Electric Double-Layer Capacitor Based Regenerative Braking Systems for Electric Bicycles
Improving the Efficiency of Emerging Transportation Technology in Developing Nations

Faculty Advisor:

Dr. Taufik
Professor, Electrical Engineering
Director, Electric Power Institute
Faculty Advisor for Previous Electric Bicycle Project

Department Chair:

Dr. Dennis Derrickson
Chair, Electrical Engineering Department
Associate Professor, Electrical Engineering

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http://goo.gl/LRcuG
**Project Objective:**

The main objective of this project is to improve the efficiency and operational range of an existing electric bicycle platform [2] through the addition of a high capacity Electric Double-Layer Capacitor (EDLC) based regenerative braking system. The project therefore investigates the effect of such systems on the operating efficiency of small electric vehicles as well as the technical and commercial feasibility of EDLC use in this industry. Because the vehicle is already in an operational state, this project provides a unique opportunity to measure the performance of the vehicle in a variety of operating circumstances both before and after the addition of the capacitive regenerative braking system. This in turn will allow us to gather accurate empirical data on the effects this system has on the performance and efficiency of the vehicle. Our goal is to have the modified vehicle exhibit 5-10% longer range than the unmodified vehicle in stop and go tests (at least two full stops per kilometer) and at least 75% of the range of the unmodified vehicle in continuous use tests (at least 5 kilometers uninterrupted use).

We anticipate that this objective will present a variety of challenges. The most prevalent is selecting, designing, and integrating the power electronics necessary for a functional regenerative braking system. Other concerns include vehicle mass, weight distribution, structural integrity of the frame, kinetic and even aerodynamic stability of the vehicle at 50 km/h, conformance to regional, state, and federal electric bicycle regulations, and ensuring that the high energy drive train components do not present danger to the user. Facing these challenges will require a very broad knowledge base and skill set, and we believe that our team possesses the diverse specialties and the motivation to learn necessary to successfully implement and study the proposed system.

**Significance:**

With the ongoing industrialization of undeveloped and developing nations, many of which include exceptionally dense population centers, the necessity for affordable, sustainable, and scalable urban transportation solutions presents itself as one of the foremost engineering problems of the twenty-first century. Electric bicycles represent an elegant solution to this problem, offering clean, compact, motorized transportation for one or two people at a few thousand US dollars per vehicle (a 2010 New York Times article [1] estimated the electric bicycle industry to be valued at $11 billion dollars, with 120 million units in China alone, and the industry is growing rapidly). However, such systems are still limited by their operating range and the additional cost and weight of extending this range.

One substantial advantage of electric vehicles over their hydrocarbon powered counterparts lies within the infeasibility of converting the kinetic energy of the combustion vehicle back into combustible fuel on the fly, which substantially reduces the efficiency of the vehicle in stop and go operating conditions, such as urban transit. Every time the vehicle stops all of its kinetic energy must be dissipated thermally, and then more fuel must be burned to accelerate the vehicle back to its initial velocity. Electric vehicles do not exhibit this shortcoming, as the transformation between electrical and mechanical energy within the electric motor is a highly reversible process. Most commercial hybrid and electric vehicles rely on chemical batteries, however, and these batteries’ chemical characteristics limit the rate at which they can take on energy. This creates an inherent
incompatibility with regenerative braking implementations, as the power generated by regenerative braking often greatly exceeds the maximum charge rate of the batteries.

The vehicle we are working with currently suffers from this exact shortcoming. Although the motor controller offers regenerative braking support, which can be used to recharge the battery with energy from the pedaling mechanism, the current system can only load the hub motor onto the lithium-ion batteries. These batteries cannot take on electrical energy nearly as rapidly as any reasonably safe braking system requires to dissipate kinetic energy, so the current regenerative braking system cannot be used for efficient kinetic energy recovery. We will attempt to correct this in the modified system with the addition of a high-capacity rapid-charge EDLC ultracapacitor bank for short term energy storage. In the modified configuration the vehicle will be primarily powered by its current batteries, with a supporting EDLC bank capable of storing all the energy recaptured by braking the vehicle. Whenever possible the controller will use power stored in the EDLCs, allowing the system to capture and reuse a significant portion of its operational kinetic energy. Furthermore, because the capacitors support discharge rates far greater than that of the battery bank, there exists the possibility of improving the acceleration characteristics of the vehicle after regenerative deceleration, or at least of offsetting the added weight of the EDLC system.

By increasing the efficiency of the vehicle in urban transit scenarios, we hope to partially alleviate the primary shortcoming of electric vehicles in general (that they have relatively limited range compared to their hydrocarbon powered counterparts) and help humanity move toward a cleaner, less fossil fuel dependent future.

Additional Opportunities Seeded by This Project

The primary opportunity this presents is in providing the capacitive framework necessary to support additional rapid power generation systems. Hydrocarbon powered range extenders (internal combustion-driven generators designed to charge the power supply) are an excellent way to add inter-city transit capabilities to an otherwise short range vehicle. They tend to burn fuel more efficiently than mechanical drive internal combustion systems because the engine operates at it’s most efficient speed and output power, and the engine is always providing useful work, even when the vehicle is not moving. With normal battery systems these range extenders are difficult to utilize efficiently. Like regenerative braking mechanisms, they typically supply much more than a normal battery’s charging current. Recently there has been promising research into gas microturbine based range extenders, as demonstrated by the recent debut of Capstone Turbine Corporation’s CMT-380 microturbine range-extended electric supercar concept [3]. Very small microturbines have the potential to deliver relatively lightweight, efficient, and quiet range extension for electric bicycles when compared to piston driven alternatives. Furthermore, many of the core disadvantages of gas turbine engines in surface vehicles - their poor response to variable power demands, high idle fuel consumption, and the narrow RPM range at which they operate efficiently - are largely overcome by using them to drive a generator at a constant speed and power. This technology is highly experimental, even for large vehicles, but investigating its feasibility on very small electric vehicles represents an extremely exciting opportunity for cutting edge research in a field very relevant to a rapidly growing global industry.
Milestones and Schedule

1. Milestones needing only confirmation of project approval:
   a. Test power requirements and power output of hub motor - within 1 month of [1]
   b. Return the vehicle to a reliable state - within 2 months of [1]
   c. Subject vehicle to performance and efficiency testing - within 2 months of [1b]
      i. Mount precise power instruments and readouts for testing purposes
      ii. Design a variety of performance and efficiency tests to benchmark the vehicle in an unmodified state
   d. Begin initial design work on packaging and mounting solutions for the EDLC system. - Ongoing until completion of [2e]

2. Milestones Requiring Distribution of Project Funding:
   a. Order system components outlined in the budget. - within 1 week of [2]
   b. Receive components by mail - conservative estimate at 1 month of after [2a]
   c. Test interface characteristics of power electronics components to ensure proper functionality. - within 3 months of [2b], can be done concurrently with [2d]
   d. Design and implement mounting mechanisms for power electronics, notably capacitor banks, and ensure weight distribution and other mechanical characteristics are acceptable. - within 3 months of [2b], can be done concurrently with [2c]
   e. Rebuild the vehicle’s component mounting frame - within 1 month of [2d]
   f. Rebuild electronics system mounted on bicycle frame - within 1 month of [2e]
   g. Subject vehicle to comprehensive functionality tests to ensure it’s capability of completing tests. - within 1 month of [2e] and [2f]
   h. Conduct second round of vehicle testing - within 1 month of [2g]
   i. Compile results into a presentable form - within 1 month of [2h]

Estimated completion date: 12 months after distribution of funding

Project Team
Forrest Reiling - Computer Science - Project Lead, Android Smartphone Bluetooth Integration
Brandon Ivy - Computer Engineering - Extensive Microcontroller Experience, Embedded Systems
Scott Leonard - Electrical Engineering - Power Electronics Expertise, P.E.S. Liaison
Isaac Nitschke - Aerospace Engineering - Vehicle Stability and Thermal Control Systems
Trevor Jones - Mechanical Engineering - Mechatronics, Control/Power Systems Interface
William Meijer - Mechanical Engineering - Motorcycle Expertise, Designated Test Driver
Vincent Khougaz - Industrial Engineering - Bicycle and Unicycle Expertise, Manufacturing QA
Mathew Hei - Business and Information Systems - Corporate and Legal Liaison
Zechariah Thurman - Physics - Solid State Systems, Energy Dynamics Expertise
Jennifer Berg - History - Social Impact and Sustainability Outlook
Facilities and Equipment:
This project will be assembled and stored in room 101 of building 20. Our team will use personal tools for the majority of the construction process. We also have access to Cal Poly’s Mustang ‘60 Machine Shop for specialized fabrication. Our faculty advisor Dr. Taufik can provide us with additional resources and contacts for the project, including the power electronics and machines lab.

Plans for Findings
At present this project mainly serves as an educational exercise that will attempt to investigate the feasibility of relatively low cost regenerative braking systems in small electric vehicles. We do not expect this project to produce any intellectual property or participate in any formal competitions. However, with help from our Faculty Advisor, we will disseminate the results of this project to venues such as technical conferences as well as outreach activities to local middle and high schools.

Budget

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<th>Item Name</th>
<th>List Price</th>
<th>Qty</th>
<th>Item Total</th>
<th>Miscellaneous Specifications</th>
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<td>Maxwell 650 Farad Ultracapacitor</td>
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<td>$828.00</td>
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<td>Ultracapacitor Charge Controller</td>
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<td>MOSFET N-CH 30V 40A TO251-3</td>
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<td>DIODE SCHOTTKY 75A 200V</td>
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<td>RES 2.2 OHM 50W 5% WW LUG</td>
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<td>CAP CER 100PF 2KV 10% RADIAL</td>
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<td>Power Wire 20’ Rolls</td>
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<td>8,12,16 AWG, Stranded Copper</td>
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<td>AC Inverter</td>
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<td>Colored Hookup Wire 550’</td>
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<td>Low Voltage Electrical Socket</td>
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<td>Shrink Wrap</td>
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<td>Multi Colored, 8 &amp; 22 AWG</td>
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<td>Assorted Brackets &amp; Braces</td>
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<td>Assorted Length Bolts</td>
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<td>Assorted Length Machine Screws</td>
<td>$14.99</td>
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OTHER ESTIMATED EXPENDITURES
Electrical System Component Enclosures | $150.00 | N/A |
Frame and Mounting Components | $100.00 | N/A |
Specialty tools | $100.00 | N/A |
Miscellaneous / Unanticipated Expenses | $200.00 | N/A |

GRAND TOTAL | $2,999.99 | N/A |
Technical Considerations:

When used as power supply systems, ultracapacitors suffer from two major problems that need to be addressed for this project. First, the maximum rated voltage of most ultracapacitors is between 2.5 and 2.7 volts. This voltage is far too low for a direct interface with our system’s 48v components. Our solution to this problem is to use multiple ultracapacitors in series to raise their collective operating voltage to a more useful value. This series configuration will require a highly reliable monitoring system to keep the capacitor voltages in a safe operating range. In addition, a balancing circuit will need to be implemented between each of the series capacitors to assure an equal charge distribution across the bank.

The second challenge we must overcome is the exponential decay of our capacitor’s output voltage during discharge. The output voltage of a capacitor drops down to zero during a discharge cycle, so a capacitor’s output voltage is tied to its stored energy at a given time. We address this problem by using a DC-DC converter to draw energy from our capacitive bank by boosting its output voltage to a steady 48v from a dynamic input range.

The usable voltage range of our capacitor bank will be determined by the input limits on our DC-DC converter. Because our converter can only accept an input from 19 to 72 volts, the capacitor bank must charge to 19 volts before any useful energy can be extracted from it. This will place a limit on the usable capacity of the EDLC, but preliminary calculations estimate that no more than 15% of the bank’s capacity lies below the 19 volt floor.

We are currently planning on limiting power transfer to 1kW at all points on the bike both for the purpose of design simplification and as a means of unambiguously maintaining the vehicle’s legal classification as an electric bicycle (which eliminates the need for DMV certification and registration). We are willing to add circuitry to enforce this limit if necessary, and each component listed in the budget is capable of handling it’s respective current requirements. We are also leaving the standard cable brake system unchanged as a redundancy measure for the regenerative braking system. The EDLC system should be fully capable of taking the place of conventional brakes - especially on such a small vehicle - but in the event of system failure cable brakes will guarantee normal operational safety.

References:
Electronics Block Diagram

- **Battery Wall Charger**
  - 56.4v
  - 48v Lithium-Ion Pack
  - 12v DC Buck Converter 120W

- **Power Flow**
  - 48v
  - Power Input Regulator
  - DC-DC Boost Converter 1000W

- **Motor Controller**
  - 48v
  - Ultracapacitor Bank
  - 0-34v

- **Excess Power Discharge Resistor**
  - 0-48v
  - Ultracapacitor Charge Controller
  - 0-48v

- **Components**
  - Existing Electric Drive Train Components
  - Components to be Added for This Project
  - Regenerative Braking Trigger Mechanism
  - Electric Double Layer Capacitor Array
  - 1000 Watt Hub Motor with Hall Effect Sensor Array

- **Sticky Notes**
  - Variable Voltage
  - Conditioned Voltage

- **Throttle and Control Mechanism**
  - 576 Watt Hour Lithium Ion Battery Pack With Integrated Charge Mechanism
  - Motor Controller Assembly