4-2-2010

Implementation and Performance Evaluation of a Regenerative Braking System Coupled to Ultracapacitors for a Brushless DC Hub Motor Driven Electric Tricycle

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For the degree of Master of Science

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IMPLEMENTATION AND PERFORMANCE EVALUATION OF A REGENERATIVE BRAKING SYSTEM COUPLED TO ULTRACAPACITORS FOR A BRUSHLESS DC HUB MOTOR DRIVEN ELECTRIC TRICYCLE

A Thesis

Submitted to the Faculty

of

Purdue University

by

Sandun Shivantha Kuruppu

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

May 2010

Purdue University

West Lafayette, Indiana

To my mother, father & brother for being with me, every step of the way …!

ACKNOWLEDGMENTS

First of all I would like to convey my heartfelt gratitude to my Major Professor Dr. Athula Kulatunga for providing me the opportunity to join IR-PEDAL (International Rectifiers - Power Electronics Development and Applications Lab) as a research assistant. Also my appreciation goes to him for directing me in this field of research and guiding me along every step of the way. His continued encouragement and advice has been invaluable. I would like to express my gratitude to Professor James Michael Jacob, for sharing his knowledge and experience, guiding me at times where I struggled with the research. Great appreciation goes to Dr. Rodney G. Handy for encouraging me and for providing me swift feedback on the research work.

I would like to appreciate the contribution of International Rectifiers, General Motors & Menards Engine Group to this research paving a path to success. I would also like to mention all the colleagues who supported me in any and all ways.

Finally, I would like to thank my mother, father and brother for being there with me at all times and for encouraging me.

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ABSTRACT

Kuruppu, Sandun Shivantha. M.S., Purdue University, May, 2010.
Implementation and Performance Evaluation of a Regenerative Braking System coupled to Ultracapacitors for a Brushless DC Hub Motor Driven Electric Tricycle.
Major Professor: Athula Kulatunga.

Research related to electrical vehicles is gaining importance due to the energy crisis. An electric vehicle itself is far ahead of an internal combustion engine based vehicle due to its efficiency. Using regenerative braking when braking, improves the efficiency of an electric vehicle as it recovers energy that could go to waste if mechanical brakes were used. A novel regenerative braking system for neighborhood electric vehicles was designed, prototyped and tested. The proposed system utilizes an ultracapacitor bank to capture energy where as the conventional systems regenerate to the batteries. The switching frequency of the current plays a key role in controlling the negative torque applied by the motor while capturing energy. The user has direct control over the amount of current regenerated and hence the amount of negative torque applied for braking. The research has shown that the proposed regenerative braking system is significantly better in recovering energy and slowing the vehicle compared to a commercially available regenerative braking system.

CHAPTER 1. INTRODUCTION

An investigation has been carried out in order to explore the effectiveness of regenerative braking system for an electric tricycle. This chapter introduces the significance of the research discussed throughout the document. The significance and purpose of the research, the research question, scope, limitations, and assumptions used in doing the project are presented in this chapter.

1.1. Background

A mass in motion is storage of energy, which is lost as heat due to friction when stopped with non-regenerative braking. At present, many applications exist which involve conversion of electric energy into mechanical energy. Motors are the vastly used electric to mechanical energy converter. Applications can vary from elevators to electric/hybrid vehicles. When a motor is used for acceleration, some of the stored kinetic energy can be recovered during the deceleration due to the generating effect of the motor in the form of electricity. The conversion must be done in a controlled fashion to prevent harmful stresses on passenger(s), mechanical systems, and electric system while braking.

Regenerative braking has been tested for electric locomotives/tram cars (Ashiya M., et al, 2000). Regenerative braking systems are finding their way into transportation systems due to the trend towards a greener future. Regenerative braking has more opportunity to recover energy on an electric vehicle (EV) or a hybrid electric vehicle (HEV), improving their fuel economy. The amount of energy recovered depends on the vehicle/system in discussion and how the systems kinetic energy is varying (driving style and route) (Gao Y.,Chen L., &

Ehsani M.,1999). The driving style and where the vehicle is driven determine the average driving speed. How often the vehicle engages the brakes and how frequently the vehicle stops determines the overall speed profile. These characteristics for a city differ when compared with the highway.

Different electric-to-mechanical energy conversion systems may require different topological changes in the power converter to facilitate regenerative braking. AC machines and DC machines have their own advantages and disadvantages in regarding controllability, efficiency, drive system and dynamic behavior (Krause P.C., Wasynczuk O.& Sudhoff S. D.,2002). Required negative torque and maximum negative torque the machine can generate, will determine whether the braking system needs to be a hybrid braking system (mechanical and electrical combined).

The regenerative braking system discussed here was developed for a brush-less DC hub motor (Trapezoidal Permanent Magnet AC machine) based recumbent tricycle. It has two lead acid battery banks of different capacity acting as the main and auxiliary power sources. Main battery bank provides power only to the motor and the auxiliary power system powers the sensors, electronics, touch screen display and the regenerative braking system. Ultracapacitors were used to recover the regenerative energy as it is capable of absorbing large currents compared to a battery (Burke A., 2000) (Henson W., 2008). The motor is driven by a commercially available controller which does not have regenerative braking. *Figure 1.1* shows the recumbent tricycle under development at the *International Rectifiers – Power Electronics Development and Applications Lab (IR-PEDAL)*. It has a data acquisition system from *Menards Engine Group (MEG)* collecting data for analysis. *Figure 1.2* provides an overview of the main systems on the tricycle. A detailed discussion of how the system operates is presented in Chapter 3.

Figure 1.1. Tricycle Under Development

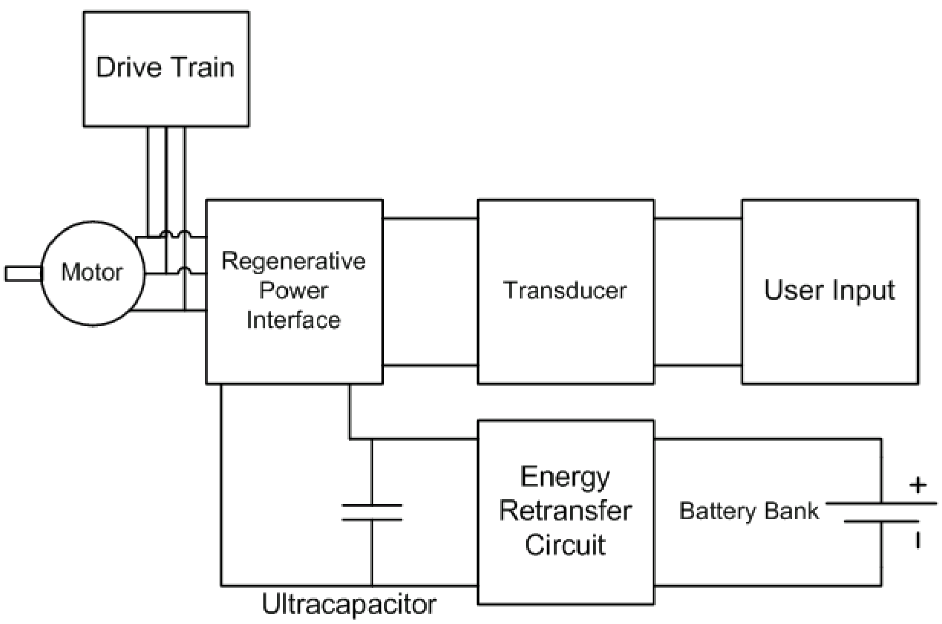

Figure 1.2. Basic Regenerative Braking System

1.2. Significance

Increasing energy cost has resulted in researchers trying to find ways to save energy whenever possible. The transportation industry accounts for 28% of the energy consumed in USA (US EIA Annual Energy Outlook, 2004). In a gasoline engine, only 15% of the energy in the fuel will contribute to useful work. The rest of the energy is lost. In an HEV or an EV, the wasted amount of energy is much less. This is due to the reduced usage of the IC (internal combustion) engine or avoidance of the IC engine, removal of inefficient couplings and traditional mechanical transmission. In addition, regenerative braking allows energy to be regained during braking. Regenerative braking systems vary in design, depending on the motor construction and require different power electronic concepts to be used to develop an effective energy recovery system. This research focuses on developing a regenerative braking system that is more effective in recovering energy from the brush-less DC motor based system and was compared with currently available systems.

The recumbent tricycle under discussion is considered as a neighborhood electric vehicle. Neighborhood electric vehicles (NEV) are becoming more popular as a mode of transportation. Regenerative braking systems, built for NEV type vehicles, lack effectiveness in braking and recovering energy from the mass in motion. This study is important as it seeks for a more efficient regenerative braking system for NEV type vehicles than the systems being used at present. Additionally, the regenerative braking system under discussion utilizes an ultracapacitor bank during regeneration, whereas, typical systems regenerate to the battery bank.

1.3. Statement of Purpose

The purpose of this research was to develop and evaluate an effective regenerative braking system with the capability to recover more energy than the commercially available system. The regenerated energy was transferred to the auxiliary supply/storage to be used again to power the auxiliary systems on the tricycle to improve the mileage per charge. Braking effectiveness (i.e., how fast can the vehicle stop), energy recovered, and performance of the system as a whole can be adopted to further develop and enhance regenerative braking systems for electric vehicles. Effectiveness of the regenerative braking system was compared with a commercially available regenerative braking system with the capturing device being either the battery bank or ultracapacitors.

1.4. Research Questions

During this study, the **proposed regenerative braking system (custom regenerative braking system)** was compared against a **commercial regenerative braking system**. The Following questions were considered during the study:

1. Is there a statistically significant difference between the vehicles stopping time among the two systems?
2. Is there a statistically significant difference between the energy recovered by the two systems?

1.5. Assumptions

The following assumptions will be inherent to the pursuit of this research:

1. Semiconductor devices used to construct circuitry functioned according to the manufacturers specifications.
2. Changes in battery characteristics due to usage are negligible.

1.6. Limitations

The following limitations will be inherent to the pursuit of this research:

1. The test equipment available at the *International Rectifier's – Power Electronic Development and Applications Lab (IR-PEDAL) at Purdue University, West Lafayette, Indiana* were used to design, prototype, and evaluate the performance of the overall system.
2. The measured parameters are limited by the maximum range and maximum sensitivity of the instrument used.
3. The regenerative braking system was tested for a brushless DC motor based system.
4. Mechanical regenerative braking was not considered as a reference for evaluation.

1.7. Delimitations

The following limitations will be inherent to the pursuit of this research:

1. The semiconductor device selection was based upon availability that would best match the component ratings required.
2. The maximum average power output of the hub motor is limited to 1900W.
3. The limitations in the integrated circuits determined the minimum operating voltage levels.
4. The electric discharge mechanism was used to avoid overcharging of capacitors.
5. The energy re-transfer circuit was implemented in current limited voltage regulation mode.

1.8. Definition of Key Terms

Neighborhood Electrical Vehicles –According to the classification of US Department of Transportation, golf cart type vehicles that can achieve 25mph are considered Neighborhood Electric Vehicles.

Ultracapacitors - Electrical double layer capacitors that have more energy capacity per unit volume than a normal capacitor (Burke A., 2000).

Regenerative Braking - Braking of a vehicle, a locomotive or a mass in motion that recover the kinetic energy and convert it to electric energy.

Electric Braking - Braking of a vehicle, a locomotive or a mass in motion by converting the kinetic energy in to electricity and dissipating it through resistive loads as heat.

Pulse Width Modulation (PWM) - The control over the switching cycle averaged value of the output voltages achieved by adjusting or varying the on period of a pulse. (Mohan N., 2002).

Switching Power Supply - Switching power supply is a non linear power supply that converts voltages into different forms (wave shape) and levels of voltages (amplitudes) using high speed switching and L-C filtering.

Pulse Batteries – A type of specially designed battery that is capable of drawing significantly higher amounts of current.

1.9. Summary

This chapter has provided an overview of the research to be carried out, including background, significance, purpose, research question, and scope definitions. This chapter concludes with an overview of the study. The next chapter outlines various aspects related to regenerative braking systems designs and their limitations.

CHAPTER 2. REVIEW OF RELEVANT LITERATURE

Regenerative braking technology, to recover energy from masses in motion, has been studied on before. This could be in either electrical means or mechanical means. Hybrid and electric vehicles currently in use have some means of regenerative braking to recover energy. But still the braking technology is not a fully electrical regenerative braking (there are mechanical regenerative braking means as well). This chapter provides an overview of research done so far in the field of regenerative braking.

2.1. Introduction

The regenerative braking system considered in this research is for a small electric vehicle. For a vehicle, there are several interconnected systems operating in order to perform regenerative braking. The focus of this literature review was to determine what research has been done so far on power electronic aspects of electric regenerative braking systems. In addition to the main topic, several vital topics related to regenerative braking are highlighted.

2.2. Transportation

Technology for transportation has evolved with the advancement of humankind. The unique role it plays in the society is what allows it to advance. Twenty eight percent of the energy consumed in the US (US EIA, 2004) per year is consumed by the transportation sector (US EIA, 2004). Internal combustion engine based systems account for a significantly large portion of that energy conversion. The renowned inefficiency in the internal combustion engine and transmission in a vehicle has resulted in wasting energy unnecessarily (Lumley J.L., 1999). Hybrid and electric vehicles operate more efficiently, consuming less energy compared to gasoline based vehicles. Hybrids and electric vehicles have a built in electrical energy to mechanical energy conversion system which can be used to generate energy when braking, slowing down or while moving down hill.

2.3. Braking Power Analysis

Research has highlighted what factors in a vehicle in motion contribute to the amount of energy available for recovery via regenerative braking. These mainly include the weight of the vehicle, driving style and power handling capability of the electrical system (Wyczalek F.A., & Wang T.C., 1992).

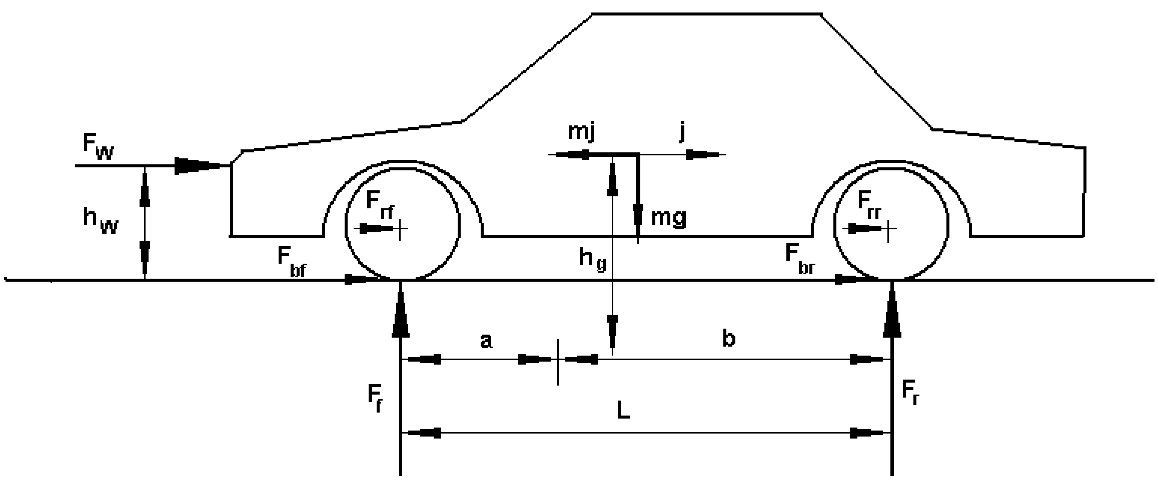

Figure 2.1. Forces Acting on a Vehicle while braking on Level Ground (Gao Y.,Chen L., & Ehsani M., 1999)

j is the deceleration of the vehicle, $\mathbf{f_r}$ is the tire rolling resistance, **r** is tire radius, and $\mathbf{F_w}$ is the aerodynamic resistance. $\mathbf{F_{br}}$ and $\mathbf{F_{bf}}$ are rolling resistances on the rear and front wheels respectively.

Energy in a mass in motion = $\frac{1}{2} * m * V^2$ Eq 2.1

The energy stored in a vehicle before applying braking can be found by equation 1. *Figure 2.1* shows the forces applied on a vehicle braking on a level ground (Gao Y.,Chen L., & Ehsani M., 1999). Further this article analyses the effect of front and rear wheel braking.

Air resistance and rolling resistance draw a certain portion of the energy in the mass during braking. Air resistance can be reduced by having an aerodynamic design with a smaller drag coefficient. The following equation gives the required braking power (**P_b**) for a vehicle on level ground.

$$P_b = \left(\frac{v}{1000}\right) * \left[m * \delta * \left(\frac{dv}{dt}\right) - m * g * f_r - \left(\frac{1}{2}\right) * \rho_a * C_D * A_f * v^2\right] \quad \text{Eq 2.2}$$

(Gao Y.,Chen L., & Ehsani M., 1999)

Whereas **m** is the vehicle mass in kg, **v** is the speed in m/s and **dV/dt** is the deceleration of the vehicle in m/s^2. **f_r** is the rolling resistance coefficient, **ρ_a** is the air density, **C_D** is the aerodynamic drag coefficient and **A_f** is the front area of the vehicle.

Depending on the weight of the vehicle and how rapid the deceleration, the amount of power to be absorbed varies. Most of the regenerated energy is from the inertia of the vehicle (Lee J., & Nelson D.J., 2005). Research has found that regenerative braking is more beneficial to driving schedules with frequent starts and stops (Wyczalek F.A., & Wang T.C., 1992). Systems currently in use utilize an electrical and mechanical hybrid braking system to assure the safety and limitations in the power electronics (issues related to the minimum operating voltages of ICs).

2.4. Energy Capturing Devices

The capturing device is what absorbs the electric energy during regenerative braking. If the vehicle weighs 132kg and was traveling at an instantaneous speed of 32kmph the energy stored in it at that moment is about 5.2kJ. Neglecting other losses, if it needs to be stopped in 2 seconds, the power absorption rates maximum limit should be 2.6kW. This provides a basis to compare energy storage devices to be used for regenerative braking.

Speed of the Vehicle = 32 km/h

= 8.89 m/s

Weight of the vehicle = 132 kg

Instantaneous Energy = $\frac{1}{2} * m * V^2$

= 5216.1 joules

Required Stop Time = 2 s

Required Energy Absorption Rate= 5216.1 / 2 (J/s)

= 2.6 kW

Different battery technologies are available for energy storage, including lead acid, Nickel Metal Hydride, Li – ion, Li polymer and Nickel Cadmium. Very few types are used for electric energy storage on hybrid electric vehicles (HEV) and electric vehicles (EV). Each battery type has its own advantages and disadvantages (Battery University, n.d.). But Nickel Metal Hydride (NiMh) is best proven for its robustness, energy density, power density and cycle life (Battery University, n.d.). The drawback in using batteries as regenerative braking charge absorbers is that the amount of current a battery can handle without damaging itself is small compared to the current required to be drawn for a fast stop.

Ultracapacitor technology is an emerging yet promising technology that is promising in bridging gaps in technology. It's capability to handle high currents makes it ideal for absorbing energy during regenerative braking. Researchers have discovered that ultracapacitors can be used in parallel with battery banks to improve the battery banks current handling capability (Burke A.F.,2007).

2.5. Ultracapacitors

An ultracapacitor is also known as an electric double layer capacitor. It has two electrodes with micro porous and an electrolyte. “Energy is stored in the double-layer capacitor as charge separation in the double-layer formed at the interface between the solid electrode material surface and the liquid electrolyte in the micro pores of the electrodes” (Burke A., 2000). They are developed as an alternative to pulse batteries and can draw high currents without damage to itself. In addition, ultracapacitors have longer shelf life and cycle life (typical cycle life – 500,00 to 1000,000 cycles) when compared to batteries. But the energy density is relatively low (Burke A., 2000) in comparison. Table 2.1 provides some specifications of Maxwell’s BMOD0058-E015-B01 ultracapacitor compared to a 12V 10Ah lead acid battery. Energy stored in an ultracapacitor can be calculated using $\frac{1}{2} * C * V^2$, where as C is capacitance and, V is the voltage across the capacitors terminals.

Table 2.1

Ultracapacitor, Battery Comparison

Characteristic	Lead Acid Battery* Specifications	Ultracapacitor Specifications
Capacitance	36,000F (10Ah)	58F
Maximum Terminal Voltage	12V	15V
Maximum Charging Current	3A*	1500A
Internal Resistance	-	19mΩ
Power Density	-	2100 (W / kg)
Energy Density	21.14 (Wh/kg)	2.67 (Wh / kg)

* 12V, 10Ah sealed lead acid battery SLA BP Series battery.

** Maximum charging current changes depending on the type of lead acid battery used. Less current prevents possible damage to battery cells.

2.6. Ultracapacitor Battery Combination

Ultracapacitor internal resistance is low compared to a battery. Research has been done with different DC/DC converter interconnecting ultracapacitors and batteries (Gao L., Dougal R.A., & Liu S., 2005):

Advantages in having a DC/DC converter between the battery and the ultracapacitor are (Gao L., Dougal R.A., & Liu S., 2005)

1. Ultracapacitor voltage can be different from the battery voltage.
2. Power capacity of the ultracapacitor can be higher than the battery.
3. Power source terminal voltage can be kept relatively constant.
4. Weight of the power source for a given peak power is smaller than the passive power source (battery).
5. DC/DC converter can be used as the battery charge regulator.

The type of DC/DC topology to be used depends on the application (e.g., buck, boost etc…). The power handling capability of the generator (motor) is one of the main limitations in a regenerative system. A bi-directional buck-boost converter along with ultracapacitors has proven to reduce the peak battery (deep cycle valve regulated lead acid battery) current by 40% (Pay S., & Baghzouz Y., 2003). The DC bus voltage regulation has improved by 30%. But the same researchers claim that there are converter control issues when using the ultracapacitor as the load. A.F. Burke has done computer based simulations related to ultracapacitors and batteries being used for electric and hybrid vehicles and the results are presented in his paper named "Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell vehicles." His work concludes that "fuel-efficient hybrid-electric vehicles can be designed using either batteries or ultracapacitors and that the decision between the two technologies is dependent on their cost and useful life".

2.7. Drive Control and Regen Control Aspects

A vehicle's braking must be controllable by the person driving the vehicle. Mechanical energy is converted into voltage by a motor acting as a generator. The output of the motor can be either AC or DC.

One method to control AC machines is to use reference frame transformation. Control of electric machinery has been an interesting topic for engineers. A new realm of machine control was discovered by R.H. Park in 1920, by introducing the concept of reference frame transformation. Since then, reference frame transformation has reached a stage where AC machine controllers are based on inverse reference frame transformation. This is important because the brushless DC motor being used in this research (also known as Trapezoidal Permanent Magnet Synchronous Machine) is also an AC machine that can be controlled using reference frame transformation based controls for regenerative braking purposes. An electrical machine is simply a magnetically coupled electro-mechanical circuit. The magnetic coupling allows the energy transfer between the stationary circuits (also known as the stationary reference frame) to the rotating circuit (also known as the rotating reference frame). It can be shown that the inductances of a machine vary depending on the position of the rotor (Krause P.C., Wasynchzuk O., & Sudhoff S.D., 2002). When the machine is rotating the position is a function of time, resulting in the inductances to be time varying. This complicates the machine analysis and hence the control algorithm. Reference frame theory simplifies these inductances by transforming those time varying variables into a different reference frame where the inductances do not vary with time. *Figure 2.2* shows the typical power electronic drive used to drive brushless DC motors. It consists of a three phase H-bridge and a programmed controller which controls operation.

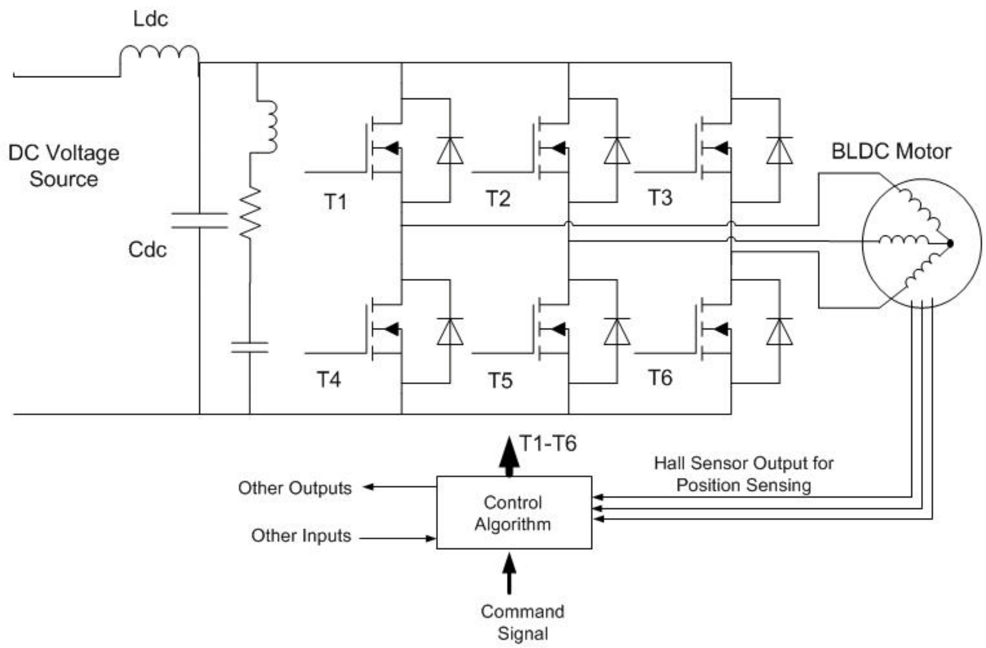

Figure 2.2. Typical Brushless DC Drive Configuration

Figure 2.3 shows hysteresis current controlled brushless machine control block diagram. Torque command (T_e*), DC link voltage (Vdc) and angular speed (ωr) are the inputs fed to the controller to determine q and d (reference frame based quantities) axis current commands. The q and d axes current commands are then converted into actual current commands (stationary reference frame currents) that are fed to the switch control block.

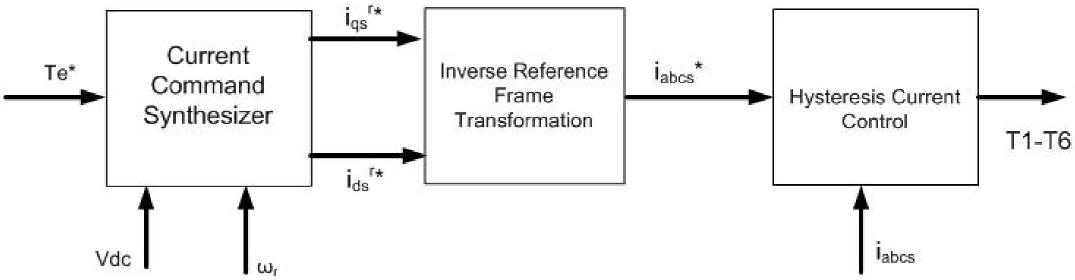

Figure 2.3. Hysteresis Current Controls for Brushless DC Machine (Krause P.C., Wasynchzuk O., & Sudhoff S.D., 2002)

Figure 2.4 shows the sine triangle modulation based control algorithm. Here the switches are turned on and off in order to achieve a sinusoidal voltage output to each phase of the machine.

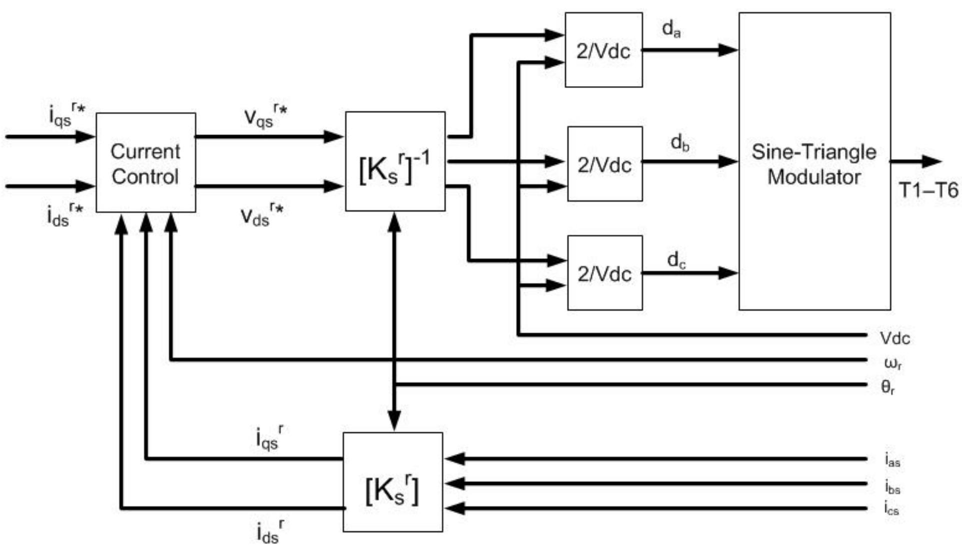

Figure 2.4. Sine Triangle Based Current Control (Krause P.C., Wasynchzuk O., & Sudhoff S.D., 2002)

The other possible method for controlling AC machines for regeneration is to convert the AC voltage in to DC and control it by using a DC/DC converter. Power electronic converter acts as the regulator of power to facilitate regenerative braking. When braking, a negative electromagnetic torque is generated in the motor. This occurs due to the reversed current (**I**) flow. In a motor, electromagnetic torque (**T**) is proportional to the magnetizing current. Machine construction dependent constant is defined by **k**.

$T = k * I$ (in a PMDC motor) Eq 2.3

Controlling the current drawn from the generator will allow the amount of braking to be controlled. There are several techniques that can be used to control converters.

1. PID (Proportional, Integral & Differential) control
2. Voltage mode control (Mohan N. ,2002)
3. Current mode control (Mohan N. ,2002)
4. Current regulation
5. Current limited voltage control
6. Digital current control

Properly designed power converter control will allow a stable current or voltage output. Digital or analog control can be used in order to control a converter. Switching devices used, capacitor size, inductor size, topology used, switching frequency and the type of p.w.m. controller used are some of the major factors considered in determining the type of controller. Type 1, type 2 or type 3 controllers are typically used for voltage mode control in DC-DC converters and the selection of each type depends on the converter transfer function (Mohan N., 2002). Each converter type has a specific transfer function which may have a lagging or leading phase in the frequency domain at the cut off frequency (phase plot in the bode plot). A phase margin of 60 degrees is preferred for a typical stable power converter (Mohan N., 2002). The controller adds the required phase to shift the converter from the unstable region to the stable region. Filtering is required at the feedback path to suppress unwanted noise without adding a significant delay in the feedback path. Most control techniques regulate the output current of a converter, instead of the input current. Switch mode converters are designed assuming small perturbations at the input (Mohan N., 2002). Therefore, the input to the converter has to be relatively steady. Current control can be done by operating a bipolar junction transistor (BJT) in its linear region. But the I^2*R losses due to high currents are very inefficient. Hence it is rarely used.

There are other issues with regards to switch mode power converters. Since power converters consist of fast switching devices, they produce significantly high amounts of switching noise, harmonics. This will affect the DC bus and the signals in the form of switching noise. Power converters are operated at several hundreds of kilo hertz to several mega hertz frequency to obtain higher efficiency (only at low power levels). Switching frequency is decreased as the power levels increase. But this in turn causes higher dv/dt and di/dt , resulting in voltage spikes and current spikes across the switch. Large enough voltage or current spikes can cause the switching device to operate out of its safe operating area (SOA). Properly designed turn on and turn off snubbers assure that the device will operate within the safe operation region (Mohan, 2005).

2.8. Thermal Management

Heat generated in a converter has to be properly vented to prevent unwanted shutdown of switching devices and pwm controllers as some of them contain internal thermal shutdown mechanisms. Switching devices dissipate more heat as switching frequency increases (Mohan N., 2002). This is of utmost importance, because the failure of a braking system involving live passengers would be catastrophic. Active or passive cooling can be performed to guarantee safe operation of the power handling system (PHS). Design and placement of heat sinking mechanisms is a critical aspect in order to avoid heat buildup in the internal system causing malfunctions or fire (International Rectifiers, n.d.).

2.9. General Aspects

Circuit board layout is as important as the heat dissipation. Improper circuit board layout could result in higher noise levels disrupting proper operation of the converters. Switching frequencies were in the range of 100 kHz to 10 MHz. Multi-layered and properly laid ground plane along with isolated grounds provide reliable system functionality.

2.10. Summary

This chapter has provided an overview to the literature related to various aspects of regenerative braking technology, power converters and electric power storage. While there is some amount of regenerative braking involved with EVs and HEVs, fully regenerative braking is far from being a reality due to limitations in technology.

Studies on this will generate more knowledge on regenerative braking that can be used to recover a significant portion (e.g., 80%-90%) from the braking a vehicle. Thus, the next chapter provides the approach planned to be followed to achieve the required regenerative braking system.

CHAPTER 3. METHODOLOGY

The purpose of this research was to develop a regenerative braking system for a neighborhood electric vehicle type vehicle that can recover significantly higher amounts of energy compared to commercially available regenerating systems. Regenerated energy was utilized to improve the vehicles energy efficiency. This chapter outlines approach, systems and techniques followed in prototyping and testing the system.

3.1. Requirement Analysis

The braking requirements of a vehicle need to be designed specifically for that vehicle. Maximum weight and maximum speed are two critical factors that influence the braking system design. These factors for the tricycle were measured prior to designing the braking system. Ideally, the electrical braking system should perform similar to the mechanical braking system. A speed profile during braking with mechanical brakes engaged provided the required energy absorption rate and the duration of the deceleration required.

The second step was to analyze the electrical system for its limitations. The motor's maximum power handling capability, the current rating of machine's windings, and the other wire linkages interconnecting the systems were main properties to consider in designing the braking system because the higher the negative torque required, the higher the negative current into a machine.

3.2. Proposed Regenerative Braking System

This section presents the overall system design for the regenerative braking system. *Figure 3.1* presents the overall system block diagram.

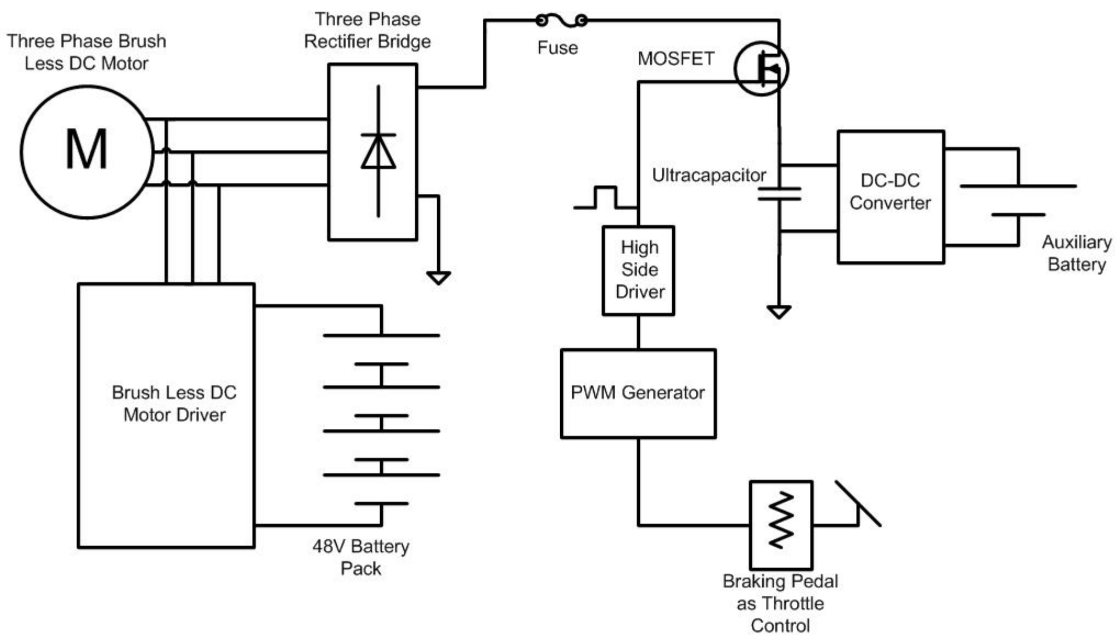

Figure 3.1. Overall System Design for Regenerative Braking System

When regenerating, the brushless DC motor generates a trapezoidal back emf across its terminals. The rectifying bridge rectifies this AC voltage to a DC voltage to be controlled by the MOSFET that follows. A high current, high voltage MOSFET is placed between the ultracapacitor and the rectifier which turned on and off depending on the throttle level signal provided to the PWM generator. Due to the low resistance in the ultracapacitor, it draws a significantly higher current when the switch is turned on, when compared to a battery. The switch turnoff has to be properly timed to prevent damage to the system. This is controlled by selecting the proper switching frequency that limits the peak current fed to the ultracapacitor.

3.3. Prototype

Figure 3.2 shows the prototype used on the tricycle for testing. The power supply stage of the prototype boosts 12V from the auxiliary battery to 15V using a boost circuit to power the regenerative braking circuitry. Input signal conditioner obtains the user throttle request and converts it to the PWM controller reference in order to control the pulse width of the MOSFET. PWM generator passes the pulses to a driver which controls the actual turning on and off of the MOSFET.

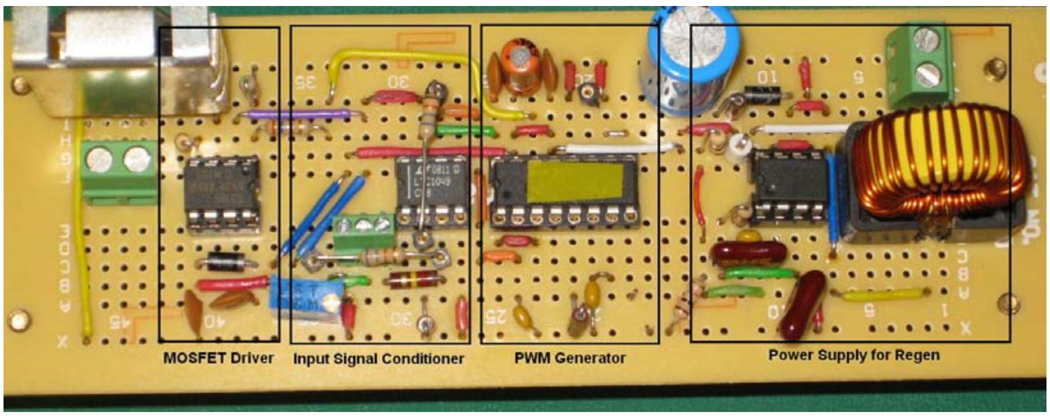

Figure 3.2. Prototyped Regenerative Braking System for NEVs

The auxiliary battery provides power to the regenerative braking controls, the touch screen display, the data acquisition system, and to the instrumentation circuitry. The DC-DC boost converter connected to the ultracapacitor transfers the energy into the auxiliary battery. This converter is self-powered and turns on automatically when the ultracapacitor voltage reaches 5.2 V or above.

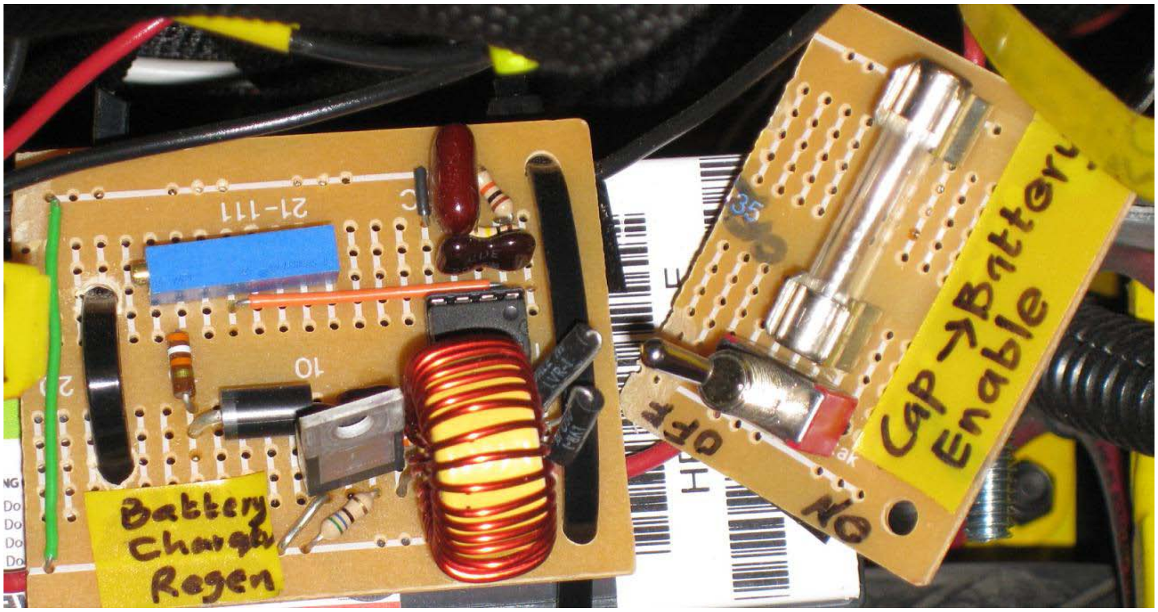

Figure 3.3. Regenerated Electric Power Transfer Circuit

Figure 3.3 is utilized to transfer the regenerated energy from the ultracapacitor to the auxiliary battery to be used. The power transfer circuit is self-powered and initiates energy transfer once the ultracapacitor voltage reaches above 5.2 Volts. It is a boost converter based on LM3578AN regulator. The current limit in the circuit prevents high currents during battery charging.

3.4. PWM Switching Frequency Selection

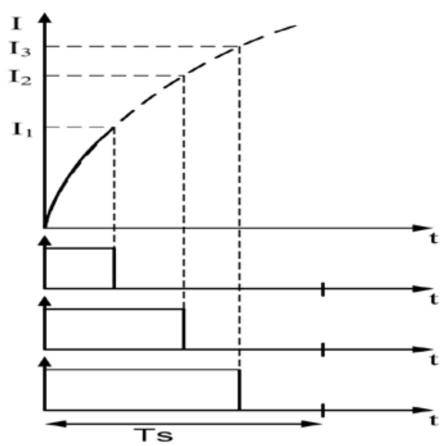

Figure 3.4. Capacitor Current

Switching frequency is important in this design because it is determined based on the time constant of the energy capturing system (ultracapacitor bank). Current drained from the electric machine (BLDC Motor) establishes the negative torque in it, causing deceleration. When the MOSFET is turned on during regenerative braking, the DC bus voltage directly comes in contact with the ultracapacitor. Due to the low impedance in the ultracapacitor the current starts to rise rapidly. As shown in *Figure 3.4,* turning the MOSFET off at different time intervals result in different current levels. Higher on time provides a higher current draw. This provides a user-controlled regenerative braking system. Mainly, the current rise time has to be considered in selecting the switching frequency. Higher frequency will prevent the capacitor reaching higher currents, and hence, higher negative torque. Very low frequency would instantly reach the maximum current instantly. The user will not have enough time to adjust the throttle level to change the braking level. The following figure shows how an actual switching current waveform when regenerative braking is performed and the pulse width is not 100%. The current switching frequency used was 390 Hz.

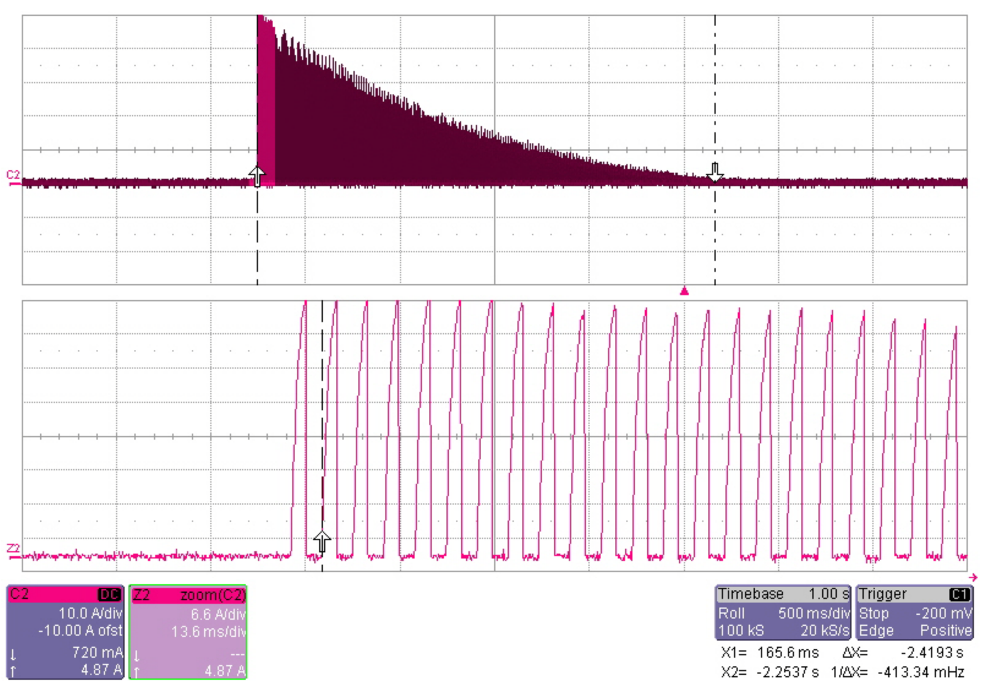

Figure 3.5. Current Switching Waveform

3.5. Instrumentation System Information

Measurement system calibration and accuracy data is critical in evaluating the validity of the data. The data logging system mounted on the tricycle requires a calibration file in order to perform proper scaling. Table 3.1 presents information of the data logging system and other instruments used to calibrate the data logging system.

Table 3.1

Instrument Specification

	Instrument	Device Classification	Accuracy	Resolution	Sampling Rate
1	MEG 703 DAQ	Voltage	-	76.294 µV	1000 Hz
2	MEG 703 DAQ	Pulse Counter	-	-	1.9 MHz
3	LEM LA25 NP	Current Sensor	±0.5%	-	-
4	Automation Direct AE1-AN-1A	Magnetic Proximity Switch	-	-	-
5	CEN-TECH	Digital Multimeter	±0.5%	10mV	-
6	Fluke 45	Digital Voltmeter	±0.025%	1 µV-0.01 V	-
7	VWR Tachometer 8000	Tachometer	0.04%	0.01 RPM	-

Specifications for the LeCroy WaveRunner 6030A can be found at *http://www.lecroy.com/Oscilloscope/OscilloscopeModel.aspx?modelid=870&capid=102&mid=504* , which was utilized for system diagnosis and basic waveform capturing.

3.6. System Design & Prototyping

The power electronics system was sized and designed to perform the regenerative braking using the brushless DC motor. Initial system testing was done utilizing a power supply as the power source instead of the motor. This system was prototyped and implemented on the tricycle, once the bench top testing reached an acceptably successful level of operation. The amount of power drawn was strictly controlled by a user input. Prototype implementation was on a prototyping board for the proof of concept.

3.7. Testing

Initially, regenerative braking system was tested on the custom built simple test platform (shown in *Figure 3.6*) at the *IR-PEDAL.* Track testing was done once the system performance on the test platform concluded successfully.

Figure 3.6. Custom Built Dyno for Tricycle Testing

3.8. Data Acquisition

Data acquisition on the test platform was done using *LeCroy* oscilloscopes available at the *IR-PEDAL*. Track testing required a signal conditioning system and a data acquisition system. The data acquisition system was permanently mounted on the tricycle and the data was downloaded to the computer for analysis. Speed profile, regenerative current, main battery voltage and ultracapacitor voltage were monitored during track testing. The data logging system was programmed to initiate data logging as the wheel speed exceeds 5.74 miles per hour.

3.9. Performance Analysis

The goal of this research is to implement a regenerative braking system for NEV type vehicles that recuperate more energy when compared to commercially available alternatives. A commercially available drive was utilized for comparison. The following aspects of the regenerative braking systems were compared with the mechanical braking in order to evaluate performance.

- Comparison of the speed profiles of:
    - Custom built regenerative braking system.
    - Commercial drive’s regenerative braking system.
    - Mechanical braking system.

- Commercial regenerative braking system and the custom built regenerative system will be compared for their:
    - Breaking time from 15 mph to 5mph with braking throttle at maximum.
    - Energy recovered in the above braking process.

The above test will be done for 15 test cycles for each system.

Table 3.2

Sample Data Collection Form

Attempt	Commercial Regenerative Braking		Custom Built Regenerative Braking System		Mechanical Braking System	
	Stop Time	Energy Saved	Stop Time	Energy Saved	Stop Time	Energy Saved
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						

3.10. Summary

This chapter has provided an overview of the methodology that was followed in designing, testing and evaluating the regenerative braking system for Neighborhood Electrical Vehicle type of vehicles. The next chapters will discuss the design in detail and performance.

CHAPTER 4. DATA

The objective of this research was to evaluate the performance and effectiveness of the regenerative braking system developed for the neighborhood electric vehicle type vehicles. It is compared against the mechanical braking and a commercial regenerative braking system. Field test data for the three systems were gathered for analysis. Deceleration time and energy recovered were the main aspects in focus.

4.1. Field Test Data

Field testing was done inside the *Armory Building* at *Purdue University, West Lafayette* Campus. The building is approximately 73 meters in length and about 45 meters in width. Testing was not affected by wind, as the building was a closed during the tests. Data was collected using MEG 703 data logging system. Data was collected for the following cases:

1. Coasting to a stop without any means of braking.
2. Braking with the commercial regenerative braking system.
3. Braking with the mechanical braking system.
4. Braking with custom regenerative braking system.

When performing each test, the tricycle was accelerated to the required speed using the onboard drive system. The custom regenerative braking system utilized the thumb throttle based drive system and the commercial regenerative braking system utilized the foot pedal based drive system. The tricycle ran on a circular track inside the *Armory Building,* because the length was not enough for a full acceleration and a stop. The tricycle speed was monitored by the rider using a speedometer which senses the rear wheel speed. The rider observed the speed as the tricycle accelerated. When the required speed was reached, the rider released the acceleration command and engaged the regenerative braking to a maximum. During the acceleration phase the data logging system starts logging data once the speed passes 5.74 miles per hour and stops logging data as speed drops below 5.74 miles per hour.

Data collected are presented here with a sample speed profile for each case. *Figure 4.1* represents sample speed profile during a coast stop. The tricycle accelerates to 18.72 miles per hour. The two troughs during acceleration are due to the accelerator disengagement when passing the curved portions of the circular track to prevent possible imbalance conditions that might occur due to centripetal force.

Table 4.1

Data for Coasting Stop

Data Set #	Speed at the Start of Coasting / mph	Time at the Start of Coasting / s	Time at the End of Coasting / s
1	18.31829	6.102606	44.766708
2	18.06182	24.451708	64.014664
3	18.72904	14.354437	56.11343
4	18.88301	15.843328	57.799316
5	18.31383	33.969666	73.099167

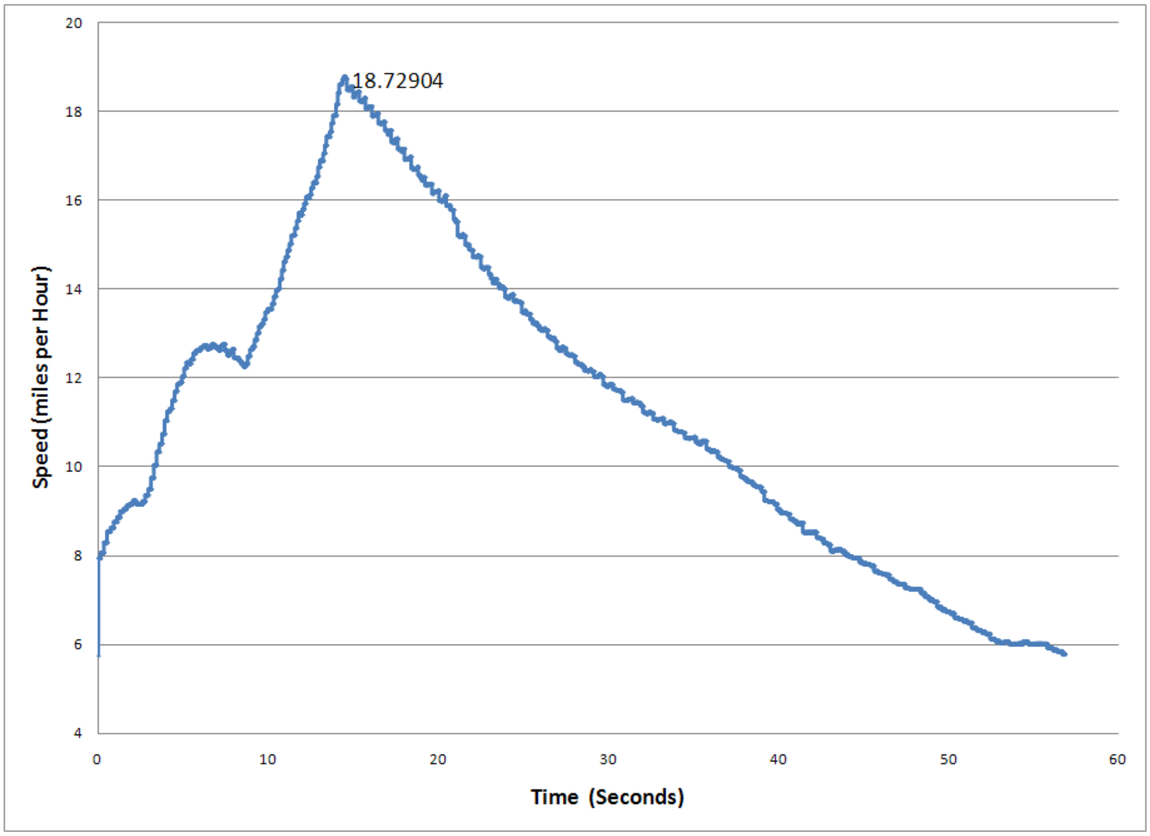

Figure 4.1. Speed Profile during a Coast Stop

Table 4.2 presents the data when stopped using mechanical braking system. *Figure 4.2* presents a sample speed profile when mechanical braking was engaged. It also shows the troughs due to accelerator disengagement during acceleration. Mechanical braking was gradually engaged as rapid mechanical braking can be harmful to the rider as well as the mechanical structure of the tricycle. The steep drop of speed resembles the rapidity of the stop due to mechanical braking.

Table 4.2

Data for Mechanical Braking System

Data Set #	Speed Before Engaging Brake / (mph)	Brake Start Time / (s)	Brake End Time / (s)
1	15.60	32.2715	34.7619
2	14.30	74.7462	77.0434
3	15.28	118.1659	119.7577
4	17.12	35.5419	38.4162
5	16.94	77.6997	81.0734
6	17.86	119.4970	123.0609
7	19.91	21.1035	26.0475
8	19.70	14.2685	17.4055
9	19.53	8.7703	12.1349
10	20.73	10.4465	13.6760
11	20.99	8.6936	11.8617
12	21.00	9.8233	13.1725
13	20.61	9.0159	12.7305
14	20.90	11.2767	15.2294
15	19.82	8.7181	11.7696

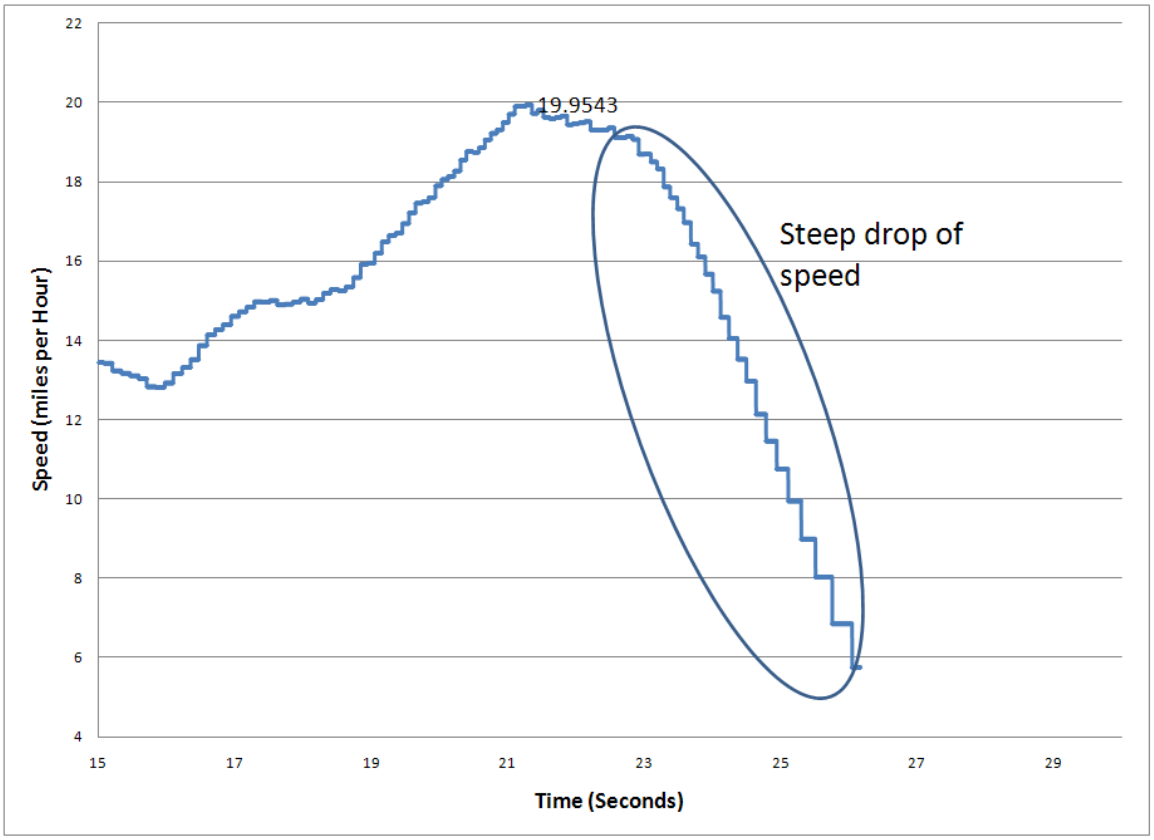

Figure 4.2. Speed Profile with Mechanical Braking

Table 4.3

Data for Custom Regenerative Braking System

Data Set #	Speed Before Engaging Breaks / (mph)	Voltage of Capacitor Before Engaging Brakes / (V)	Voltage of Capacitor After Braking / (V)	Break Start Time / (s)	Break End Time / (s)
1	18.89	0.20	0.80	27.2813	33.5827
2	16.56	0.80	1.40	25.4522	35.1888
3	14.66	1.40	1.96	25.4307	35.5082
4	15.24	1.95	2.50	24.3811	35.0537
5	14.15	1.50	2.03	28.1313	37.4520
6	17.53	1.43	2.09	24.2768	35.6740
7	16.53	2.08	2.65	31.1757	42.6816
8	16.88	1.77	2.44	30.8964	41.8955

Table 4.3 (continued)

Data for Custom Regenerative Braking System

Data Set #	Speed Before Engaging Breaks / (mph)	Voltage of Capacitor Before Engaging Brakes / (V)	Voltage of Capacitor After Braking / (V)	Break Start Time / (s)	Break End Time / (s)
9	14.97	1.69	2.25	31.2371	41.4656
10	16.36	1.34	2.01	39.3160	49.3945
11	16.90	1.25	1.97	29.9267	40.2894
12	16.60	1.46	2.10	30.0095	40.8207
13	15.32	2.10	2.66	31.5500	41.9900
14	17.31	2.08	2.74	28.5300	40.6100
15	16.70	2.74	3.32	38.7500	51.3800

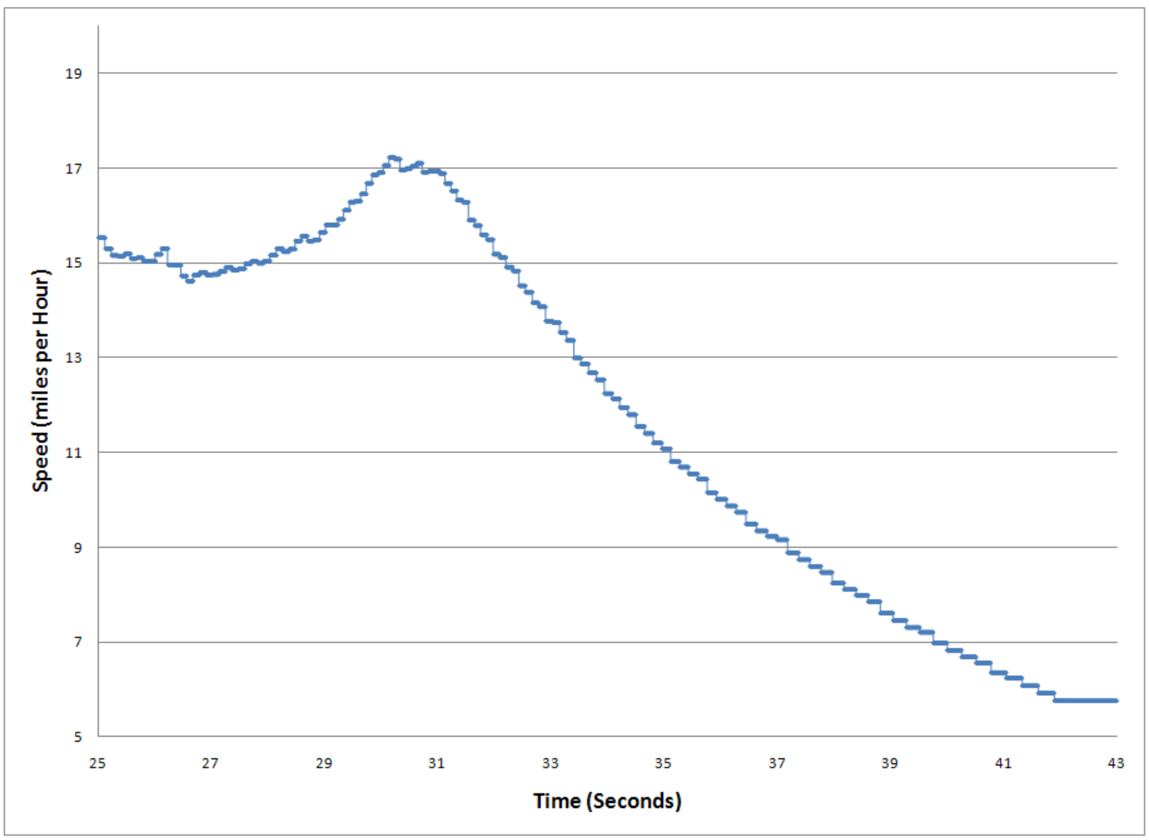

Figure 4.3. Speed Profile with Custom Regenerative Braking System

Table 4.4

Data for Commercial Regenerative Braking System

Data Set #	Speed Before Engaging Breaks / (mph)	Break Start Time / (s)	Break End Time / (s)
1	18.88	14.8518	34.8295
2	16.98	23.0830	44.0850
3	19.25	15.4995	35.9565
4	20.17	13.0252	36.2574
5	19.26	12.5555	36.2206
6	19.93	8.8778	32.2623
7	19.27	22.7147	44.3092
8	19.09	13.3414	36.3373
9	19.00	9.7865	30.6233
10	18.54	10.7105	31.3967
11	20.77	12.7827	37.1449
12	21.33	9.5102	34.8633
13	20.44	5.2922	28.7574
14	18.54	21.4165	41.5393
15	20.30	10.7934	33.5633

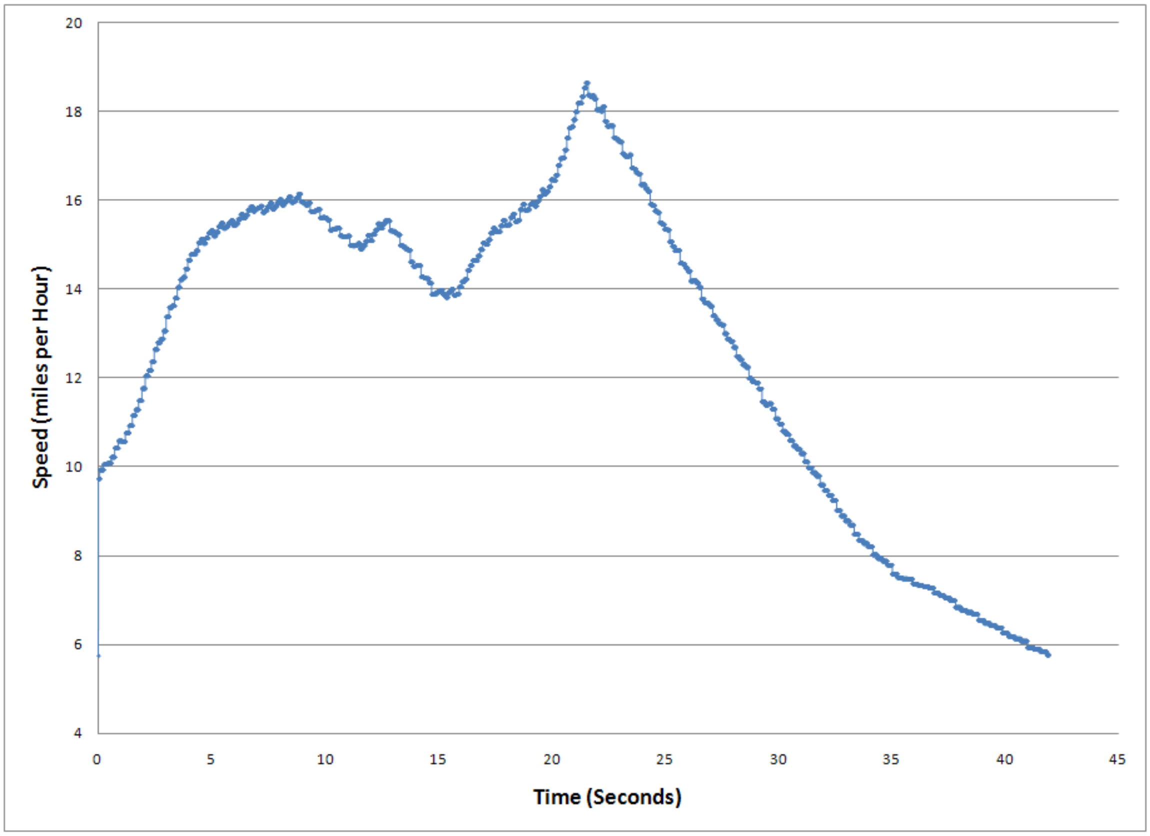

Figure 4.4. Speed Profile with Commercial Regenerative Braking System

Weight of the Tricycle	= 69 kg
Passenger Weight	= 63 kg

4.2. Summary

This chapter summarizes the process of the switching frequency selection, the instruments used for in-house testing, the field testing, and the data acquired for analysis. The next chapter presents the analysis of the data acquired.

CHAPTER 5. DATA ANALYSIS & CONCLUSION

An analysis of the data collected for this research is presented in this chapter. The custom built regenerative braking system is compared with a commercially available regenerative braking system and the mechanical braking system. The performance evaluation criterion is based on the energy recovered by each method and the time taken to stop the vehicle. *Figure 5.1* highlights the data collected. It shows the speed profile of the tricycle with each braking technique.

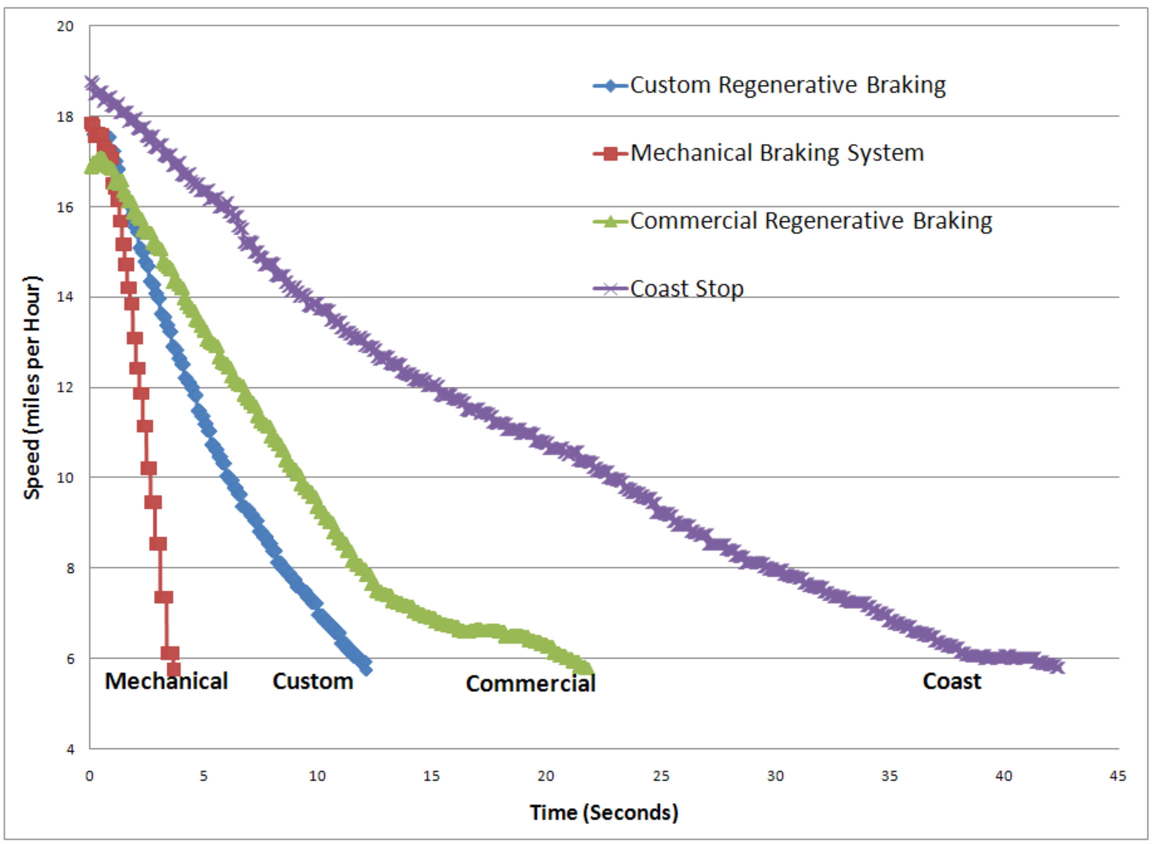

Figure 5.1. Speed Profiles with Different Braking Conditions

5.1. Analysis of Coast Stop Data

Data was collected while the tricycle coasted to a stop. The speed profiles captured using the data logger were utilized to find the energy at the instant when deceleration started and the duration of the coasting. This presents the energy lost under rolling friction, when brakes are not engaged.

Table 5.1

Analysis of Coast Stop Data

Data Set #	Speed at the Start of Coasting / (ms^{-1})	Duration of Coasting / (s)
1	8.19	38.6641
2	8.07	39.5630
3	8.37	41.7590
4	8.44	41.9560
5	8.19	39.1295

5.2. Analysis of Mechanical Braking Data

Table 5.2 presents the analysis of data for mechanical braking. The mechanical braking system dissipates all the energy as heat. Hence the energy recovered is negative.

Table 5.2

Analysis of Mechanical Braking Data

Data Set #	Speed Before Braking / (ms^{-1})	Total Kinetic Energy Before Braking / (J)	Duration of Braking / (s)	Energy Recovered / (J)
1	6.9719	3208.07	2.4904	-3208.07
2	6.3921	2696.65	2.2972	-2696.65
3	6.8308	3079.51	1.5918	-3079.51
4	7.6534	3865.97	2.8743	-3865.97
5	7.5715	3783.67	3.3737	-3783.67
6	7.9832	4206.28	3.5639	-4206.28

Table 5.2 (continued)

Analysis of Mechanical Braking Data

Data Set #	Speed Before Braking / (ms^{-1})	Total Kinetic Energy Before Braking / (J)	Duration of Braking / (s)	Energy Recovered / (J)
7	8.9024	5230.74	4.9440	-5230.74
8	8.8079	5120.25	3.1370	-5120.25
9	8.7285	5028.31	3.3646	-5028.31
10	9.2674	5668.44	3.2295	-5668.44
11	9.3842	5812.12	3.1681	-5812.12
12	9.3883	5817.31	3.3492	-5817.31
13	9.2122	5601.05	3.7146	-5601.05
14	9.3451	5763.84	3.9527	-5763.84
15	8.8608	5181.86	3.0515	-5181.86

5.3. Analysis of Custom Regenerative Braking System Data

The custom regenerative braking system stored energy into the ultracapacitor during braking. Ultracapacitor voltage was used to evaluate the energy captured in each test run. A sample calculation is shown below:

Sample energy calculation for Ultracapacitor

Initial Voltage of Capacitor = 1.5 Volts

Final Voltage of Capacitor = 2.1 Volts

Initial Energy in Capacitor = $0.5*C*V^2$

= 522.00 Joules

Final Energy in Capacitor = 1023.12 Joules

Energy Recovered = 1023.12 – 522.00

= 501.12 Joules

Sample charge calculation for Ultracapacitor

Initial Charge in Capacitor = C x V

= 464 x 1.5 C

= 696.0 C

Final Charge in Capacitor = 464 x 2.1 C

=974.4 C

Transferred Charge = 974.4 – 696.0

= 278.4 C

Table 5.3

Analysis of Custom Regenerative Braking Data

Data Set #	Speed Before Braking / (ms^{-1})	Total Kinetic Energy Before Braking / (J)	Duration of Braking / (s)	Energy Recovered / (J)
1	8.4446	4706.53	6.3015	139.2000
2	7.4030	3617.07	9.7366	306.2400
3	6.5536	2834.68	10.0775	436.5312
4	6.8129	3063.42	10.6725	567.8200
5	6.3256	2640.89	9.3206	434.0488
6	7.8366	4053.22	11.3972	538.9824
7	7.3896	3603.98	11.5059	625.4952
8	7.5460	3758.21	10.9990	654.4024
9	6.6922	2955.84	10.2285	511.8848
10	7.3136	3530.23	10.0785	520.7240
11	7.5550	3767.13	10.3628	537.8688
12	7.4209	3634.57	10.8112	528.5888
13	6.8487	3095.67	10.4400	618.4192
14	7.7383	3952.13	12.0800	738.0384
15	7.4656	3678.49	12.6300	815.4336
16	7.9126	4132.22	13.3200	818.1248

5.4. Analysis of Commercial Regenerative Braking Data

The data acquisition system was used to record the current regenerated by the commercial regenerative braking system, into the battery. This data, along with the battery voltage, was used to analyze the total energy regenerated, as the commercial system directly regenerates back into the battery.

Calculation for Battery:

Coulombs Transferred = (Average current for the Interval) x (Interval) Eq 5.1

Table 5.4

Analysis of Commercial Regenerative Braking System Data

Data Set #	Speed Before Braking / (ms^{-1})	Total Kinetic Energy Before Braking / (J)	Duration of Braking / (s)	Energy Recovered / (J)
1	8.4406	4702.10	19.9777	303.09
2	7.5903	3802.45	21.0020	290.00
3	8.6058	4887.97	20.4570	325.92
4	9.0154	5364.32	23.2323	320.07
5	8.6093	4891.97	23.6651	327.39
6	8.9114	5241.26	23.3845	344.29
7	8.6129	4895.98	21.5945	321.53
8	8.5334	4806.08	22.9959	307.65
9	8.4955	4763.51	20.8369	312.65
10	8.2865	4531.98	20.6862	308.48
11	9.2864	5691.60	24.3622	360.95
12	9.5340	5999.19	25.3531	340.05
13	9.1377	5510.84	23.4652	388.50
14	8.2861	4531.54	20.1227	311.62
15	9.0747	5435.08	22.7699	355.17
16	8.4406	4702.10	19.9777	303.09

5.5. Comparison of Braking Time

The following table compares the braking time of each scenario. The data indicates that the braking duration of the commercial regenerative braking system is approximately twice that of the custom regenerative braking system. However both the custom regenerative braking system and commercial regenerative braking system are significantly slower than the mechanical braking system.

Table 5.5

Comparison of Braking Time for Different Braking Systems

Data Set #	Coast Stop / (s)	Mechanical Braking / (s)	Commercial Regenerative Braking / (s)	Custom Regenerative Braking / (s)
1	38.6641	2.4904	19.9777	6.3015
2	39.5630	2.2972	21.0020	9.7366
3	41.7590	1.5918	20.4570	10.0775
4	41.9560	2.8743	23.2323	10.6725
5	39.1295	3.3737	23.6651	9.3206
6	-	3.5639	23.3845	11.3972
7	-	4.9440	21.5945	11.5059
8	-	3.1370	22.9959	10.9990
9	-	3.3646	20.8369	10.2285
10	-	3.2295	20.6862	10.0785
11	-	3.1681	24.3622	10.3628
12	-	3.3492	25.3531	10.8112
13	-	3.7146	23.4652	10.4400
14	-	3.9527	20.1227	12.0800
15	-	3.0515	22.7699	12.6300
16	-		19.9777	13.3200

5.6. Comparison of Recovered Energy

Table 5.6 compares the energy recovered under each braking system. The comparison shows that the custom regenerative braking system recovers two to three times more energy than the commercial regenerative braking system.

Table 5.6

Comparison of Energy Recovered During Braking

Data Set #	Mechanical Braking		Commercial Regenerative Braking		Custom Regenerative Braking	
	Energy / (J)	As a Percentage of total Energy	Energy / (J)	As a Percentage of total Energy	Energy / (J)	As a Percentage of total Energy
1	-3208.07	-100%	303.09	6.45%	139.20	2.96%
2	-2696.65	-100%	290.00	7.63%	306.24	8.47%
3	-3079.51	-100%	325.92	6.67%	436.53	15.40%
4	-3865.97	-100%	320.07	5.97%	567.82	18.54%
5	-3783.67	-100%	327.39	6.69%	434.05	16.44%
6	-4206.28	-100%	344.29	6.57%	538.98	13.30%
7	-5230.74	-100%	321.53	6.57%	625.50	17.36%
8	-5120.25	-100%	307.65	6.40%	654.40	17.41%
9	-5028.31	-100%	312.65	6.56%	511.88	17.32%
10	-5668.44	-100%	308.48	6.81%	520.72	14.75%
11	-5812.12	-100%	360.95	6.34%	537.87	14.28%
12	-5817.31	-100%	340.05	5.67%	528.59	14.54%
13	-5601.05	-100%	388.50	7.05%	618.42	19.98%
14	-5763.84	-100%	311.62	6.88%	738.04	18.67%
15	-5181.86	-100%	355.17	6.53%	815.43	22.17%
16	-		303.09	6.45%	818.12	19.80%

5.7. Statistical Analysis

The research questions of this study focuses on two aspects related to the regenerative braking systems compared:

- Is there a statistically significant difference between the vehicles stopping time among the commercial regenerative braking system and custom regenerative braking system?
- Is there a statistically significant difference between the energy recovered by the commercial regenerative braking system and custom regenerative braking system?

The data compares the responses of two distinct systems and the two systems are independent from each other; therefore, the data were treated as a two-sample problem. Since the population standard deviations were unknown, two-sample "t" procedures were used to conclude the findings of the research. The energy recovered depends on the maximum speed reached. Therefore the percentage of energy recovered provides a better interpretation of the data and was utilized for the statistical analysis.

Table 5.7

Statistical Analysis of the Percentage of Energy Recovered by Regenerative Braking Systems

System	Sample Size	Sample Mean	Sample Variance
Custom Regen (μ1)	15	0.16561	0.00109983
Commercial Regen(μ2)	15	0.06585	0.00001994

H_0 :	μ1 = μ2
H_a :	μ1 > μ2
t-test Statistic	351.22
P-Value	2.53795E-29

According to the statistical analysis presented in Table 5.7, the t-test results in a probability value that is extremely small; i.e., there is strong evidence against the null hypothesis (H0: μ1 = μ2). Therefore the alternative hypothesis (H0: μ1 > μ2) is true, and hence the conclusion can be made that the custom regenerative braking system is better than the commercial regenerative braking system in recovering energy.

Table 5.8

Statistical Analysis of the Stop Time for the Regenerative Braking Systems

System	Sample Size	Sample Mean	Sample Variance
Custom Regen (μ1)	15	10.91	1.2195901
Commercial Regen(μ2)	15	22.26	2.855730532
H_0 :		μ1 = μ2	
H_a :		μ1 < μ2	
t-test Statistic		14.15	
P-Value		5.46297E-10	

According to the statistical analysis presented in Table 5.8, the t-test results in a probability value that is extremely small; i.e., there is strong evidence against the null hypothesis (H0: μ1 = μ2). Therefore the alternative hypothesis (H0: μ1 < μ2) is true and hence the conclusion can be made that the custom regenerative braking system is better than the commercial regenerative braking system in stopping the vehicle.

5.8. Conclusions

According to the analysis, the custom regenerative braking system is significantly better at recovering energy and stopping compared to the commercial regenerative braking system. The mechanical braking system stops significantly faster, but no energy is recovered. The custom regenerative braking system is approximately 200% better in recovering energy and 200% faster in stopping when compared with the commercial regenerative braking system. The main reason for the custom regenerative braking systems performance is the usage of ultracapacitors. High current handling capability of the ultracapacitor compared with a battery is advantageous as higher current generates more negative torque. However the custom regenerative braking system may require a mechanical braking system for emergencies.

The internal resistance of an ultracapacitor is 19mΩ. Eight capacitors in parallel result in an internal resistance of 2.375mΩ, but the motor winding resistance is 0.4Ω per winding. Therefore, when regenerating at high currents, significant amount of power gets dissipated in the windings. Current ultracapacitor bank consists of eight, 15V, 58F ultracapacitors in parallel (Maxwell Technologies, 2009). Theoretically, this configuration results in a capacitor bank which can withstand 15V and 12000A. The reason to add eight capacitors in parallel was to achieve faster power absorption. Fewer capacitors did not result in a faster stop as expected. The amount of charge stored in the ultracapacitor determines the ultracapacitor voltage and hence, how much energy can be captured in a regenerating cycle. Maintaining this voltage at a minimum would allow better operation of the regenerative braking system. According to the data, the maximum amount of coulombs captured during braking was 1636. Transferring this charge to the auxiliary battery before the next braking cycle, would allow optimum operation of the regenerative braking system. The auxiliary battery is a 12V, 6Ah lead acid battery. If the auxiliary battery was charged at a rate of 6Amperes, total time to transfer all the captured energy is 272 seconds (Eq 5.1). Therefore, for this system having a minimum time span of 4.53 minutes between two braking events will facilitate optimal regeneration in each cycle. The voltage rating of the capacitor bank can be reduced to 8Volts as the continuous discharging of the capacitor will maintain the capacitor voltage low. Therefore the cost of the capacitor bank can be reduced.

5.9. Future Work

Regenerative braking systems require further research to develop a better system that captures more energy and stops faster. The mechanical braking system on average dissipates energy at a rate of -1.8kW in order to achieve braking (including all friction losses). The custom regenerative braking system brakes at a maximum of -458W and an average of -243W. Future work includes research that focuses on improving the energy absorption rate to facilitate faster. Improving the machine design will be advantageous as the losses in the machine can be minimized. As a future potential extension to this research avenues related to improving regenerative braking systems as a whole and making it reliable may be explored.

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APPENDIX

APPENDIX .

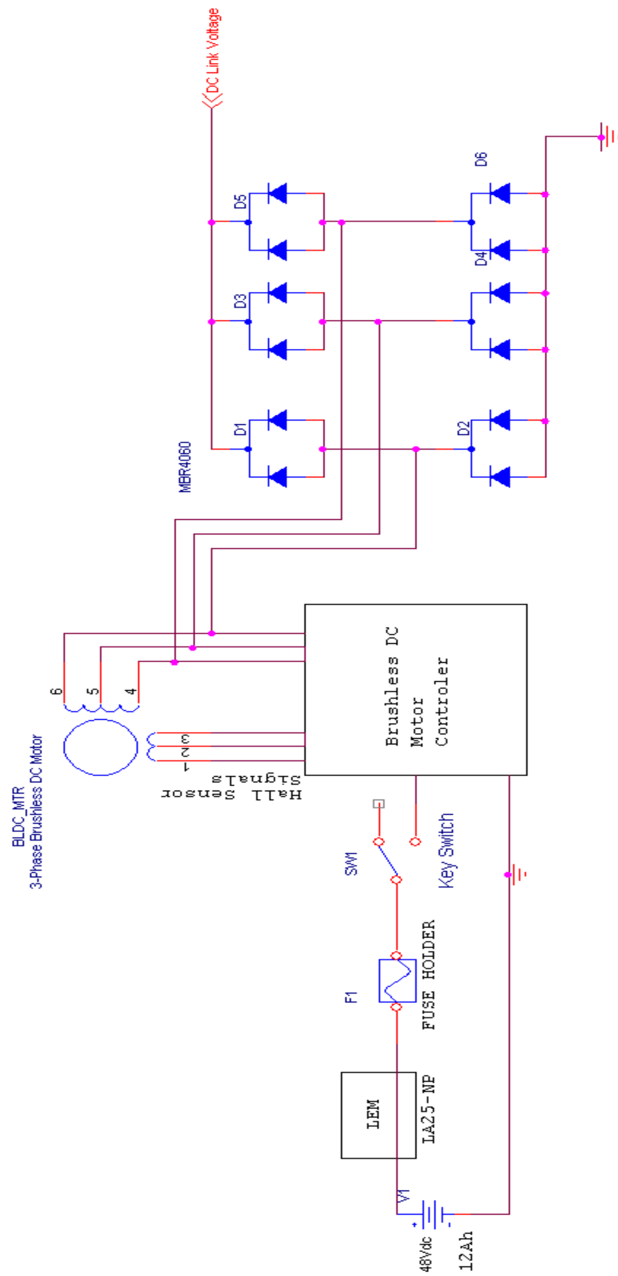

Figure A.1. Custom Regenerative Braking System Rectification Circuit

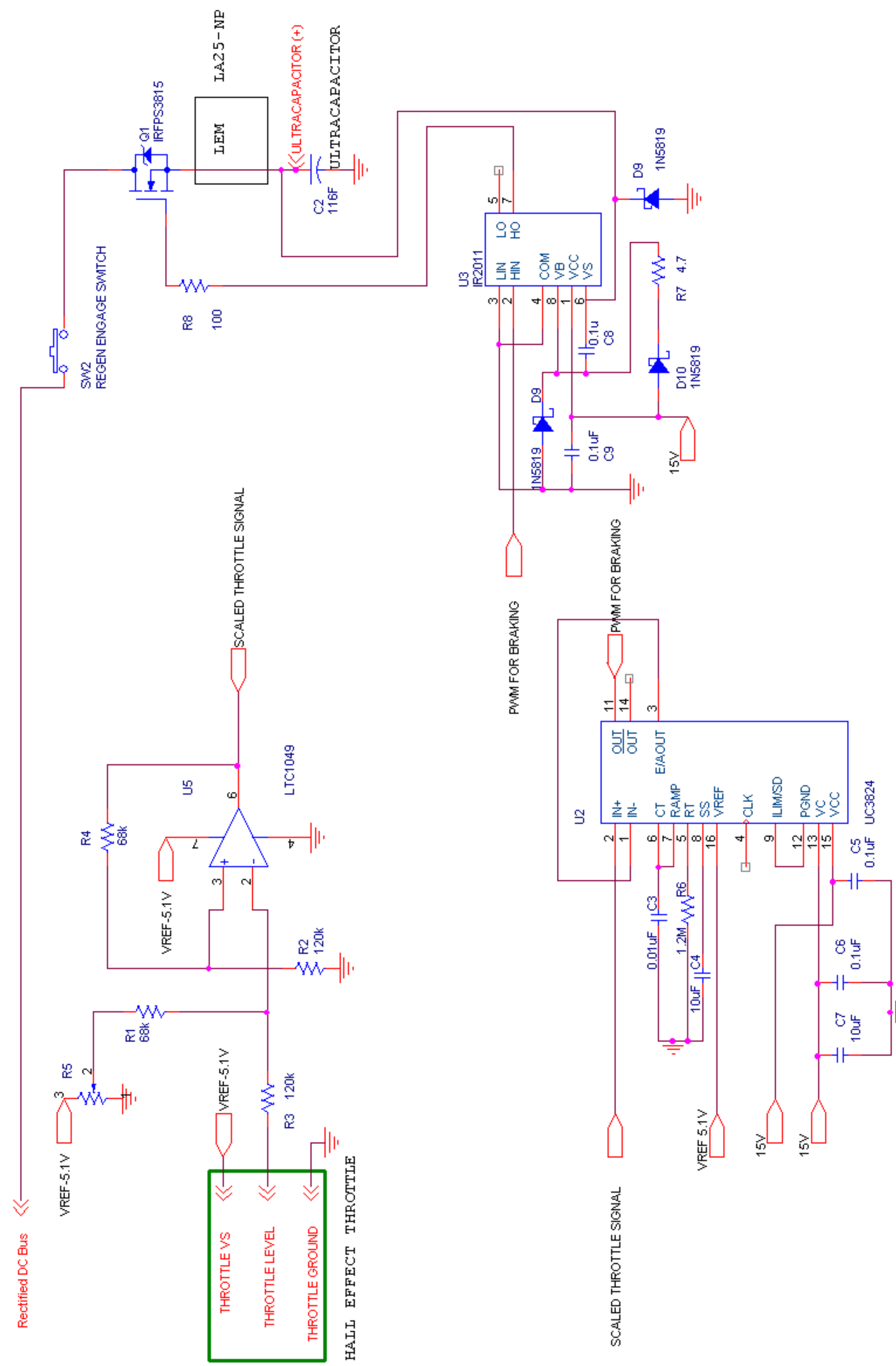

Figure A 2. Custom Regenerative Braking System Main Control Circuit

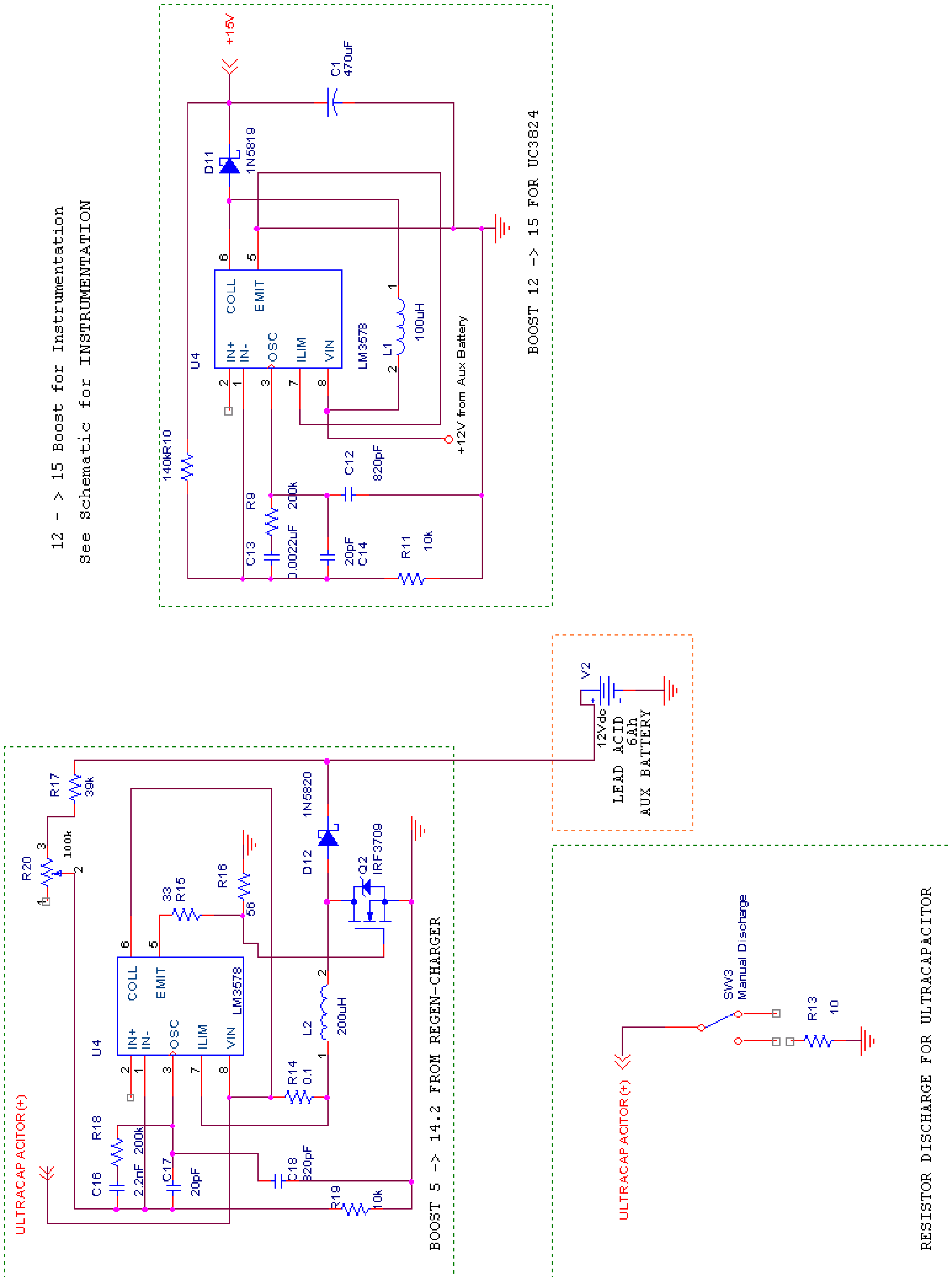

Figure A 3. Custom Regenerative Braking System Auxiliary Power System

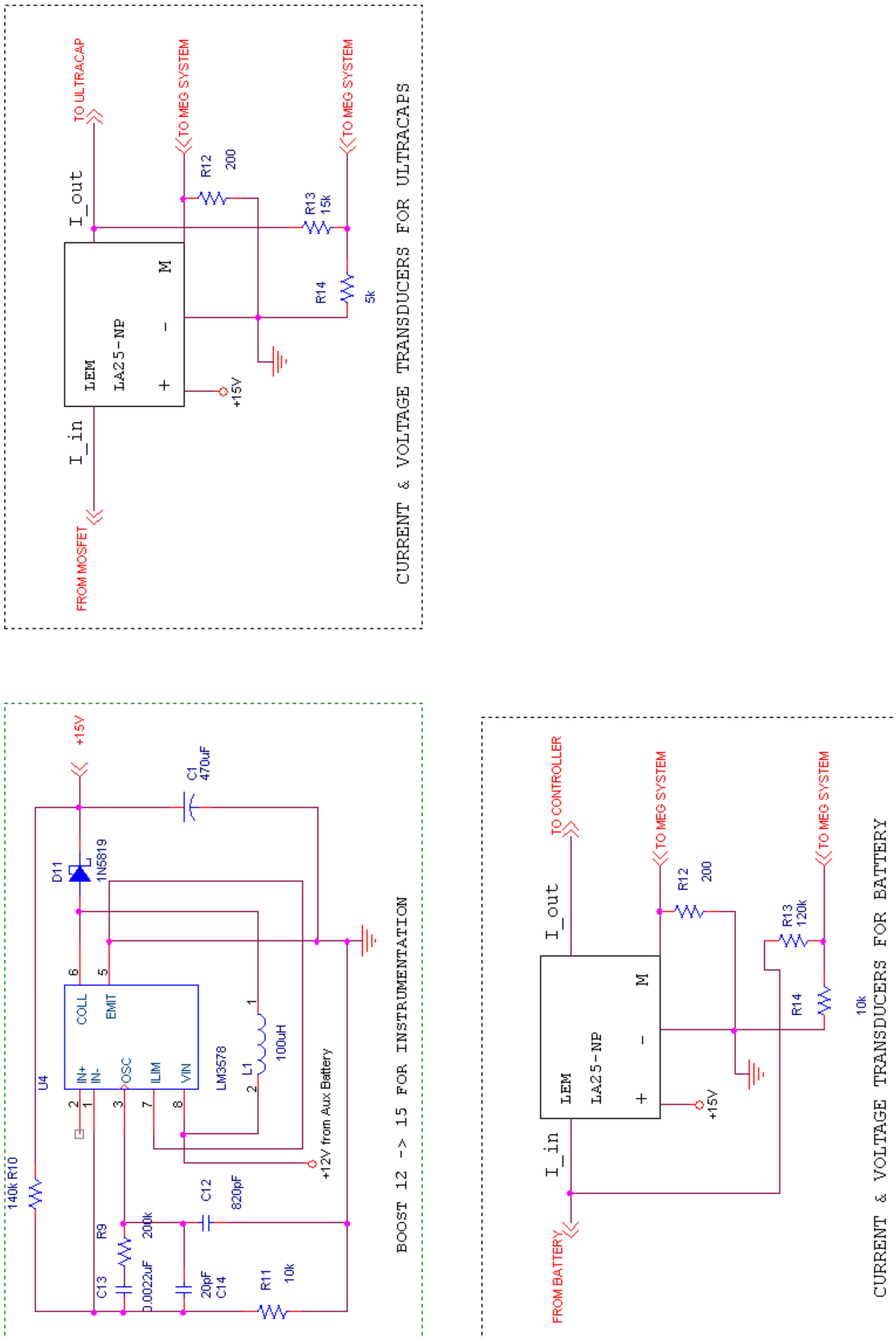

Figure A 4. Custom Regenerative Braking System Instrumentation System