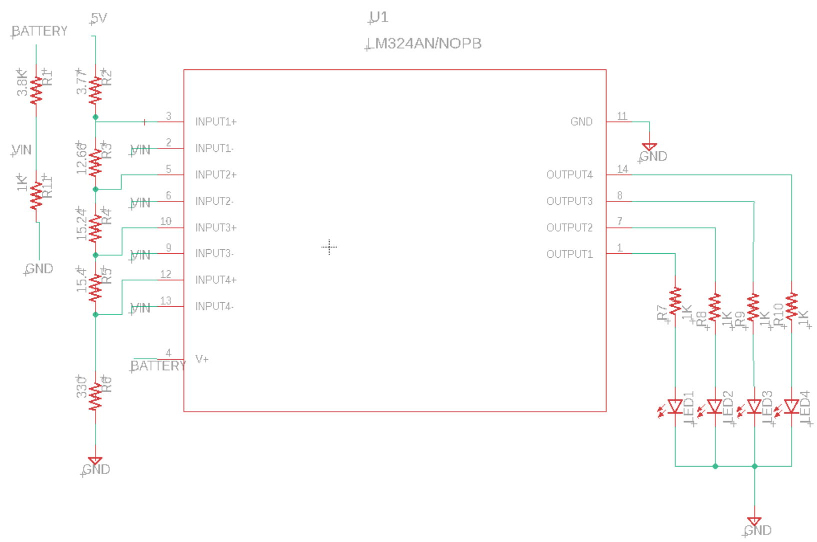

Figure 6. Battery Life LED Indicator Circuit Schematic.

2.5 PCB Layout

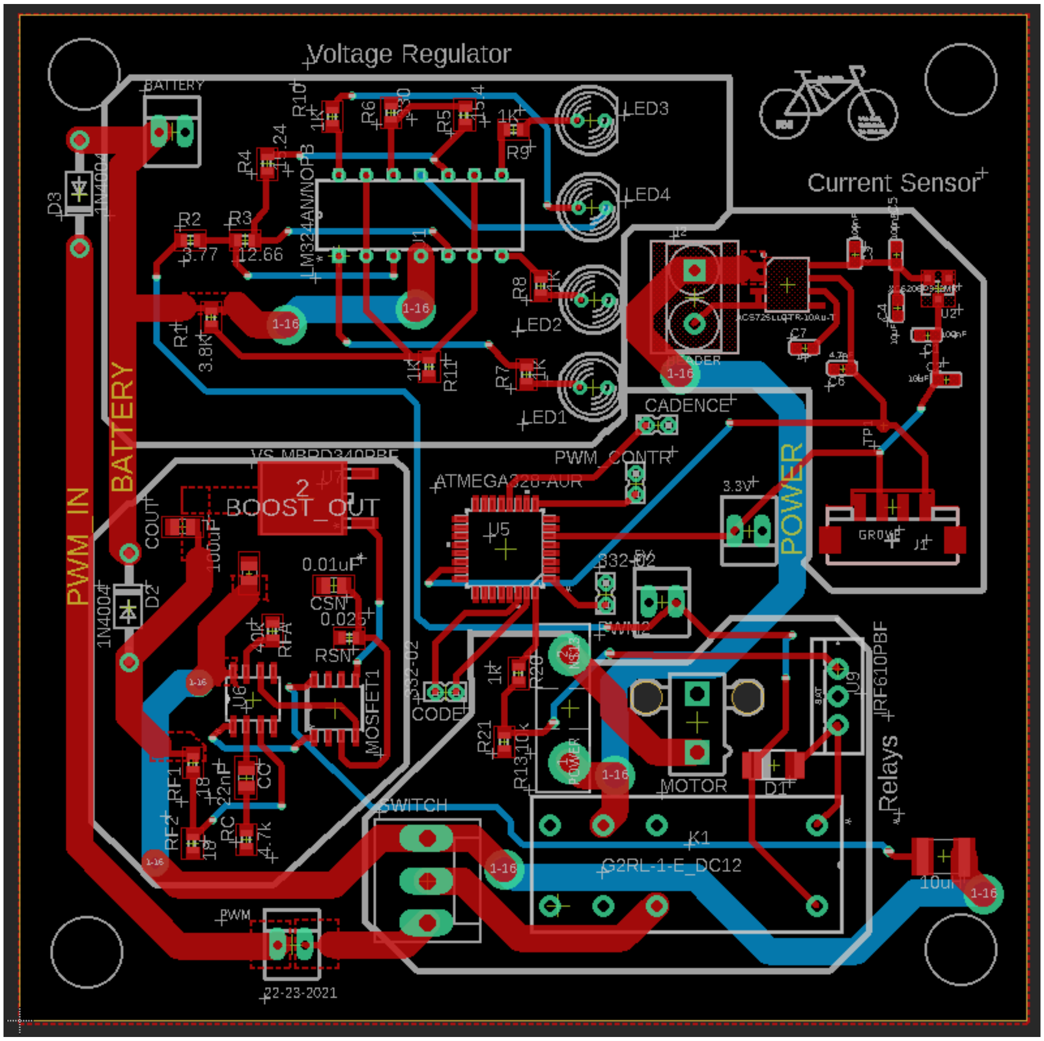

Figure 7. PCB Design of the Components

3. Verification

3.1 Power Electronics

3.1.1 Battery:

Our battery verification process started with connecting the battery to the motor and letting the motor run until the battery is out of charge, which is around 22 V as shown in Figure 8 below. It took about 250 minutes for the whole battery to discharge which satisfies the requirement that it must be able to power the motor for at least one hour. Next, the battery also needs to be charged with the AC-DC adapter, and that was verified through adding clips to the adapter leads and connecting it to the battery leads for direct 24 V DC charging from the wall power in the situation where the user decides to use charging from the grid instead of pedaling if the exercise gets too rigorous but the pedal-assist e-bike functionality is still desired. Finally, our last option that we wanted to verify with the battery was that when the battery is at low charge, we would connect the output of the boost converter to the battery leads to test its charging efficiency. However, with the boost converter not being able to function in time, this portion of the requirement was unfortunately not able to be integrated and tested.

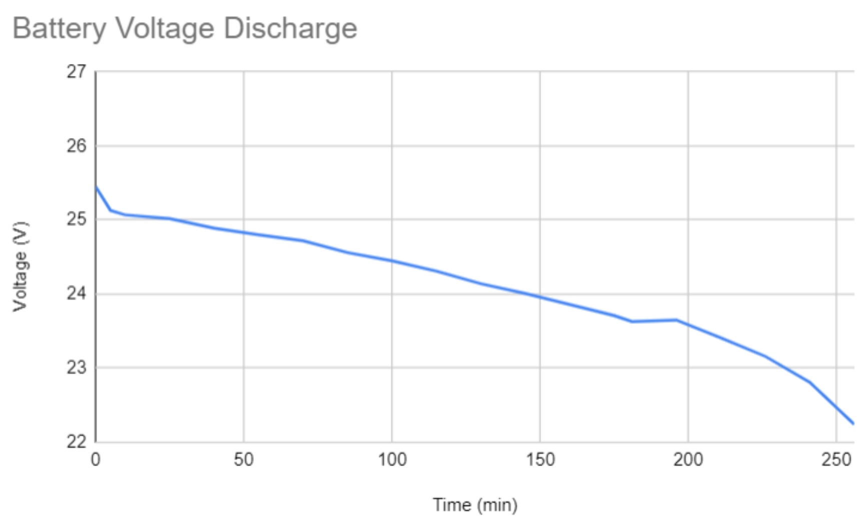

Figure 8. Voltage vs. Time of Battery Discharge

3.1.2 Grid Power and AC-DC Adapter:

The grid power and AC-DC adapter is a simple subcomponent and we verified it by measuring the output terminals of the outlet itself as well as the adapter with a multimeter to confirm the expected values.

3.1.3 DC-DC Boost Converter:

We first verified the boost converter by replicating the reference design from the TI datasheet [4]; using the exact values for the feedback resistors in the schematic. Once we tried the 3.3 V input and the circuit was working with obtaining a 5 V output, we changed the feedback resistor values in order to always achieve a 24 V output on the converter so that it directly charges the battery. The 24 V output comes from calculating that the first feedback resistor value needs to be 18 times larger than the second feedback resistor value as shown in (1).

The efficiency of the boost converter was also calculated by varying the input voltage and testing with 10 V, 15 V, 20 V, and 25 V values and getting around 24 V as the output while also measuring input current and output current. The results are shown in Figure 10 with the relationship between efficiency and input voltage displayed, observing that the efficiency was generally high with low losses. The values could also be slightly inaccurate because the average numbers for the voltages and current were not taken. Ultimately, while we were able to get the boost converter to work in isolation, we could not implement it with the rest of our subsystems as additional LM3478 ICs did not come in time for our demonstration.

$$R_{F2} = \frac{1.26\,V\,(R_{F1})}{(V_{out} - 1.26\,V)}$$

$$R_{F2} = \frac{1.26\,V\,(R_{F1})}{(24\,V - 1.26\,V)}$$

$$R_{F2} = \frac{1.26\,V\,(R_{F1})}{(22.74\,V)}$$

$$R_{F1} = 18\,(R_{F2}) \tag{1}$$

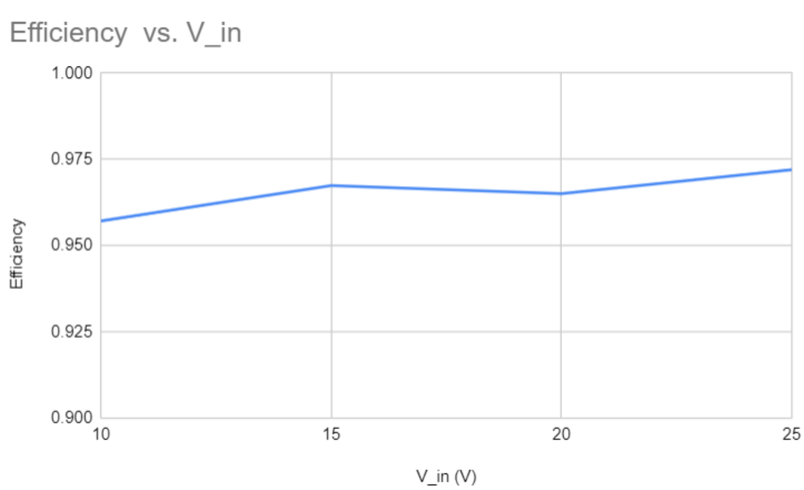

Figure 9. Efficiency vs. Input Voltage Graph for Boost Converter

3.2 Motor / Generator

3.2.1 Motor / Generator:

The motor was tested by connecting it directly to the battery to ensure that it would run at the maximum speed. We then tested the generator capabilities by connecting a 10 Ω load to the positive and negative terminals and measuring the current and voltage output as we increased the pedaling speed.

3.3 Control Module

3.3.1 Microcontroller / PWM Controller / Cadence Sensor:

We tested the PWM controller by connecting it to the voltage supply, motor, and Arduino, and ensuring that different PWM values sent from the Arduino were altering the speed of the motor. We also checked that changing the motor direction worked as expected.

For the cadence sensor, we first tested it by pedaling the bike and confirming that the light on the side of the sensor was lighting up to establish that it was reading data. Next, we connected the output of the cadence sensor to the oscilloscope to determine that the output was a digital signal. We also observed the frequency changes as pedaling speed increased, and measured the frequency values for low, medium, and high pedaling speed. Finally, we tested code that printed out frequency values for the user’s pedaling and checked that the frequency values matched the ones from the oscilloscope.

3.3.2 Current Sensor:

The current sensor was tested by connecting a voltage source, a 10 Ω load, and the sensor itself in series. We were able to calculate the expected current reading by dividing the input voltage of our voltage source by the load’s resistance, and the current sensor was connected to our microcontroller, which displayed the current reading to our computer. Since our current sensor was rated at 13 A to support the rest of our design, it was difficult to test the sensor at our expected design values due to the low limits of the current supply in the lab. We had to include an offset value to the sensor reading, as well as modify its sensitivity.

3.3.3 Switch:

We first tested the MOSFET to see if we could control it with 5 V input from the microcontroller, and then connected with the relay on a breadboard as shown in the schematic to test if the MOSFET could control the relay. 3 V was applied to one terminal of the relay and the other terminal was probed to see if it would output 3 V when the relay was turned on and off. Similarly for the physical switch, 3 V was applied to one terminal and the other three terminals were probed to see when it would output 3 V depending on the switch’s position, where two of the terminals would be the motor mode and generator mode while the third terminal would not be connected to anything and be the off mode.

3.4 Sensing Module

3.4.1 Battery Life Indicator:

The battery life indicator was tested by connecting to a voltage supply and varying the voltage input to the circuit while watching when the LEDs would turn on. We started at 20 V to ensure that all the LEDs were off, and saw that all the LEDs were on because there was an error in the PCB layout where the negative and positive terminals of the op-amps were flipped. This still worked for our design though, since the number of LEDs still indicated the battery voltage. We then incremented the input voltage by 0.1 V to determine exactly when the LEDs would turn off, and saw that it turned off at 21 V, 22 V, 23 V, and 23.8 V which was as expected.

4. Cost and Schedule

4.1 Cost Analysis

The cost of labor for three electrical engineering graduates is estimated to be \$40/hour, 10 hours/week for 12 weeks. The total labor cost would then be \$36,000.

$$3 \text{ graduates} \times \frac{\$40}{\text{hr}} \times \frac{10 \text{ hr}}{\text{week}} \times 12 \text{ weeks} \times 2.5 = \$36,000$$

4.2 Parts

Since we used an existing bike to modify, we only needed to buy the components to assemble the E-bike. The total cost of parts for our prototype was \$270.30. Adding this to the labor cost yields \$36,270.30 for the total development cost.

Part	Cost	Quantity	Total
Electric Motor 24V DC Scooter Motor Brushed Chain Motor (250W 2750RPM)	35.89	1	35.89
24 V, 10 Ah DC Battery	69.99	1	69.99
Cadence Sensor (Amazon, ZOOMPOWER)	18.50	1	18.50
100-240 V AC-24 V DC Power Adapter (Amazon, Shnitpwr)	11.99	1	11.99
Microcontroller - ATMEGA328-AUR (Digikey)	2.40	1	2.40
G2RL-1A-E-HA DC5 Relay (Digikey)	6.80	1	6.80
SWITCH TOGGLE SPDT 15A 125V (Digikey)	11.94	1	11.94
ACS725LLCTR-20AB-T Current Sensor (Digikey)	4.89	3	14.67
LM324 Amplifier (Digikey)	0.55	2	1.10
LM3478MAX/NOPB IC for Boost (Digikey)	2.49	3	7.47
XC6206P332MR-G Linear Voltage Regulator IC (Mouser)	0.67	3	2.01
IRF7807ZTRPBF N-Channel MOSFET (Digikey)	0.69	2	1.38
MBRD340G Schottky for Boost (Digikey)	0.82	2	1.64

Cytron 13A DC Motor Driver MD10C (Amazon)	11.50	3	34.5
USB UART Microcontroller Adapter (Amazon)	5.19	1	5.19
Misc. RCL components (Digikey)	45.00	-	45.00
PCB (JLC PCB)	14.80	1	14.80
Total Amount		27	$270.30

4.3 Schedule

Week	**Gina**	**Shannon**	**Yee Chan**
2/28/21	Continue testing Simulink and Simscape motor system	Order motor, cadence sensor, batteries	Finalize PCB designs and order parts
3/7/21	Work on microcontroller programming for PWM and controls	Check in with ece machine shop on motor, stand, and cadence sensor implementation	Order remaining components needed including passives, transistors, op amps, etc.
3/14/21	Start assembling and soldering PCB components	Start assembling and soldering PCB components	Start assembling and soldering PCB components
3/21/21	Debugging control circuit / microcontroller	Bench test DC-DC power converter	Bench test voltage regulator and current sensor
3/28/21	Debugging power circuit and motor system	Debugging power circuit and motor system	Debugging power circuit and motor system
4/4/21	Implement PCB, cadence sensor, motor, LEDs, and battery	Implement PCB, cadence sensor, motor, LEDs, and battery	Implement PCB, cadence sensor, motor, LEDs, and battery
4/11/21	Test microcontroller code with sensors and PCB	Test hardware system	Test hardware system and continue soldering
4/18/21	Test complete system	Test complete system	Test complete system
4/25/21	Prepare final	Prepare final	Prepare final

	demonstration and final presentation	demonstration and final presentation	demonstration and final presentation
5/2/21	Prepare final presentation and final report	Prepare final presentation final report	Prepare final presentation final report

5. Conclusion

5.1 Accomplishments and Improvements

In this project, we were able to complete the motor mode, where we were able to control how fast the motor was running depending on how fast we were pedaling. The battery supplied power to the PWM control, which determined its duty cycle output with the code in the microcontroller and the cadence sensor input. This duty cycle went through the switch and was sent into the motor, allowing the motor to increase or decrease its speed depending on the duty cycle.

We were also able to test all the components in the generator mode, specifically the boost converter which was able to take in 1-15±1 V DC and outputs 24±1 V DC, but unfortunately one of the component was fried in testing and we couldn't receive a new component in time to finish testing with rest of the components. The current sensor was also able to be tested separately and was able to read current with an accuracy up to ±1 A, but could not be integrated with the rest of the circuit because of an error in the PCB layout where it was connected in parallel to the generator instead of in series. The current sensor was able to be soldered onto a separate PCB though and we were still able to connect it to the microcontroller to turn the relay off when the current sensor detected too much current.

Overall, we were able to get all of our sub components working separately, but if given more time we would have liked to test the generator mode together with all the components as well as modify the PCB to integrate the current sensor. Furthermore, with more time and budget, we could add more functionalities such as a user friendly screen to show detailed statistics of the bike speed and power, or a regenerative brake function built into the motor mode when the physical brakes are activated.

5.2 Ethics and Safety

When designing this project, many factors went into the safety precautions that would be needed in order to finalize a secure product. Elements such as speed and power from the pedal-assist mode and even hazards that could be formed when using the bike in the generation mode can pose as harmful and dangerous to the user when not operated correctly. Regarding the IEEE Code of Ethics, there were some electrical safety issues that came up during testing, and there are possibilities of exposing harm to the general public since our design was for an E-bike [10].

To ensure that the safety of the public is protected and users of our E-bike are aware of any potential dangers associated with it, we planned to inform users on how to properly use the bike and the limitations of the components. Following the Illinois Vehicle Code under Sections 1-140.10, 1-140.15, and 11-1516, our E-bike fell under the "low-speed electric bicycle" category, since our motor was less than 750W [11]. During the testing and design process, traffic accidents and misuse of the bike was not an issue since we mainly tested the bike in the lab.

If excessive voltage is supplied to the motor, this could cause overheating and motor failure. To avoid potential safety issues regarding the components of our E-bike breaking or overheating, we controlled the amount of voltage supplied to the motor, and our design implemented a safety feature to prevent overcurrent for users. However, during our testing process, we were not always diligent about safety measures while utilizing our high voltage battery. For example, when we were assembling all of our components on the bike, we did not keep in mind that the metal frame of the bike could short our components. Although nothing disastrous occurred, this problem could have been avoided. In the future, we will make safety more of a priority in the testing environment.

References

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Appendix A

Requirement and Verification Tables

Requirement	Verification
Battery 1. From full charge, battery must be able to power the motor for at least 1 hour at 50-250 W range 2. Charge at 100% efficiency from the grid through the AC-DC adapter 3. Charge at 25% efficiency from the generator through the boost converter	1. Connect battery to the motor and let the motor run until battery is out of charge 2. Connect the AC-DC adapter and make sure battery is charging 3. With battery at low charge, connect the output of the boost converter to the battery leads to test charging
Grid Power and AC-DC Adapter 1. Outputs constant 120±0.5VAC power 2. Takes in 120±0.5VAC from outlet and outputs 24 ±1 V DC through the port to the battery	1. Measure output terminals with a multimeter to confirm expected value 2. Probe the leads of the adapter using a multimeter to ensure the correct value
DC-DC Boost Converter 1. Converts input voltage from 1-15±1 V DC from the generator and outputs 24±1 V DC to the battery	1. Vary input voltages with voltage supply and measure output with multimeter
Motor / Generator 1. The generator must be able to produce at least 100 W of power	1. Use a multimeter to measure the output of the generator
Microcontroller / PWM Controller / Cadence Sensor 1. Must vary output frequency of signal depending on how fast the bike is being pedaled 2. Take in varying signals from the cadence sensor and determine frequency, which controls PWM controller for the motor speed depending on pedal power 3. Take in signals from current sensor and be able to turn switch off	1. Connect the output of the cadence sensor to an oscilloscope to read frequency while pedaling the bike 2. Connect output of cadence sensor to PWM controller to the battery and motor of the bike, pedal until there is motor assistance on a. PWM = 0 = no assistance b. PWM = 150 = some assistance c. PWM = 255 = full assistance 3. Supply an average current value to the current sensor and see that it turns off the relay
Current Sensor 1. Reads the current output of the motor within ±1 A to be below threshold of 13.8 A	1. With the bike on motor mode, observe the read out from the Arduino current sensor reading at different input voltages in range 1-24 V

Switch 1. Current (rated current of ≤13.8A) can flow from the battery to motor in motor mode 2. Let ≤10.5A from the generator flow in generator mode 3. Signal from microcontroller will tell the switch to turn off at certain current value	1. Set the switch to motor mode then measure with an ammeter that ≤13.8A current is flowing from the battery to the motor 2. Measure with an ammeter that ≤10.5 A current is flowing from the generator to the battery 3. Output a current value, then use an ammeter to show that no current is flowing through the switch
Battery Life Indicator 1. Each LED must light up at its corresponding charge (first LED with 25%, second LED with 50%, third LED with 75%, and all four LEDs at 100%)	1. Use the voltage supply starting at 24V and decrease steadily to 21V and observe the corresponding LEDs light up at the correct voltage level

Appendix B
Code for Cadence Sensor + PWM Control

```
// cadence sensor: need to check frequency and supply power accordingly
signalState = digitalRead(cadenceSensorPin);

// if state has changed
if (signalState != lastSignalState) {
  edgeDetectCounter++;
  stateTimer = millis();
} else {
  pedalTime = millis();
  if (pedalTime > 700 + stateTimer) {      // if no state change after 700 ms, then turn motor off
    pwm_value = 0;
    analogWrite(pwmPin, 0);
    Serial.println("MOTOR OFF");
  }
}


if (edgeDetectCounter == 1) {
  startTime = millis();
} else if (edgeDetectCounter == samplingNum) {
    // calculate frequency
    endTime = millis();
    samplingTime = endTime - startTime;

    freq = 0;
    if (samplingTime != 0) {
      freq = samplePeriods / (samplingTime / thous);        // freq = 1/period
    }
    Serial.print("FREQUENCY in Hz:");
    Serial.println(freq);

    if (freq < 6) {
      pwm_value = 0;
      analogWrite(pwmPin,pwm_value);
    } else if (freq >= 6 && freq < 10) {
      pwm_value = 150;
      analogWrite(pwmPin,pwm_value);
    } else if (freq >= 10) {
      pwm_value = 255;
      analogWrite(pwmPin,pwm_value);
    }

    edgeDetectCounter = 0;
```