Ultra-Capacitor Based Electric Bicycle Regenerative Braking System

A Senior Project

Presented to

The Faculty of the Electrical Engineering Department

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

Of the Requirements for the Degree

Bachelor of Science

By

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Sincerely,
Alex Bronstein

I. BACKGROUND

In the wake of growing concerns over global warming and the risk of up-and-coming oil shortages the automotive, mass transit and rail transport industries are redoubling their efforts to increase fuel efficiency. With advances made in lithium battery technology more vehicles are becoming either partially or completely electrically driven. Diesel powered locomotives have traditionally been diesel-electric drive systems since the 1960's, with diesel generators charging batteries which, in turn, power electric motors for propulsion. This operation allows the diesel generators to operate at max efficiency, negating conversion losses.

Whenever an electric motor is available for propulsion it is also available, to some extent, to provide dynamic or regenerative braking. In the case of regenerative braking current is usually directed into a chemical battery, which is limited in how much current it can accept without degradation. In Japan a privately owned railway company, JR East, installed regenerative braking capabilities into ten diesel-battery hybrid railcars in 2010. JR East expects to see a reduction of 10% in fuel consumption, as well as quieter operation [1].

Recently electric double-layer capacitors (EDLC), also known as ultracapacitors, have dropped dramatically in price and have begun seeing operation in specialized commercial applications. Though they currently are not able to compete with lithium based batteries in terms of energy density ultracapacitors are able to accept large sustained currents reliably and thus have improved power densities. These higher currents allow for potentially more energy to be stored during regenerative braking. The motivation is to achieve +15-20% reductions in fuel consumption by storing this charge in ultracapacitors. According to Siemens, "Energy saving up to 30 % of the supplied energy: e. g. up to 80 t less CO2 -emissions per year and tram"

[2] may be achieved by using their ultracapacitor based Sitras® MES mobile energy storage unit for capturing regenerative braking energy in rail vehicles.

In China SINAUTEC and Shanghai Aowei are testing ultracapacitors in electric buses [3]. These buses are able to charge within 5 to 10 minutes while at special charging stations, as long as the local grid can handle the large, abrupt power transfers. Unfortunately, with full air conditioning they are only able to travel roughly 3 miles on a single charge. The motivation behind these trials is increased efficiency from larger amounts of energy recouped from regenerative braking.

I. INTRODUCTION

Ultracapacitor based regenerative braking applications are currently, for the most part, restricted to hybrid buses and railway cars, where stops are predictable, and space is not too much of an issue. For this experiment these applications were outside of the author's budget, so a smaller scale electric bicycle was used instead, in order to measure ultracapacitors' ability to recoup braking energy.

A 650 Farad Boostcap manufactured by Maxwell Technologies can be purchased by an individual consumer for roughly $60 through distributors such as Tecate Group [4]. The 650 Farad capacitor used in this project is rated for 60 amps of continuous current. Charging a similar sized lithium battery at 20 Amps would not be recommended. The 650 Farad capacitor is about the size of a tangerine.

Figure 1. A 650 Farad Ultracapacitor
Source: Alex Bronstein

Ultracapacitors can also withstand hundreds of thousands of charge cycles without losing their ability to store charge, thus making them more suitable for high stress applications such as regenerative braking. Special considerations need to be taken when using these devices, however.

As opposed to batteries, ultracapacitors behave just like regular capacitors, in that the energy stored in their electric field follows the $E_C = \frac{1}{2}CV^2$ law, where E_C, the energy stored, is in Joules, the capacitance C is in Farads and V in Volts. This means that a "dead" bank of ultracapacitors has a voltage of zero, whereas a "dead" battery typically still retains some voltage near its regular operating voltage.

Moreover, a capacitor with less charge on it is easier to charge, because smaller voltages are needed to transfer charge onto its plates. Therefore for the most energy to be absorbed it is best for the capacitors to have as low of charge state as possible when braking is engaged.

Typical energy densities are listed for lead acid, nickel metal hydride, and lithium ion batteries as well as ultracapacitors in table 1 [5].

Table 1. Energy densities of various storage elements

Storage Element	Energy Density [Wh / kg]
Lead Acid [6]	20-30
Nickel Metal Hydride	40-100
Lithium Ion Battery	+120
Ultracapacitor	5-10

III. DESIGN

The regenerative braking system consists of six fundamental components listed below. These components are arranged as shown in Figure 2.

1. **Electric Motor** – Provides the negative torque necessary to reduce vehicle speed as well as the voltage potential needed to transfer charge into the bank of ultracapacitors.

2. **Control Circuit** – Provides an interface between the user input (ie the brake lever on the bicycle) and the power transfer circuit.

3. **Power Transfer Circuit** – Provides a controllable path for the energy to flow from the motor into the bank of ultracapacitors.

4. **Ultracapacitor Bank** – Provides temporary storage for the energy collected during braking.

5. **Energy Transfer Circuit** – Allows for the energy contained within the ultracapacitor bank after braking to be transferred to the battery bank, allowing for its use in acceleration later.

6. **Battery Bank** – Primary energy storage used for acceleration and auxiliary loads.

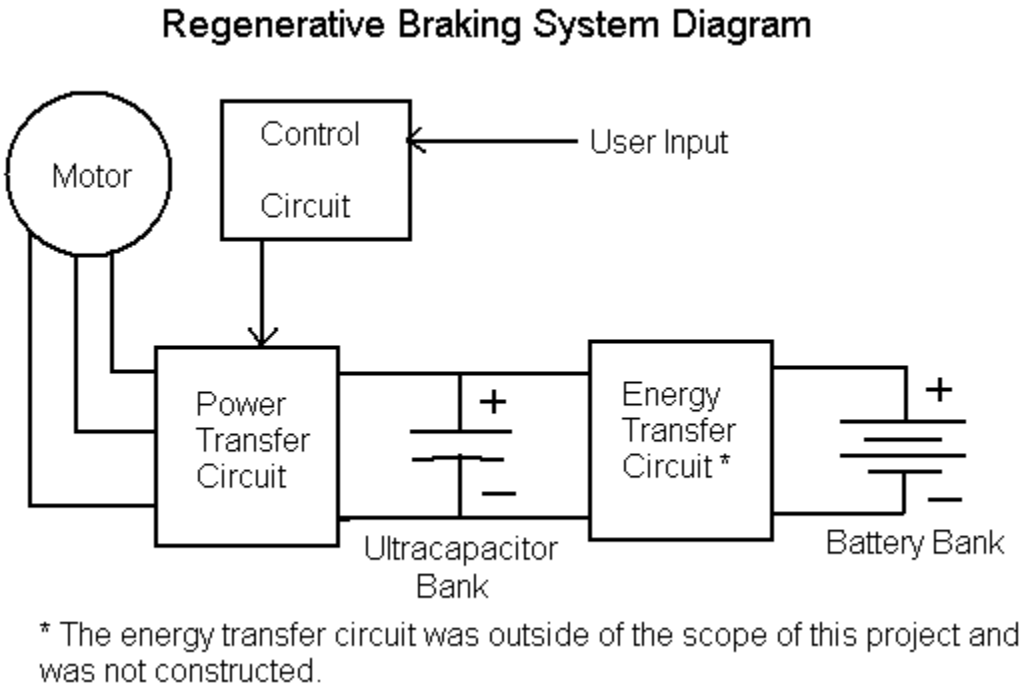

Figure 2. Overall block diagram of regenerative braking system
Source: Alex Bronstein

The Electric Motor

The electric motor used in this electric bicycle is a relatively new style of electric motor known as the Brushless DC Motor, or BLDC motor. In the case of the electric bicycle, the motor is contained inside of the rear wheel, and is known as a hub motor. A cross sectional view of a similar motor is given below.

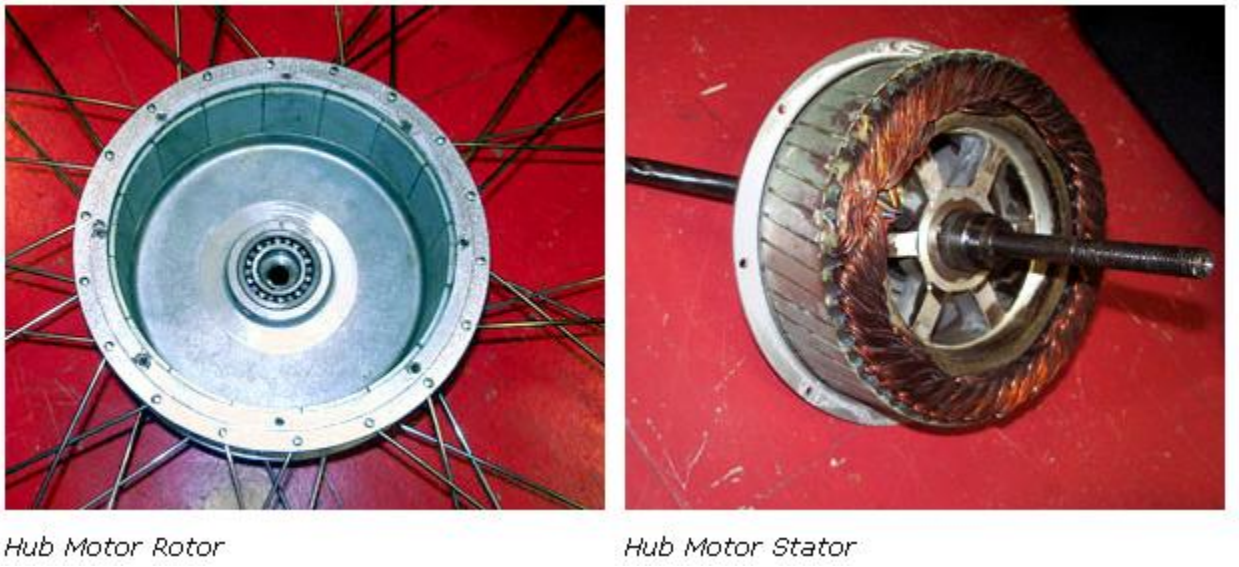

Figure 3. Cross sectional view of a hub motor
Source: www.ebikes.ca [7]

The rotor consists of several permanent magnets while the stator contains three windings representing the three phases of the motor. These motors are similar to 3 phase AC motors, and use sophisticated controllers which switch a DC voltage electronically between the three phases using either power MOSFETs or IGBTs. When the bike is in motion and the motor controller is not supplying power to the motor the BLDC motor behaves as a 3 phase generator, producing sinusoidal voltages at its 3 terminals.

The Control Circuit

The control circuit is responsible for controlling how much current is drawn from the motor during a regenerative braking cycle. This allows the user to brake hard or soft based on how far the brake lever is squeezed. The basic operation is based around a uController from TI called the msp430g2553 which is part of the MPS430 family.

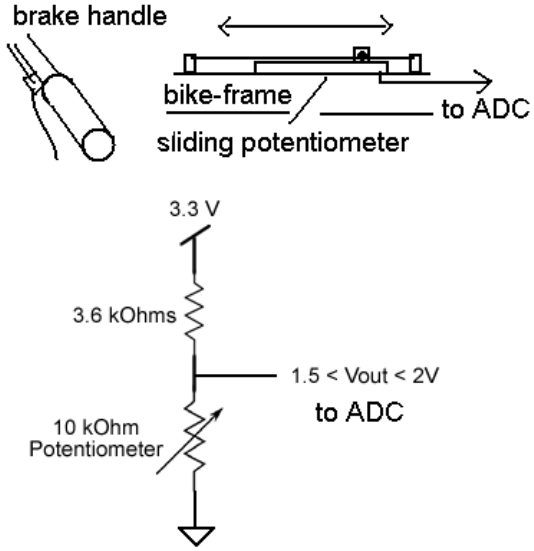

Figure 4. Variable braking scheme.

The uController comes with a built in analog to digital converter, or ADC, which is used to poll the position of the brake lever via a sliding potentiometer. This is depicted in figure 4. The uController continuously polls Vout and adjusts the duty cycle of a PWM signal that it outputs in order to control how much braking power is applied by the user. The PWM signal output is fed into the power transfer circuit. The uController is programmed in C and the code which translates the ADC input into a PWM signal is listed in the appendix. Its ADC can be programmed to reference a 2.5V internal reference voltage which is selectable through a control register. The overall system diagram for the control circuit is depicted in Figure 5 below.

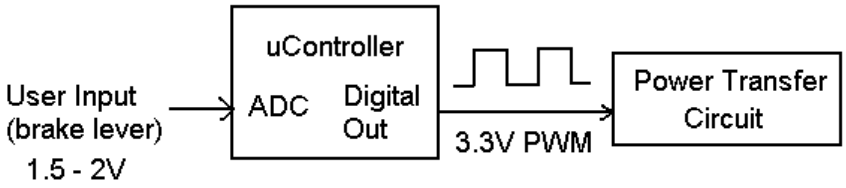

Figure 5. Control circuit signal flow.

The Power Transfer Circuit

The power transfer circuit allows for the current to flow from the motor's windings into the ultracapacitor banks. It achieves this by switching a power FET on and off at 200Hz using PWM. The duty cycle of the PWM is governed by the control circuit. Because the motor's 3 phases generate both positive and negative potentials a 3 phase rectifier is needed to ensure that the capacitors are charged in a positive fashion.

When using a power FET, in this case an NMOSFET, significant gate voltages must be achieved which are not available from the output of the uController. The FET used, an IRFB4332PBF, has a I-V characteristic shown in figure 6. From this graph it appears that for currents above 10 Amps to flow through the FET gate voltages greater than 6 volts are needed. At 200Hz parasitic capacitances from the FET are negligible so a simple inverting buffer was constructed in order to achieve these gate voltages.

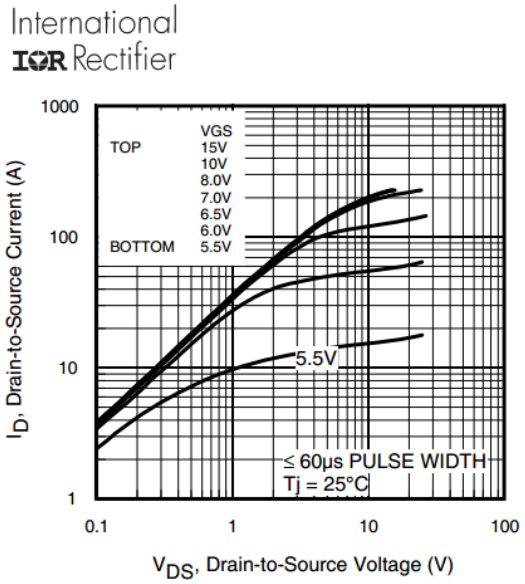

Figure 6. Typical output characteristic for an IRFB4332PBF NMOSFET.
Source: International Rectifier

Extremely important to consider are inductive spikes generated by switching on and off the current through the motor's windings. These inductive spikes can reach into the hundreds of volts and permanently short the drain and source of the FET. In order to handle these transients a metal-oxide varistor can be used across the drain and source of the FET. The varistor selected for the IRFB4332PBF begins to conduct current at 82 Volts, well below the rated V_{DS} of the FET of 250V. This prevents the inductive spikes from becoming large enough to damage the FET because the current in the windings can make its way through the Varistor and cause a less abrupt change in the magnetic flux surrounding the windings. A typical output characteristic of metal oxide varistor is given in Figure 7. An overall diagram of the power transfer circuit is given below in Figure 8.

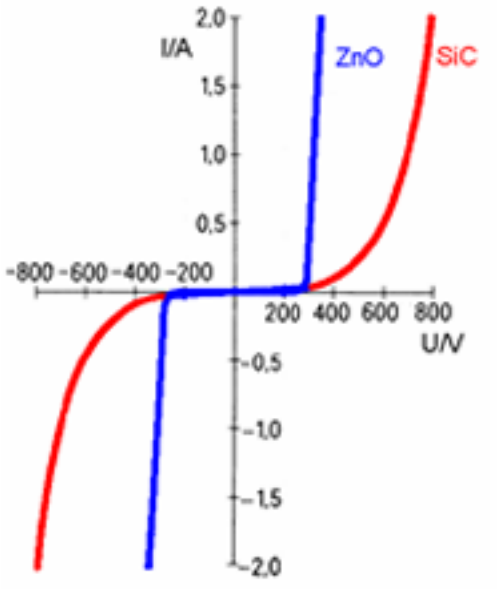

Figure 7. Typical output characteristic for a metal oxide varistor, or MOV
Source: Wikipedia

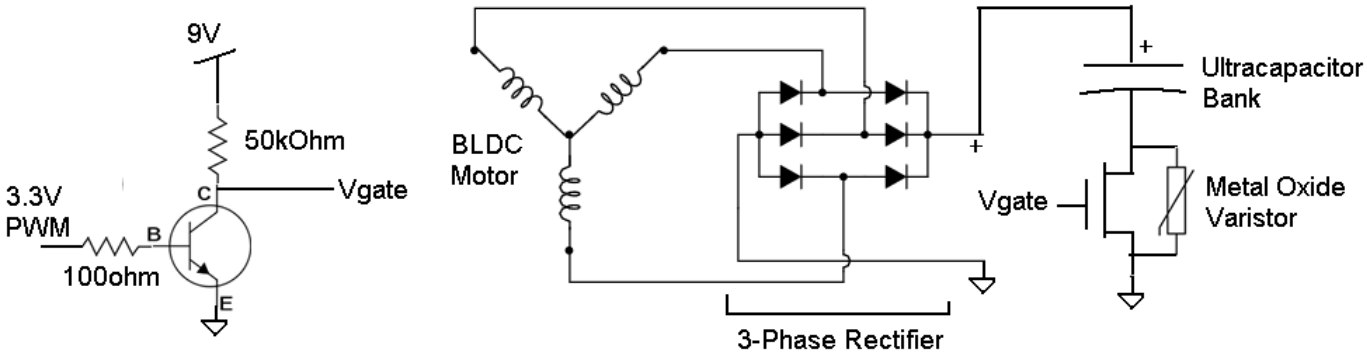

Figure 8. Circuit schematic of energy transfer circuit.
Source: Alex Bronstein

At lower speeds the rectified voltage at the output of the 3-phase rectifier decreases. In order to maximize the amount of braking energy recovered it is best for the capacitors be charged at lower voltages. A DC-DC boost to extract braking energy at lower speeds was considered for this project, though it was ultimately deemed unnecessary. The boost circuit and the energy transfer circuit were outside the scope of this project.

The Ultracapacitor Bank

Six 650 Farad ultracapacitors from Maxwell were arranged in series. Each capacitor is rated for 2.7 volts so that the entire bank can operate up to 16 volts. This is depicted in figure 9 below. A maximum series resistance of 0.8 mΩ is present in each cell, giving the six of them in series a maximum resistance of 4.8 mΩ.

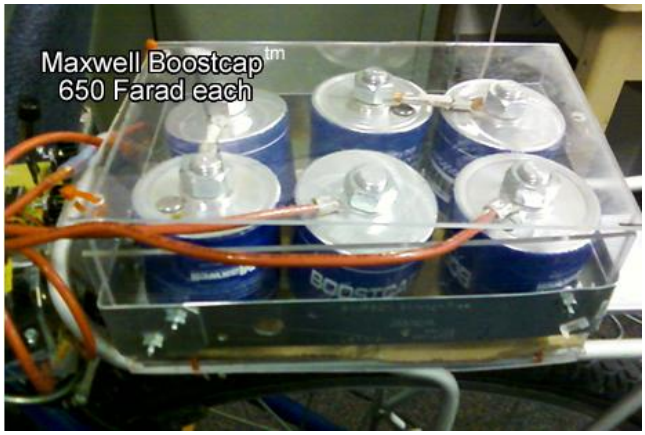

Figure 9. Ultracapacitor bank
Source: Alex Bronstein

The total bank has a total capacitance of 650/6 = 108 Farads allowing it to hold a maximum of $E = ½ CV^2 = 13kJ$. Each capacitor is rated for sustained currents up to 88amps.

The energy needed to stop the bicycle's speed from 25mph, or 11.76 m/s is calculated to be:

Vehicle + Driver mass = 135 kg

Instantaneous Energy = $½ mv^2 = 9.3kJ$

If the regenerative braking circuit can capture roughly half of that instantaneous energy or 4.67 kJ over a period of 4 seconds then the power needed to be absorbed by the capacitor bank would be 4.6 kJ/4 s = 1.15 kW At 30V this results in currents approaching 40Amps.
It is important to note that capacitor bank used for these tests would only be able to hold enough energy for 3 to 4 of these hypothetical stops. This issue would be overcome by an energy transfer circuit which would charge the batteries with this captured energy with a reduced current over a longer period of time.

IV. CONSTRUCTION

Figure 10 depicts the entire bicycle assembly. The controller that came with the motor is a Crystalyte 3640 BLDC controller which operates at 36 Volts and 40 Amps producing roughly 1000W of useable power. Three 12Volt gel cell batteries were combined in series to produce the 36 volts needed.

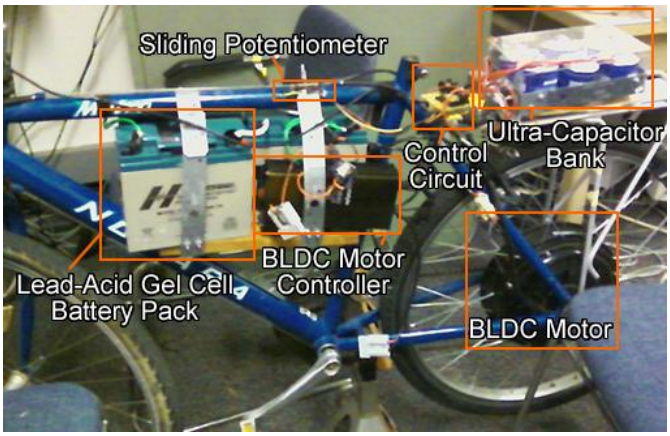

Figure 10. Entire bicycle construction used for testing
Source: Alex Bronstein

Figures 11 and 12 show the control circuit and the power circuit, which were mounted onto the same prototyping board. The LM317 regulator was used to produce the 3.3V needed for the uController. Resistor values of 120Ω and 200Ω were used to set the regulator to 3.3V. The sliding potentiometer also uses this 3.3V as its power rail. The control and power circuitry were powered by a 9V battery.

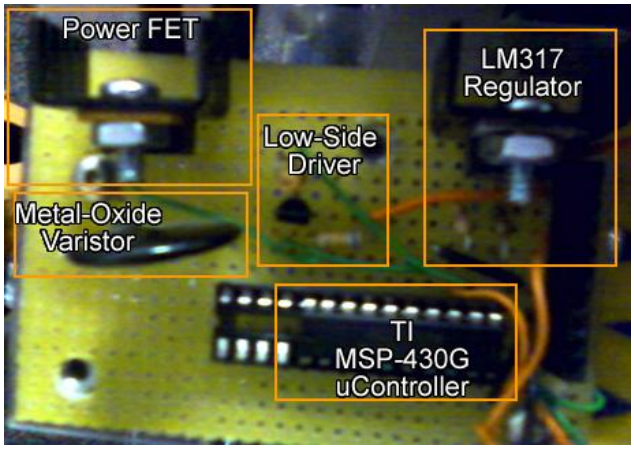

Figure 11. Prototyping board with control and power circuits.

Source: Alex Bronstein

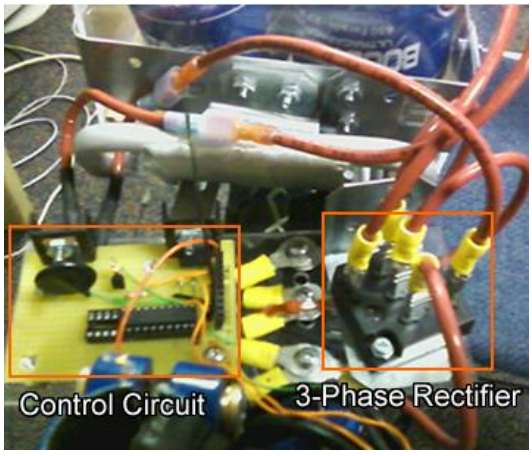

Figure 12. Prototyping board with 3 phase rectifier.

Source: Alex Bronstein

V. TESTING

Testing was done outdoors on a flat section of street following a relatively steep hill outside of Poly Canyon Village. Maximum speeds of 22mph +/- 2mph were reached and full throttle regenerative braking was applied until the bicycle slowed to 7mph +/- 2mph. Three trials were conducted using a bicycle tachometer and a stop watch.

The capacitor bank's initial and final voltages were recorded in order to assess the amount of energy captured. Mechanical braking was engaged in order to reach a complete stop using an alternate braking lever.

Vehicle + driver mass = 135 kg

Kinetic Energy: $KE = \frac{1}{2} mv^2$ (m is mass in kg, v is velocity in m/s) (1)

Capacitor Energy: $E_{CAP} = \frac{1}{2} CV^2$ (C is capacitance in Farads, V is capacitor voltage in Volts) (2)

Capacitor Charge: $Q_{CAP} = CV$ (C is in Farads, V is in Volts, Q is in Coulombs) (3)

Table 2. Initial and final velocities, capacitor voltages and stopping times.

Trial	Initial Velocity [m/s]	Final Velocity [m/s]	Initial Cap Voltage [V]	Final Cap Voltage [V]	Stopping Time [s]
1	9.287	2.235	0.8	4.2	13.8
2	8.941	3.129	1.1	4.1	12.4
3	9.835	3.129	1.2	4.3	12.6

Table 3. Initial and final energies and overall braking efficiency.

Trial	Initial Kinetic Energy [kJ]	Final Kinetic Energy [kJ]	ΔKE [kJ]	Initial Cap Energy [J]	Final Cap Energy [kJ]	ΔE_{CAP} [J]	% of Energy Captured
1	5.822	0.337	5.485	34.6	952.6	918.0	16.74
2	5.396	0.661	4.735	65.3	907.7	842.4	17.79
3	6.529	0.661	5.868	77.8	998.5	920.7	15.69

Table 4. Initial and final capacitor charge and average current while braking.

Trial	Initial Charge [C]	Final Charge [C]	ΔQcap [C]	Average Current [A]
1	86.4	453.6	367.2	26.61
2	118.8	442.0	324.0	26.13
3	129.6	464.4	334.8	26.57

Example calculations:

Initial Kinetic Energy = ½ mv^2 = ½ * 135kg * (9 m/s)^2 = 5.47 kJ

Final Kinetic Energy = ½ mv^2 = ½ * 135kg * (2.2 m/s)^2 = 0.326 kJ

$\Delta KE = KE_O - KE_F$ = 5.47kJ – 0.326 kJ = 5.14 kJ

Initial Capacitor Energy = ½ CV^2 = ½ * 108F * (0.8 V)^2 = 34.6 J

Initial Capacitor Energy = ½ CV^2 = ½ * 108F * (4.2 V)^2 = 952.6 J

$\Delta E_{CAP} = Ecap,_F - Ecap,_O$ = 952.6 J – 34.6 J = 918.0 J

Initial Capacitor Charge = CV = 108F*0.8V = 86.4 Coulombs

Initial Capacitor Charge = CV = 108F*4.2V = 453.6 Coulombs

$\Delta Qcap = Q_F - Q_O$ = 453.6 - 86.4 = 367.2 Coulombs

Stopping Time = t_{stop}= 13.8 seconds

Average Current = $\Delta Qcap / t_{stop}$ = 367.2 Coulombs / 13.8 seconds = 26.6 Amps

System efficiency: (100%)* $\Delta E_{CAP} / \Delta KE$ = 0.918kJ / 5.14 kJ = 16.74 %

VI. BUDGET

item	quantity	price per unit	total
Power NMOSFET IRFB4332PBF-ND	1	$4.29	$4.29
Sliding Potentiometer 10kOhm	1	$2.38	$2.38
TI MSP430 LaunchPad	1	$4.35	$4.35
50A Bridge Rectifier	1	$13.75	$13.75
Panasonic 82V Varistor ZNR	1	$3.33	$3.33
Prototyping PC Board	1	$4.68	$4.68
14 POS Socket IC	1	$0.96	$0.96
2N222 NPN BJT transistor	1	$0.10	$0.10
Assorted Resistors	4	$0.10	$0.40
Ring Terminals*	12	$2.00	$24.00
Maxwell Boostcap 650 F Ultracapacitors*	6	$63.00	$378.00
3ft wire, 4 gauge	1	$5.00	$5.00
		total:	$441.24

*These items were donated by Bonderson project funding

VII. CONCLUSION AND RECCOMENDATIONS

The regenerative braking efficiencies ranging from 15-8% (as listed in Table 2) are an improvement on the 10% efficiency target of most commercial systems. However, looking at the price tag of $441, it's clear that installing this system on an electric bicycle is not economical based on the increase range it provides.

With the gel-cell lead acid battery pack used a range of about 10 miles was achieved, depending on how hard the user pushes the motor. With frequent regenerative braking one could hope to extend this range to about 11-12 miles. An enthusiast may want to build their own capacitor based system for testing purposes, but investing in a lighter lithium ion pack and a controller with pedal assist functionality would be the more economical choice at the moment.

The price of ultracapacitors may come down in the near future making small scale systems like this possible. The 650 Farad cells used where fairly large and took up a lot of space on the back of the bicycle as well.

This is not to discount the usefulness of ultracapacitors in larger scale applications such as trains or even passenger vehicles. The long term benefits of using ultracapacitors are that they can be cycled 500,000 to 1 million times thus requiring little to no maintenance over the lifetime of the vehicle they were used. If a company or municipality were to invest in them for heavy use applications such as public transit, shipping or garbage collection they could quite possibly transfer capacitor banks from retiring vehicles to new fleets over the course of decades. The increased amperage allowed by the ultracapacitor banks may also help reduce

the amount of batteries needed onboard these vehicles by providing extra power when needed and the ability to recover more energy from braking during hard stops.

Improvements to the system built in this project would be to use smaller capacitors such as 350F ultracaps. This would allow for craftier placement on the bicycle. Implementation of an energy transfer circuit between the capacitors to the battery to allow for realistic testing. An example route through a city would also be needed to evaluate the system's overall feasibility. An LM3578AN switching regulator may be used for this application; however its maximum switching current is only 750mA. Energy transfer between the capacitors and batteries would not be recommended while the batteries are supplying power to the motor, as well.

Overall, purely electric vehicles use energy very efficiently to begin with; therefore, regenerative braking does not always provide an important contribution to efficiency. Onboard large vehicles such as trains or busses these efficiency gains made by introducing capacitive regenerative braking can add up over the long-term to pay for the initial investment in the relatively expensive ultracapacitor technology. On trains where electrical braking is already used, but dissipated through resistors, this makes particular sense.

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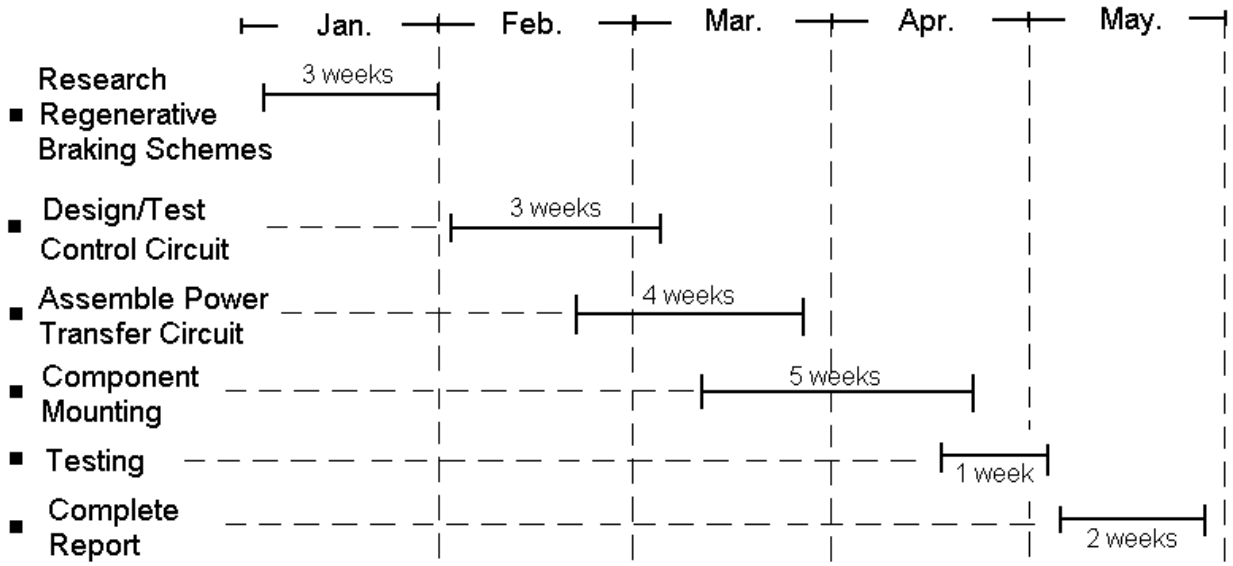
Appendix A – MSP430g2553 uController code.

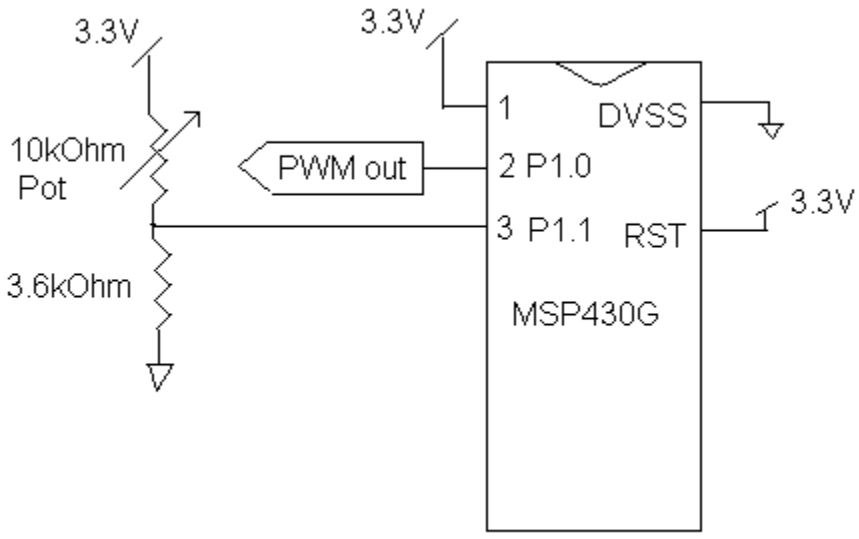
```
//Author: Alex Bronstein
//Date: May 2012
//Description:  Inputs analog brake lever voltage and converts
//                      it into a PWM signal on the output.  References 2.5V
//                      for A/D conversion

      #include <msp430g2553.h>

      // Delay function:  for 1ms ->> count = 109
      void delay(volatile unsigned int count)
      {
         do count--;       while (count != 0);
      }

      //PWM Function
      // for 100% x = 540
      // for 0%   x = 0
      // for 50%  x = 270
      void PWM(volatile unsigned int x)
      {
            P1OUT = 0x01; //P1.0 set
            delay(x);
            P1OUT = 0x00; //P1.0 clear
            delay(540-x);
      }

      void main(void)
      {
      WDTCTL = WDTPW + WDTHOLD; // Stop watchdog timer
      P1DIR  |= 0x01; // Set P1.0 to output direction

      ADC10CTL0 = SREF_1 + ADC10SHT_2 + REFON + ADC10ON + ADC10IE;
      ADC10CTL0 |= REF2_5V;
      __enable_interrupt();                     // Enable interrupts.
      TACCR0 = 30;                              // Delay to allow Ref to
                                                   settle
      TACCTL0 |= CCIE;                          // Compare-mode interrupt.
      TACTL = TASSEL_2 | MC_1;                  // TACLK = SMCLK, Up mode.
      LPM0;                                     // Wait for delay.
      TACCTL0 &= ~CCIE;                         // Disable timer Interrupt
      __disable_interrupt();
      ADC10CTL1 = INCH_1;                       // input A1
      ADC10AE0 |= 0x02;                         // PA.1 ADC option select

      volatile unsigned int dutyCycle[] =

      {1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,10,20,30,40,50,60,70,80,90,

      100,110,120,130,140,150,160,170,180,190,200,210,220,230,240,250,260,

      270,280,300,310,320,330,340,350,360,370,380,390,400,410,420,430,

      440,450,460,470,480,490,500,510,539,530,539,539,539,539,539,539,539};

volatile signed int dc = 0;
      volatile signed int temp = 0;
```

```
            while (1) // Infinite Loop
            {
                  ADC10CTL0 |= ENC + ADC10SC;
// Sampling and conversion start
                  __bis_SR_register(CPUOFF + GIE);
// LPM0, ADC10_ISR will force exit

                  //PWM Function
                  // for 100% x = 540
                  // for 0%   x = 0
                  // for 50%  x = 270
                  if(1)
                  {
                        temp = dutyCycle[(ADC10MEM/7)-55];
                        dc = temp;
                        PWM(dc) ;
                  }
            }
                        //P1.0 - OUTPUT
} //end main

// ADC10 interrupt service routine
#pragma vector=ADC10_VECTOR
__interrupt void ADC10_ISR (void)
{
  __bic_SR_register_on_exit(CPUOFF);        // Clear CPUOFF bit from 0(SR)
}

#pragma vector=TIMER0_A0_VECTOR
__interrupt void ta0_isr(void)
{
  TACTL = 0;
  LPM0_EXIT;                                // Exit LPM0 on return
}
```

Appendix B – Project Timeline



Appendix C. Circuit Diagrams



MSP430G uController Configuration for continuous operation.

Appendix D. SENIOR PROJECT ANALYSIS

Project Title: Ultra-Capacitor Based Electric Bicycle Regenerative Braking System

Student's Name: Alex Bronstein

Student's Signature:

Advisor's Name: Art MacCarley

Advisor's Initials:

Date: June 1, 2012

• Summary of Functional Requirements

To recover as much kinetic energy as possible in the form electric fields within a capacitor bank onboard an electric bicycle using a linear regenerative braking circuit.

• Primary Constraints

- Limited space on bicycle for mounting electronics, along with batteries and motor controller.
- Limited time to build and test project, due to team member issues outside of the EE dept.
- Access to oscilloscope for testing. (This was taken care of thanks to Jaime Carmo, however)
- Unfamiliar coding environment with new uController

• Economic

• What economic impacts result?

The largest economic impact of vehicles implementing robust regenerative braking mechanisms would be the reduced consumption of fuels onboard these vehicles. As different fuels become scarcer the price of fuels will rise, making mass transit and rail transport more expensive. By reducing the amount of fuel needed to move goods and people consumer goods may be less subject to inflation due to increases in transportation costs. More jobs may also be available to more people who depend on these modes of transport to commute to work. Moreover, when fuel is used more efficiently any parts of the economy which depend on transport (i.e. agriculture, tourism, textiles, etc) become more economical.

• When and where do costs and benefits accrue throughout the project's lifecycle?

A regenerative braking system based on ultracapacitors accrues nearly all of its costs upfront, with a very large portion of the costs coming from the ultracapacitors. For this project the capacitors made up 85% of the total budget of $441. The fuel savings depend greatly on how often the vehicle engages the regenerative braking system, and the price of fuel used to operate the vehicle. For an electric vehicle, the price of electricity is relatively cheap compared to gasoline, making the vehicle already fuel efficient in the monetary sense. This may hurt the argument for an expensive regenerative braking system, especially if the onboard batteries are large enough to accept the high currents needed. However, in a diesel bus, which is equipped with a hybrid drive system, regenerative braking may greatly increase the amount of miles per gallon it gets, especially in a situation where there are several stops along its route.

• What inputs does the experiment require? How much does the project cost? Who pays?

For testing, the experiment required a user input in order to control the brake throttle while at sufficiently high speeds. The project would theoretically cost around $441 if the ultracapacitors were bought new. Because they were donated, and the students in charge of the donated funds chose to purchase them from Ebay, the ultracaps were bought at $35 a piece, instead of $60. This brought the actual total budget down to $273.

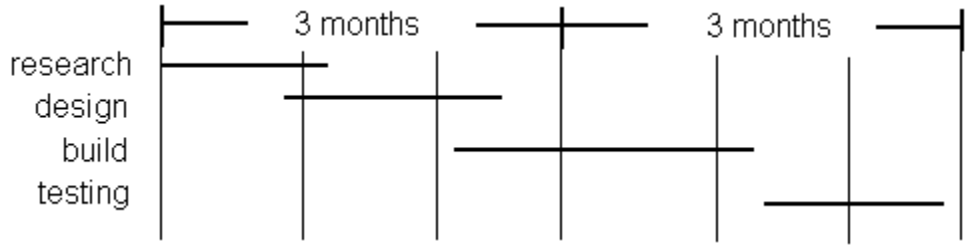
Original estimated cost of component parts (as of the start of your project). $50 ($430 with ultracaps)
Actual final cost of component parts (at the end of your project) $63 ($441 with ultracaps)
Attach a final bill of materials for all components.

item	quantity	price per unit	total
Power NMOSFET IRFB4332PBF-ND	1	$4.29	$4.29
Sliding Potentiometer 10kOhm	1	$2.38	$2.38
TI MSP430 LaunchPad	1	$4.35	$4.35
50A Bridge Rectifier	1	$13.75	$13.75
Panasonic 82V Varistor ZNR	1	$3.33	$3.33
Prototyping PC Board	1	$4.68	$4.68
14 POS Socket IC	1	$0.96	$0.96
2N222 NPN BJT transistor	1	$0.10	$0.10
Assorted Resistors	4	$0.10	$0.40
Ring Terminals*	12	$2.00	$24.00
Maxwell Boostcap 650 F Ultracapacitors*	6	$63.00	$378.00
3ft wire, 4 gauge	1	$5.00	$5.00
		total:	$441.24

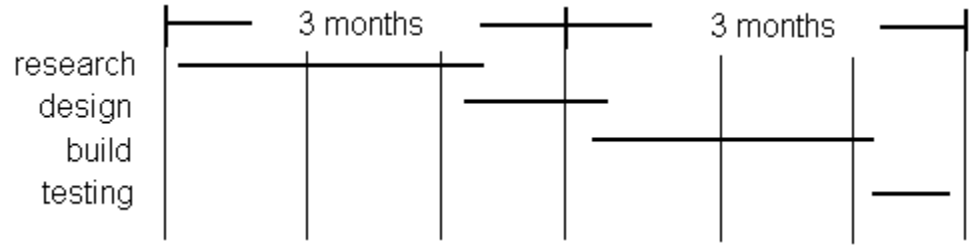
Additional equipment costs (any equipment needed for development?)
• How much does the project earn? Who profits?
If the energy transfer circuit (between the caps and batteries) was included at a cost of $30 and the entire system was marked up by 15% for resale then the profit on each bicycle system would be $70. However was manufacturing these systems would profit.

• Timing
When do products emerge? How long do products exist? What maintenance or operation costs exist?
This project would be a consumer grade product that could theoretically last the user as long as the lifetime of the bicycle system. Any failures would typically occur onboard the PCB, and be due to heavy vibrations. Replacing this PCB may cost $60-70, though they may be able to be repaired at a lower cost.

Original estimated development time (as of the start of your project), as Gantt or Pert chart



Actual development time (at the end of your project), as Gantt or Pert chart



What happens after the project ends?

• If manufactured on a commercial basis:
• Estimated number of devices sold per year
10-20
• Estimated manufacturing cost for each device
$440
• Estimated purchase price for each device
$550
• Estimated profit per year
$1500
• Estimated cost for user to operate device, per unit time (specify time interval)
$110/yr over the course of 5 years.

• Environmental
• Describe any environmental impacts associated with manufacturing or use, explain where they occur and quantify.
The effects associated with construction of small PCB electronics would be part of this product. Any chemicals used by TI to produce the uController as well as the other semiconductor devices used in this product would constitute environmental impacts. The ultracapacitors use activated carbon, which is not known to be very toxic or hard to recycle.
• Which natural resources and ecosystem services does the project use directly and indirectly?
The activated carbon used in the capacitors can be derived from coconut shells. The semiconductor devices use crystallized silicon as well as dopants such as Boron, Arsenic and Phosphorus.
• Which natural resources and ecosystem services does the project improve or harm?
The regions where the semiconductors are produced are impacted the most by damaged waterways. This project aims to improve fuel efficiency in vehicle transport. By decreasing fuel consumption this project aims to reduce the amount of mercury, CO, CO_2, NO_x and particulates in the atmosphere.
• How does the project impact other species?
No direct impact on species would be associated with this project, outside of the manufacturing process of the devices used.

• Manufacturability
• Describe any issues or challenges associated with manufacturing.
Creating a container to house the capacitors so as to fit on a variety of bicycles would be the most difficult part. The electronics and the capacitors could all be housed in a single box. Installers would need to modify their existing wiring to interface with their motor's 3 phases.

• Sustainability

• Describe any issues or challenges associated with maintaining the completed device, or system.

A protective circuit should be added in order to prevent the capacitor bank from reaching voltages above their rated voltage. If the capacitor bank is reliably protected then only component failure in the PCB would need to be checked on.

• Describe how the project impacts the sustainable use of resources.

This project aims to reduce fuel consumption onboard a variety of vehicles. If less fuel can be used to achieve the same economic results then emissions will also be less, and prolong the climate that most life forms on Earth are adapted to.

• Describe any upgrades that would improve the design of the project.

An energy transfer circuit between the capacitors and batteries is needed. This circuit should be able to handle 1-3 amps. Capacitor over-voltage protection circuitry is recommended to prevent the capacitor bank from being damaged by voltages above their 2.7 Volts, though this may not be needed except in situations involving repeated, heavy braking. A display of system performance would also be interesting to some users.

• Describe any issues or challenges associated with upgrading the design.

More terminals and connectors would be needed to interface the protective circuitry, the energy transfer circuit and panel display. Further testing would be needed to insure that the energy transfer circuit could reliably charge the batteries when not in use automatically, without user input.

• Ethical

• Describe ethical implications relating to the design, manufacture, use, or misuse of the project.

This product operates at low voltages (2-15V) and would be fairly harmless if misused. The manufacturing process is straightforward, with soldering be the most dangerous step. Overall this product aims to boost fuel efficiency and would be difficult to cause any physical damage with.

• Health and Safety

• Describe any health and safety concerns associated with design, manufacture or use of the project.

The workers assembling the PCBs risk breathing solder fumes if the facility is not well ventilated. Otherwise, only standard crimping and assembling techniques would be used.

• Social and Political

• Describe social and political issues associated with design, manufacture, and use.

If this product were to be manufactured by hand by low-skill workers, particularly overseas, the amount of worker compensation the employees assembling the components may become a social and political issue. This product would likely be purchased by electric bicycle enthusiasts and may collect a few awkward glances from people around town.

• Who does the project impact? Who are the direct and indirect stakeholders?

This project impacts electric bicycle owners directly by increasing their bicycle's range. Indirectly it explores the use of capacitive regenerative braking in vehicles which have electric motors onboard. This would ultimately impact the makers of automobiles, trains and mass transit systems. Stakeholders would include gasoline and natural gas producers as well as electric utilities.

• How does the project benefit or harm various stakeholders?

The operators of these vehicles would benefit from reduced fuel consumption. Gasoline and natural gas companies *may* see a dip in demand due to large scale implementations of these systems. If consumer goods are delivered onboard systems which become more efficient the price of these goods may become slightly lower with reduced shipping rates.

• To what extent do stakeholders benefit equally? Pay equally? Does the project create any inequities?

This product modestly benefits the operators of hybrid, and all electric vehicles. It does not harm any parties directly.

• Consider various stakeholders' locations, communities, access to resources, economic power, knowledge, skills, and political power.

In cities where large busses can increase emissions, hybrid electric drives would be welcome. Communities where products are brought in primarily by rail would also benefit from this product. This product would not play a significant part in economic power, or political power, as its effects are only to increase fuel efficiency.

• Development

• Describe any new tools or techniques, used for either development or analysis that you learned independently during the course of your project. Include a literature search.

This project dealt with currents much larger than previously experienced in the laboratory. Dealing with large transients created by switching high currents through inductive loads was the most important lesson learned. Prototyping circuits to reliably handle vibrations onboard a vehicle was also needed. Several wiring techniques were also learned to deal with the large wires needed to handle the associated currents. A laser cutter was also used to create a box housing the ultracapacitors out of clear plastic sheets.