A Simple Series Battery/Ultracapacitor Drive System for Light Vehicles and Educational Demonstration

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Edgerton Center Summer Engineering Workshop 2008

Edgerton Center Summer Engineering Workshop

- Student-Driven Projects Workshop at MIT
- Collaboration of MIT Students and Local High School Students
- Blend of Technical Challenge and Educational Experience

2007:

Team Members: Ethan Aaron, Costas Akrivoulis, Shane Colton, Ronny Contreras, Max Hill, Kevin Krakauer, David McCarthy, Mike Paresky, Edwin Perez-Clancy, Matt Robertson, Anil Singhal, and Cameron Tenny

2008 S.E.W. Project: “The Cap Kart”

Project Objectives:

- Design, build, and test a small electric vehicle, based on a go-kart, with a combined battery/ultracapacitor energy storage and drive system.
- Create a low-cost system that could be easily implemented in light, DC-drive electric vehicles and possibly expanded to full-size vehicles.
- Employ simple design, modeling, and analysis methods, consistent with the educational motivations of the project.
- Create a test vehicle that is both a reliable experimental platform and a fun educational tool:
  - Wireless data acquisition. “Drive now, analyze later.”
  - Retain or improve the level of performance of a typical gas go-kart:

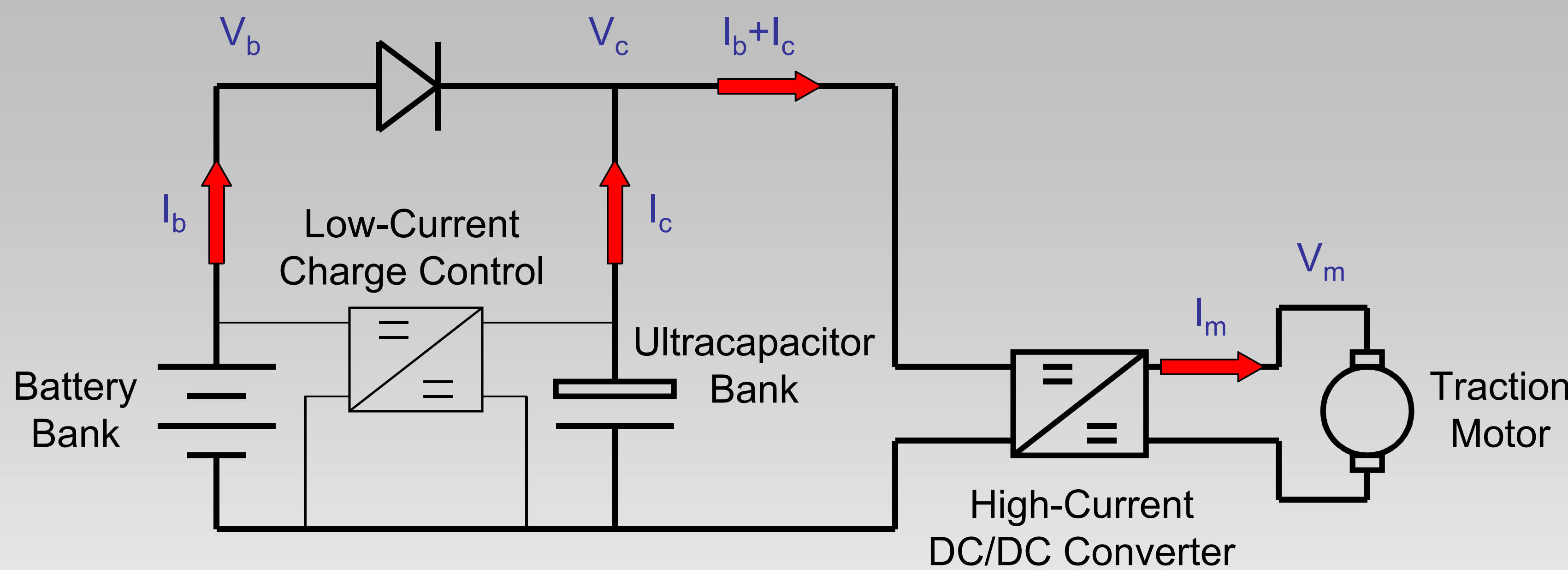
Technical Background: Battery/Ultracapacitor Hybrids

Battery	Ultracapacitor
• High energy density (by mass, volume, cost).	• Low energy density (by mass, volume, cost).
• Low power density, especially in charging.	• High power density in both directions.
• Low cycle life.	• High cycle life.

- An optimized (by cost, mass, volume) combination of batteries and ultracapacitors can take advantage of the best characteristics of each[1].
- Certain battery chemistries, such as lithium Iron phosphate, make these differences less dramatic.
- Similar optimizations exist with other combinations (fuel cell, flywheels, etc).

[1]R.M. Sclupbach et. al., “Design methodology of a combined batteryultracapacitor energy storage unit for vehicle power management,” in Proc. *Power Electronics Specialist Conference, IEEE*, Vol. 1, pp. 88-93, Acapulco, Mexico, 2003.

Battery/Ultracapacitor Hybrids: Parallel Methods



$$V_c > V_b$$

Ultracapacitor operating voltage is always greater than battery voltage.

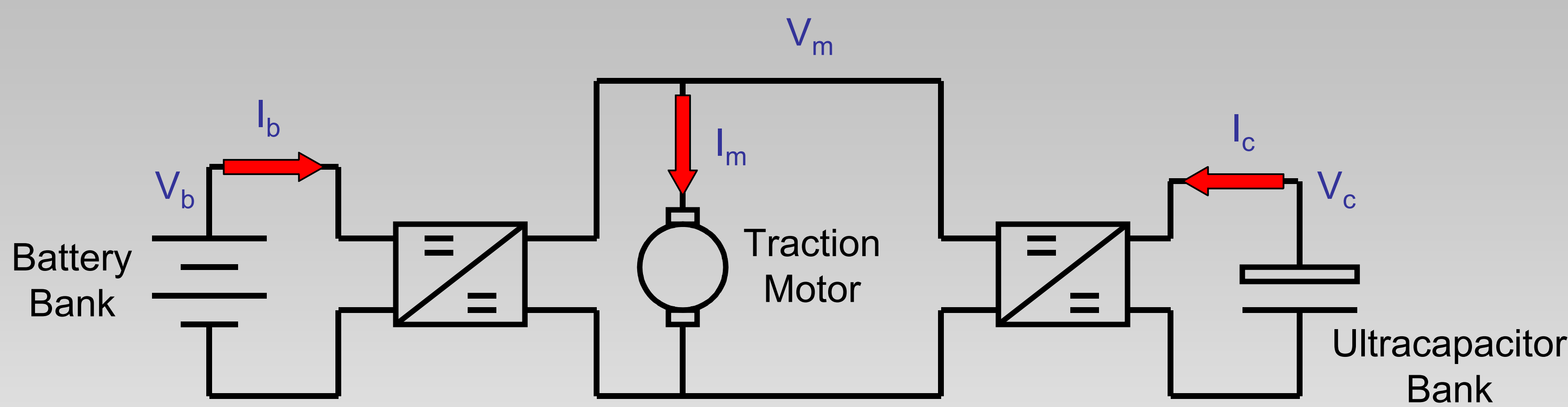
$$V_c(I_b + I_c) \approx V_m I_m$$

Power sharing by summation of currents.

Regenerative braking charges the ultracapacitor, which can then trickle-charge the battery through the low-current DC/DC converter.

Seen in: A.W. Stienecker, M.A. Flute, and T.A. Stuart, “Improved Battery Charging in an Ultracapacitor–Lead Acid Battery Hybrid Energy Storage System for Mild Hybrid Electric Vehicles,” in Proc. SAE World Congress, Detroit, Michigan, USA, 2006.

Battery/Ultracapacitor Hybrids: Parallel Methods



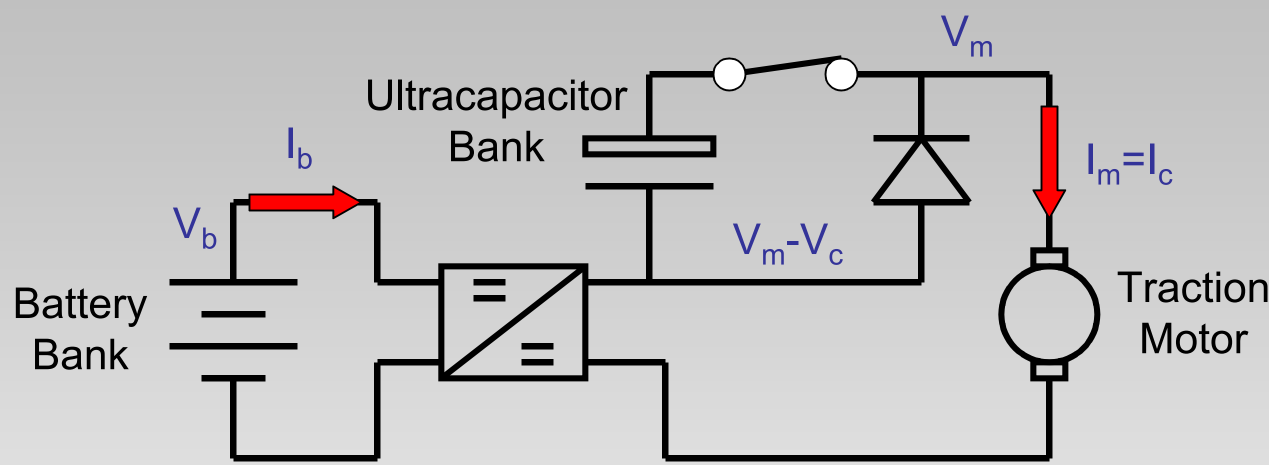
$V_b I_b + V_c I_c \approx V_m I_m$ All power transfer paths available.

Two bi-directional DC/DC converters permit power transfer in any direction between battery, ultracapacitor, and traction motor.

Seen in: P.C.K. Luk and L.C. Rosario, “Power and Energy Management of a Dual- Energy Source Electric Vehicle – Policy Implementation Issues,” in Proc. International Power Electronics and Motion Control Conference, IEEE, pp. 1-6, Shanghai, China, 2006.

Also seen in: “Electric Green Racing,” University of Manchseter, online final project video: http://www.eee.manchester.ac.uk/undergraduate/courses/specialfeatures/fourthyearproject/Electric_Green_Racing_medium.wmv, 2007.

Battery/Ultracapacitor Series Configuration



$$V_b I_b \approx (V_m - V_c) I_m$$

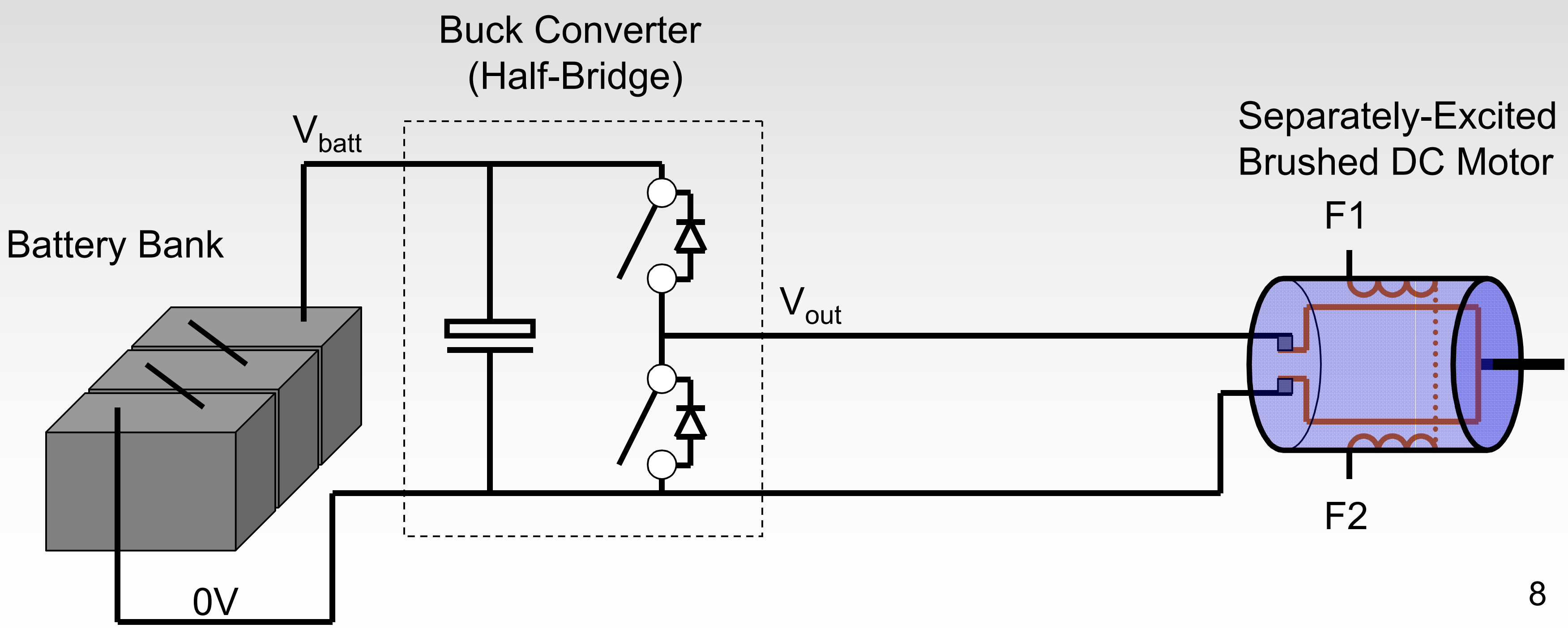
Power sharing by summation of voltages.

Voltage present on the ultracapacitor reduces the current demand from the battery at a given motor current demand.

Regenerative braking charges the ultracapacitor only. Switch and bypass diode allow for selective inclusion of ultracapacitor during acceleration.

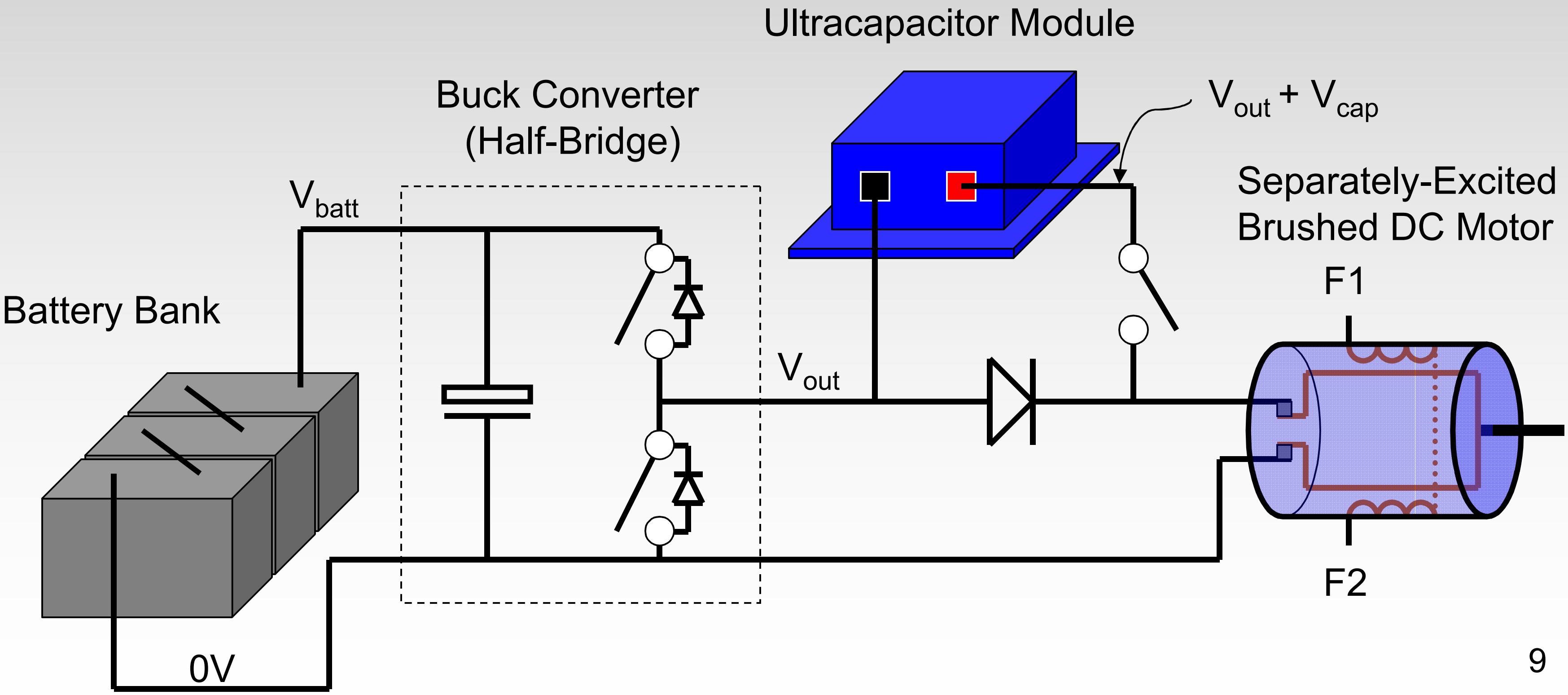
Standard Separately-Excited Drive

- Starting-point for our experimental vehicle drive system.
- High-power (300A @ 36V) buck converter for armature.
- Low-power (30A @ 36V) buck converter for field. (Not pictured.)
- Independent field control for "gearing."



Series Ultracapacitor Modification

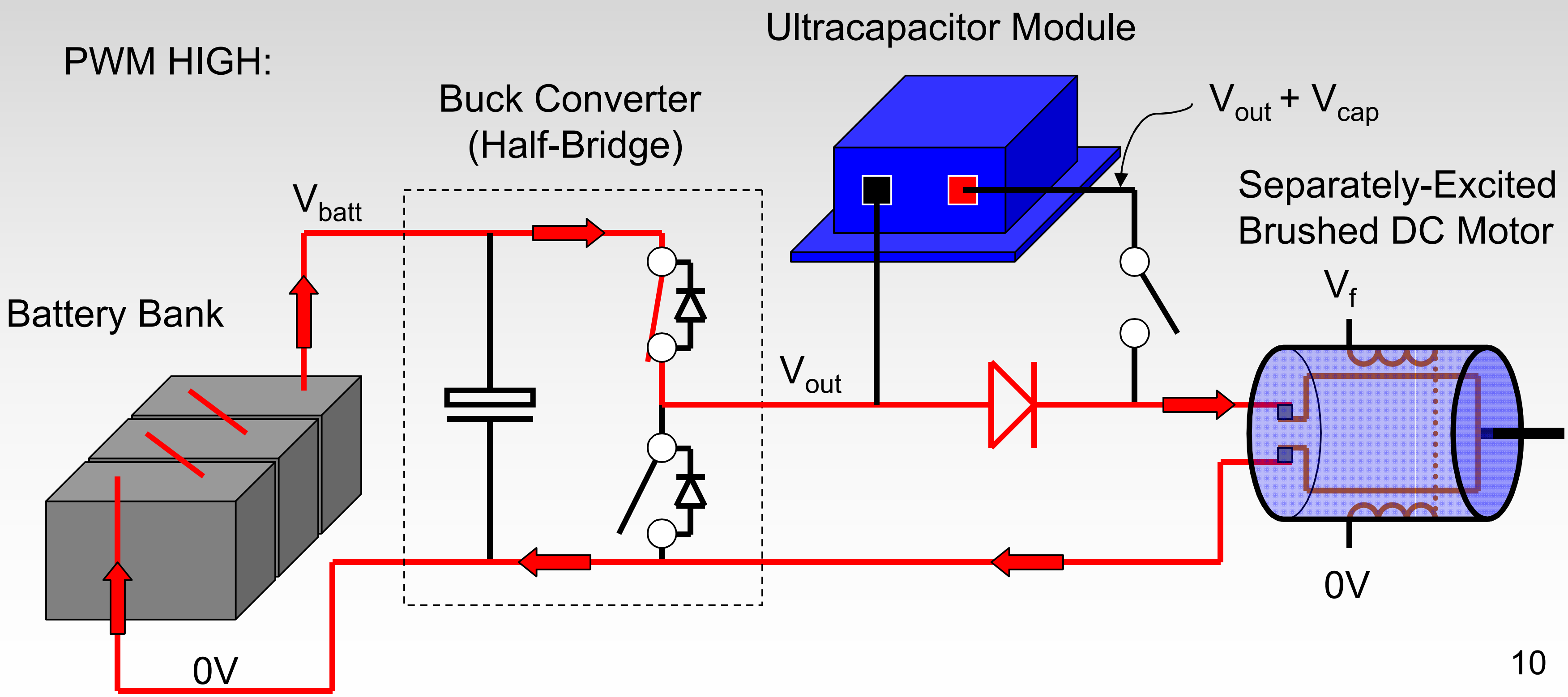
- Retain the same power converters.
- Add ultracapacitor module in series with motor.
- Add bypass diode and brake/boost relay.
- Modify control strategy as follows.



Normal Drive (Capacitor Bypass)

- Battery-only drive, same as standard separately-excited drive.

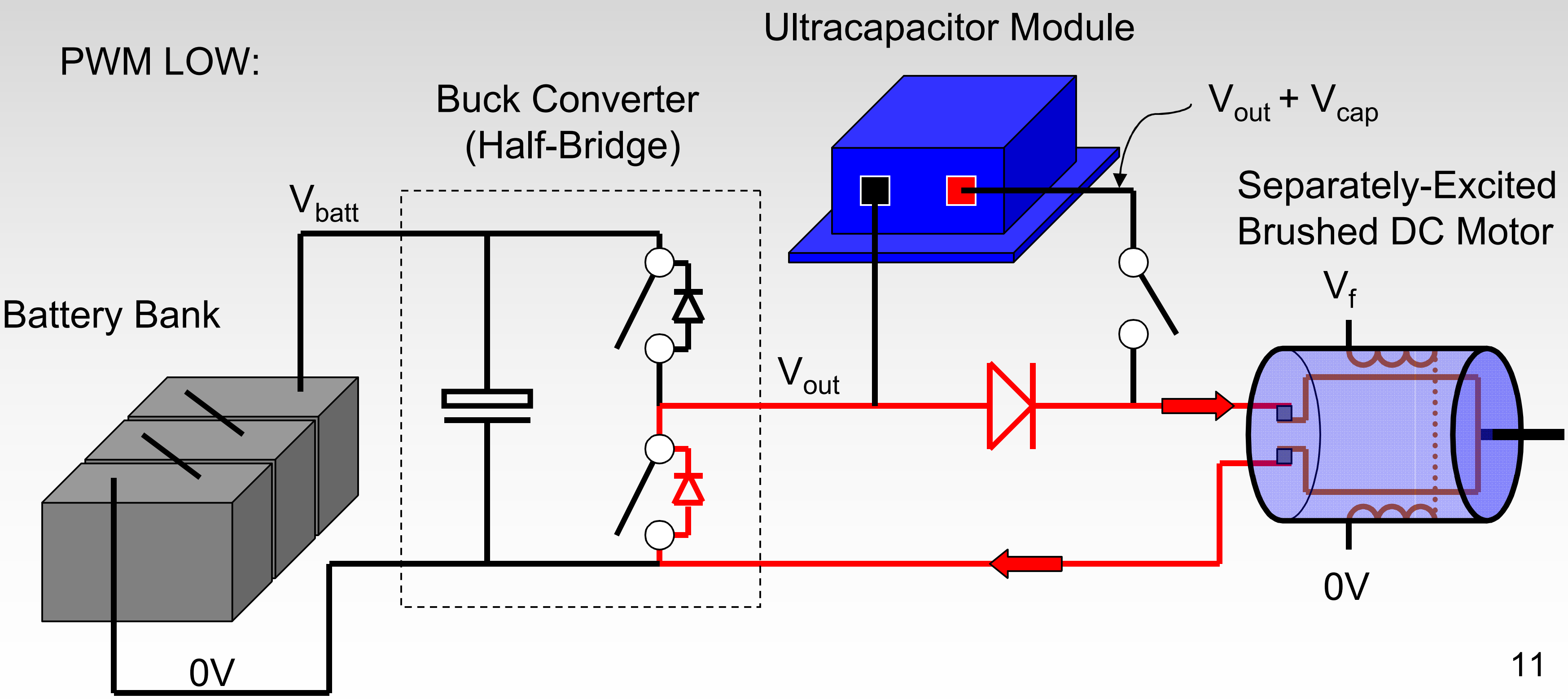
PWM HIGH:



Normal Drive (Capacitor Bypass)

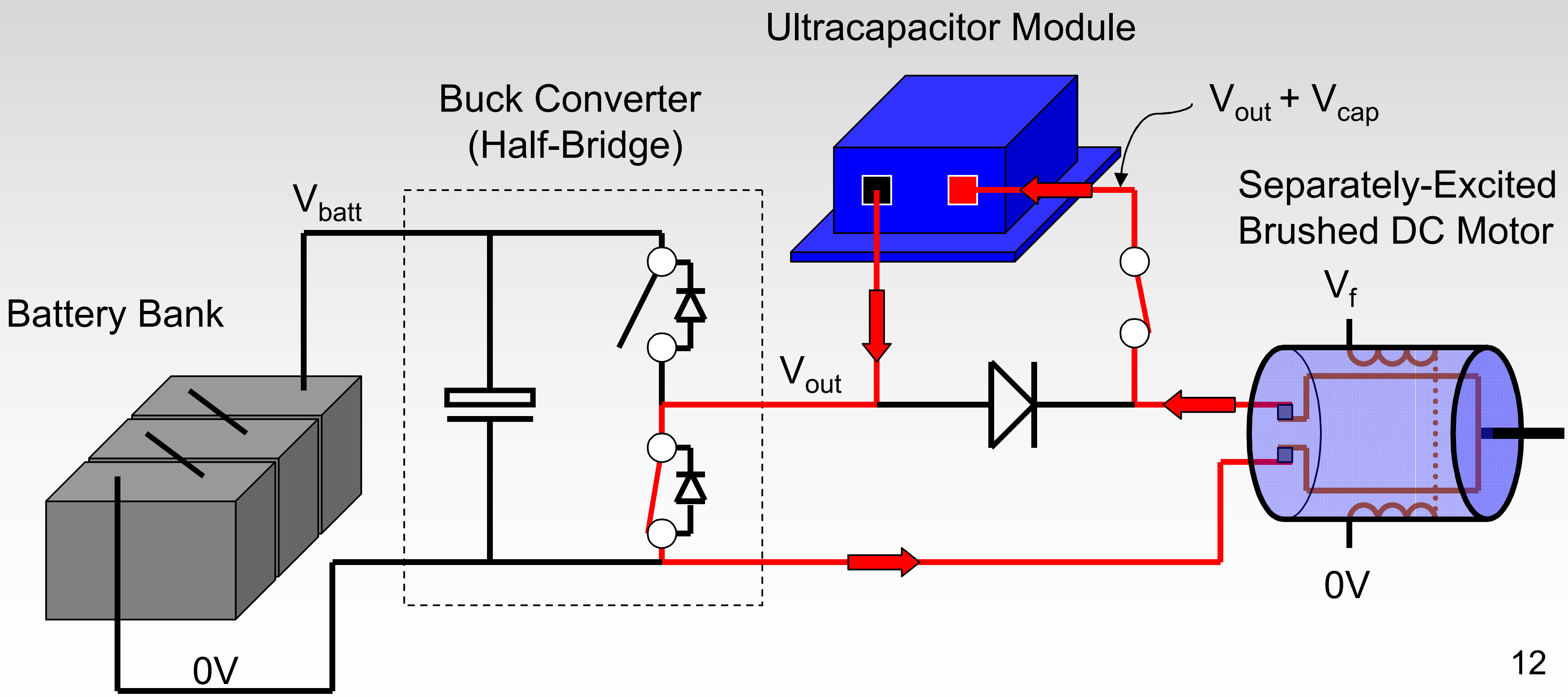
- Battery-only drive, same as standard separately-excited drive.

PWM LOW:



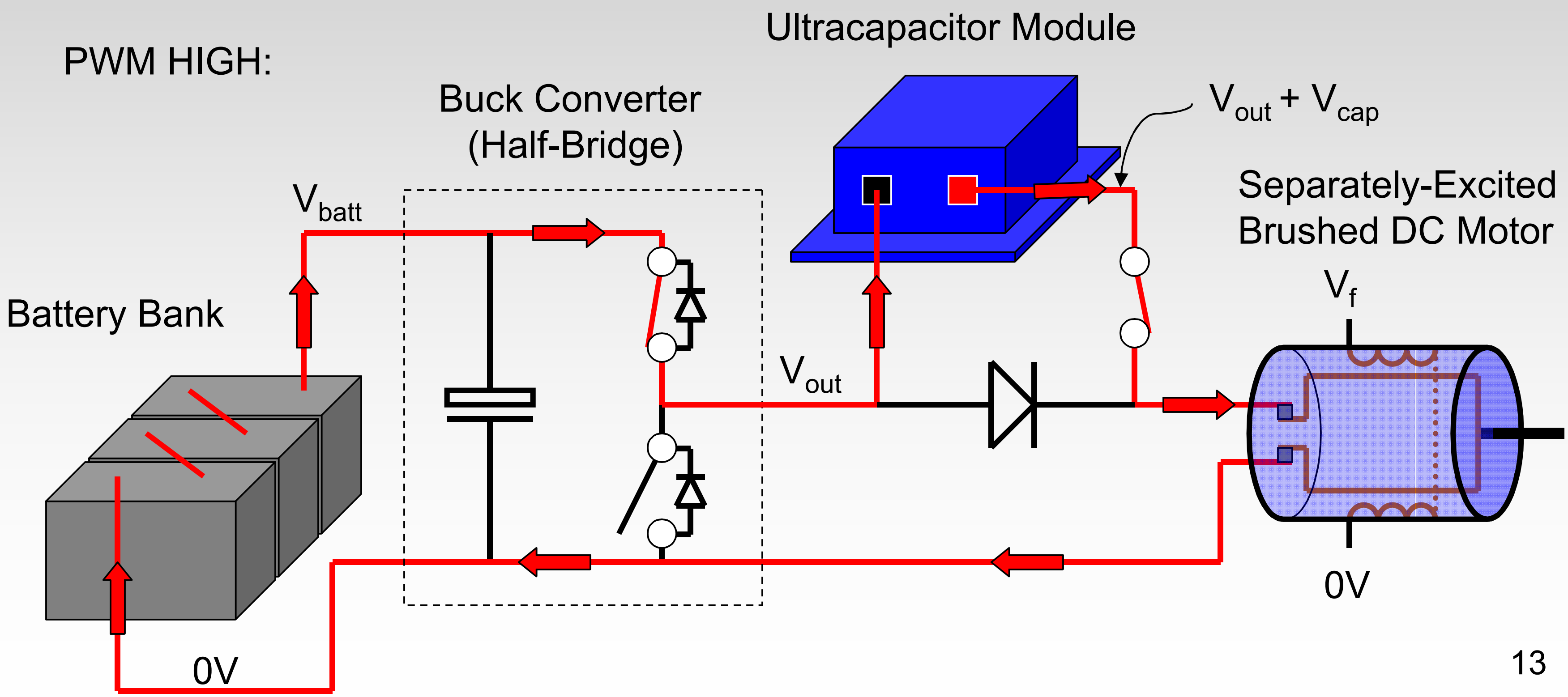
Regenerative Braking

- Low side of half-bridge held closed. Capacitor relay closed. All regen current flows through ultracapacitor. *Batteries are not involved*.
- Field strength controls braking force.
- No high-current switching.



Capacitor Assist

- Same as normal drive, but with power assist from the ultracapacitor.
- Series power sharing by sum of voltages. Battery current automatically reduced by half-bridge controller.



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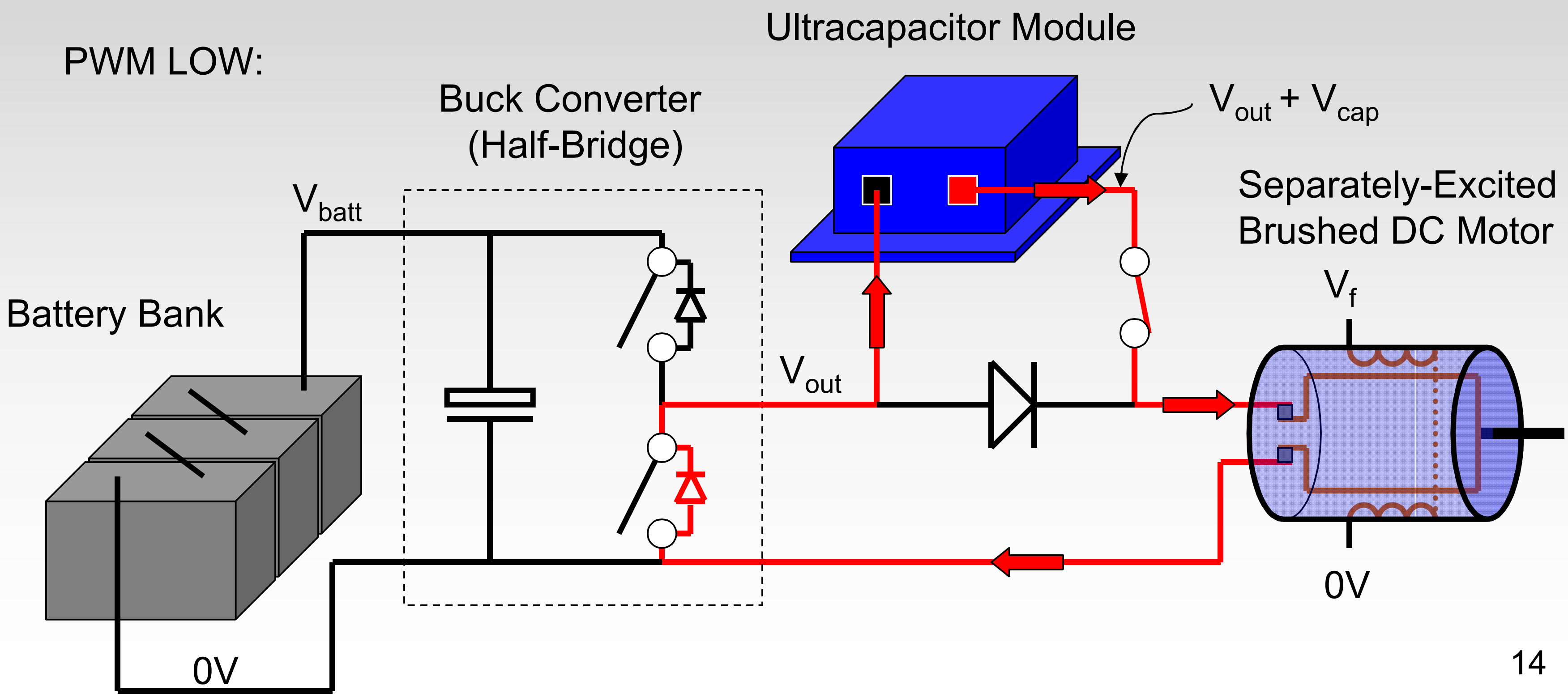
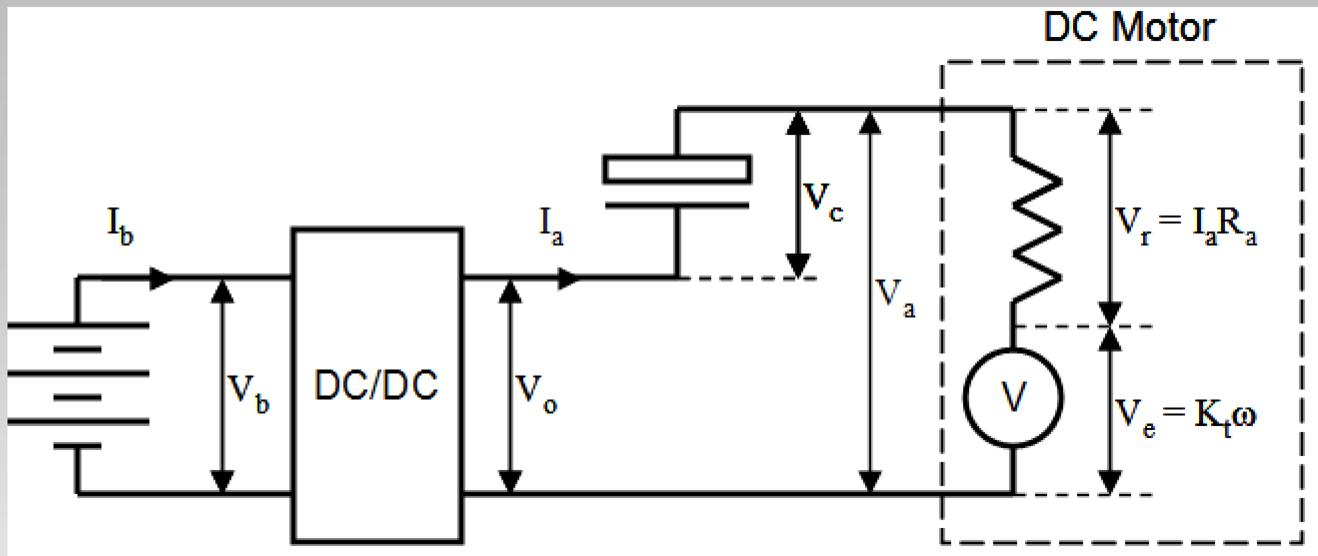


Simple Analytical Model



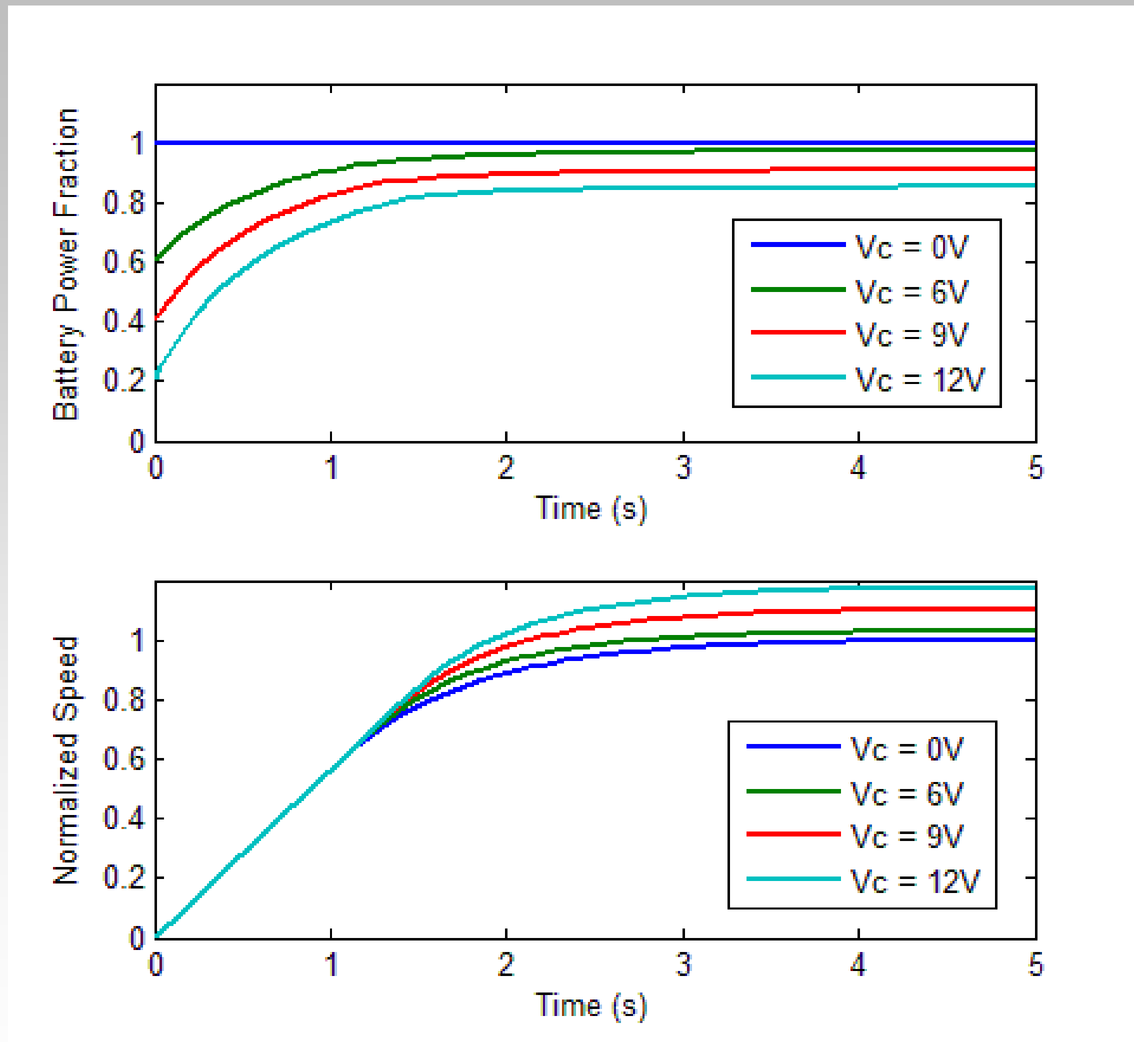
Armature resistance dominates dissipative effects, suggests a simple power conservation approach:

$$P_{motor} = P_{batt} + P_{cap} - I_a^2 R_a = \tau_a \varpi \,, \quad (1)$$

$$P_{cap} = I_a V_c \Rightarrow \quad (2)$$

$$P_{batt} = \tau_a \varpi + I_a^2 R_a - I_a V_c \,, \quad (3)$$

Series Power Sharing During Acceleration Assist



Example simulation showing reduced battery load, increased top speed.

Series Configuration Attributes

- Smaller ultracapacitor. Entire voltage range used, down to zero volts. Can be significantly lower voltage than the battery.
  - Decreased cost.
  - Decreased series resistance.
  - Easier cell balancing.

- No external inductors. All switched current passes through motor windings.

- One single-directional DC-DC converter; could be an off-the-shelf DC motor controller. Converter sees fixed battery input voltage.

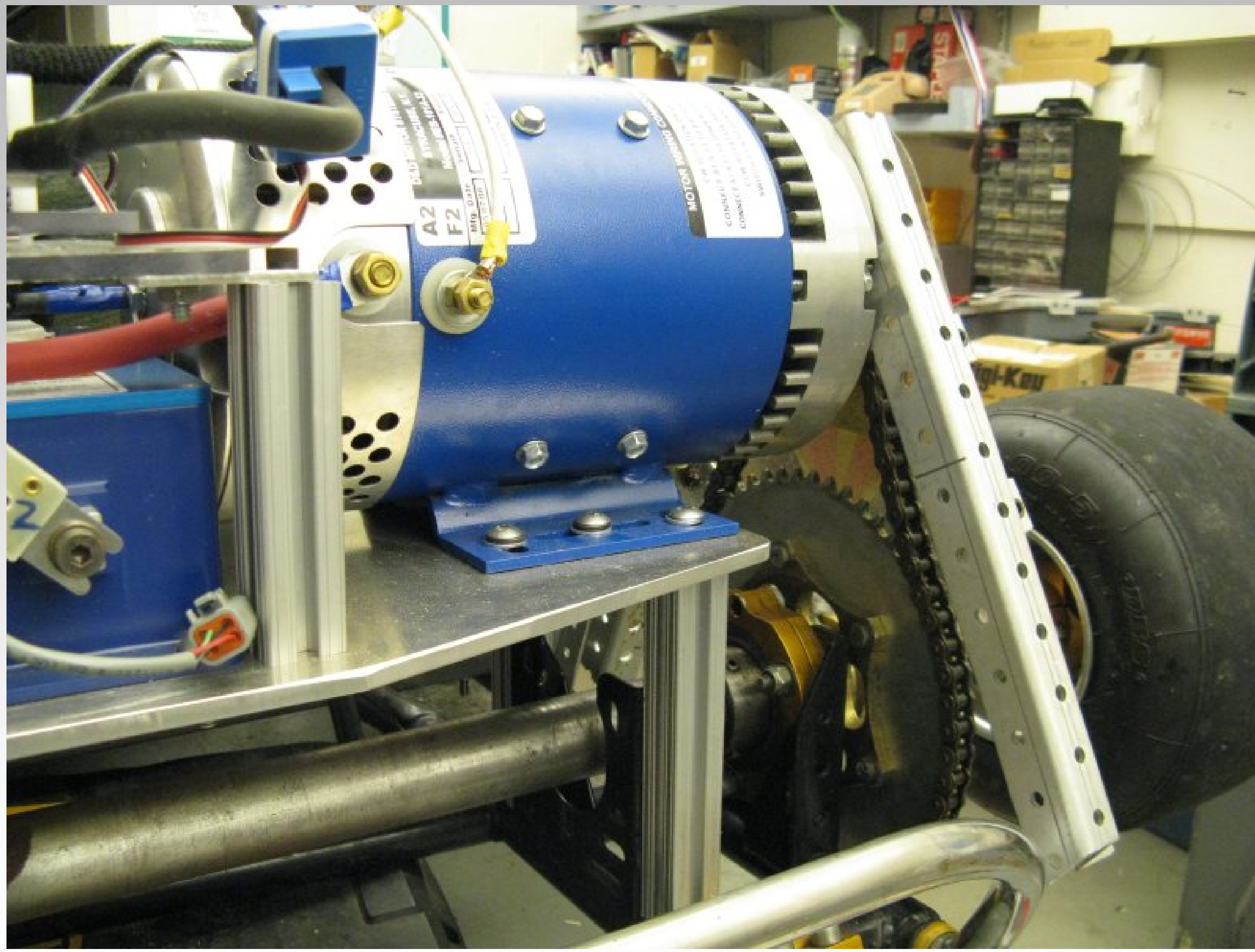
- No pre-charge circuit required for the ultracapacitor.

- Simpler circuit to model, build, explain, and demonstate, important for the educational objective.

- Disadvanatge: No direct power transfer path between battery and ultracapacitor. All regenerated energy can only be re-used by motor.

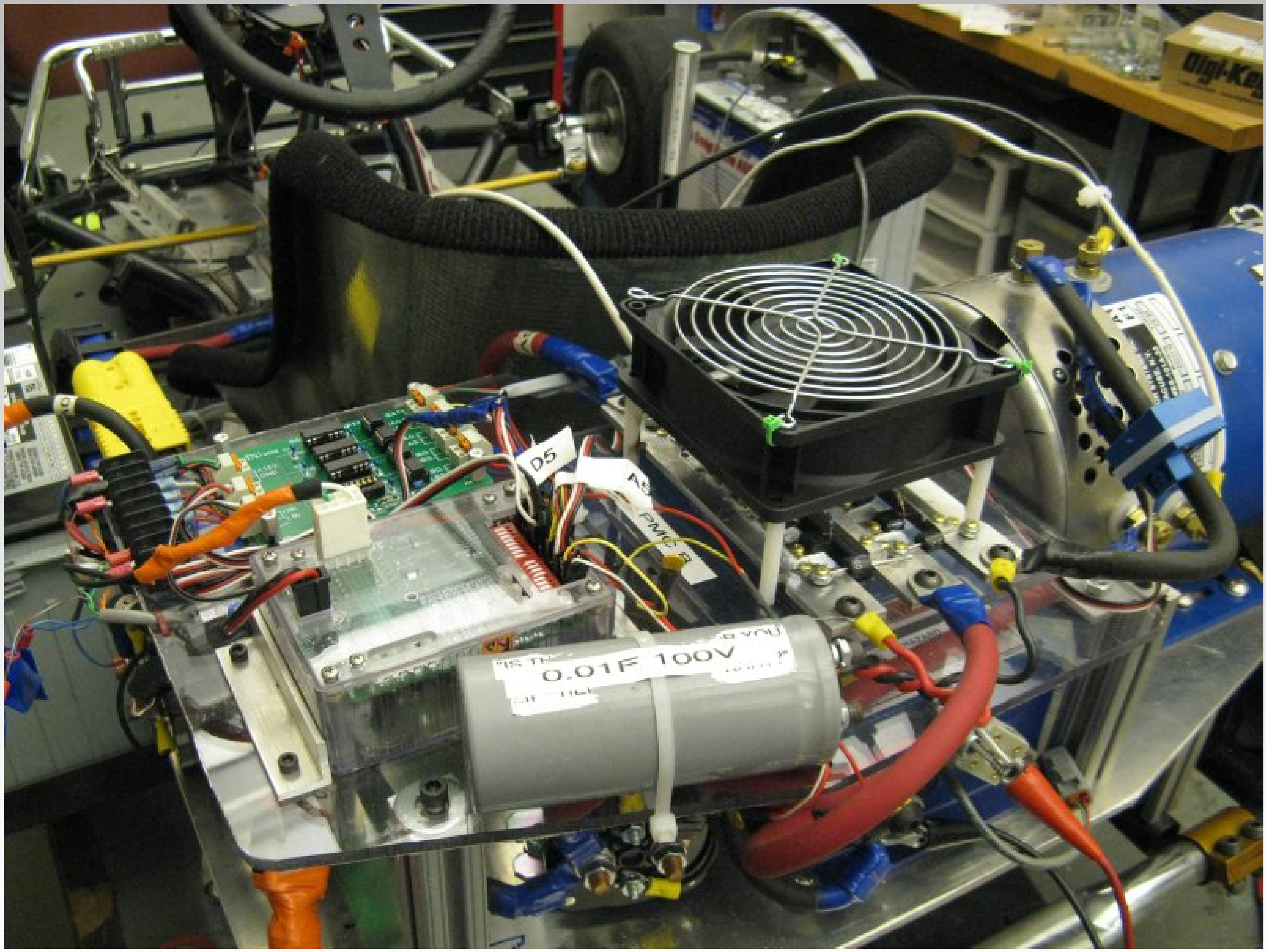
Vehicle Layout

Electric Motor



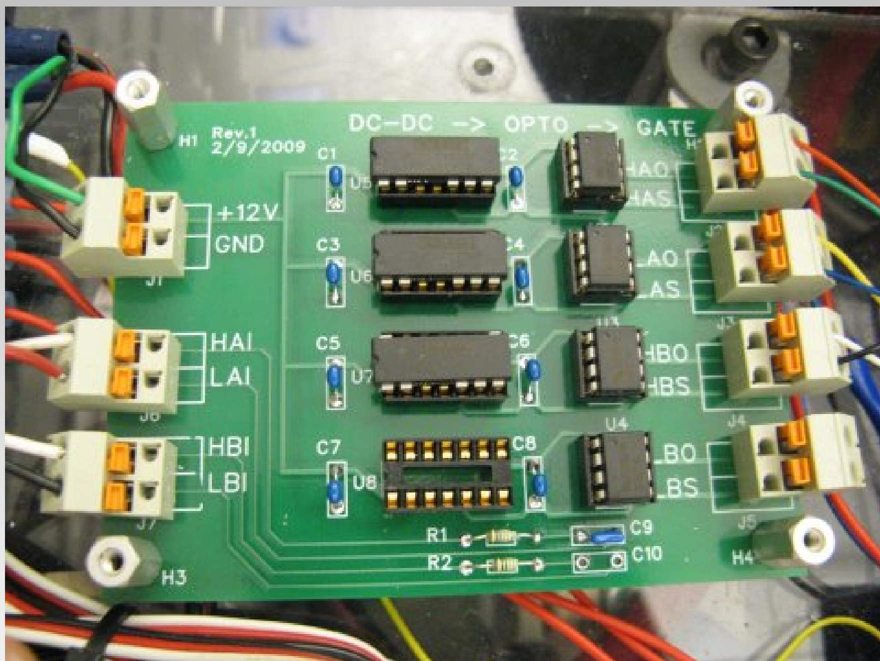
7kW, 48V Separately-Excited DC Motor

Electrical System

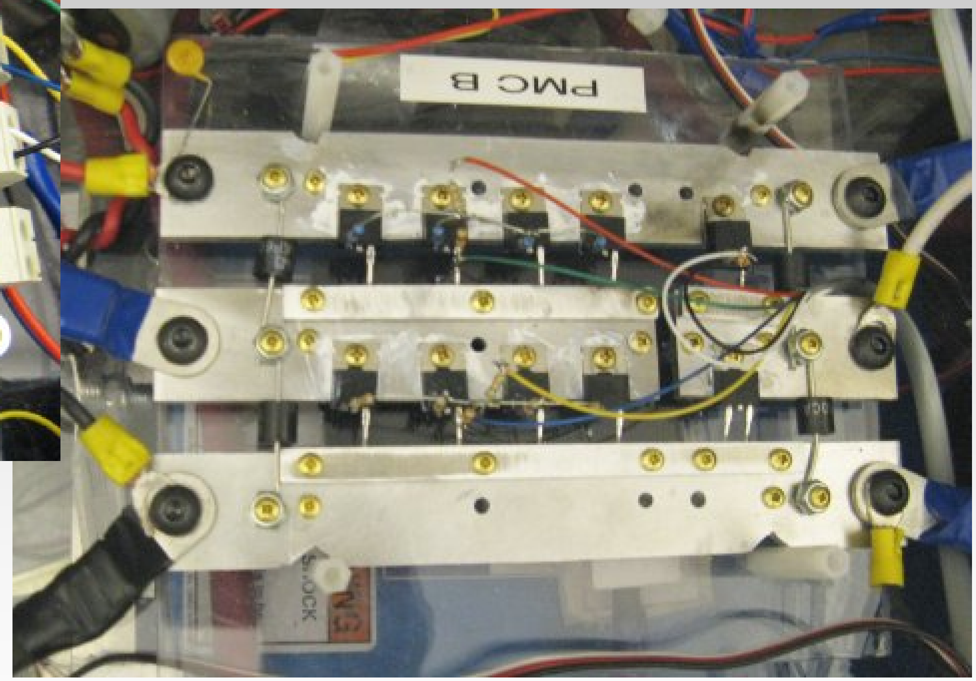


300A-peak Motor Controller and Wireless Interface

Electrical System

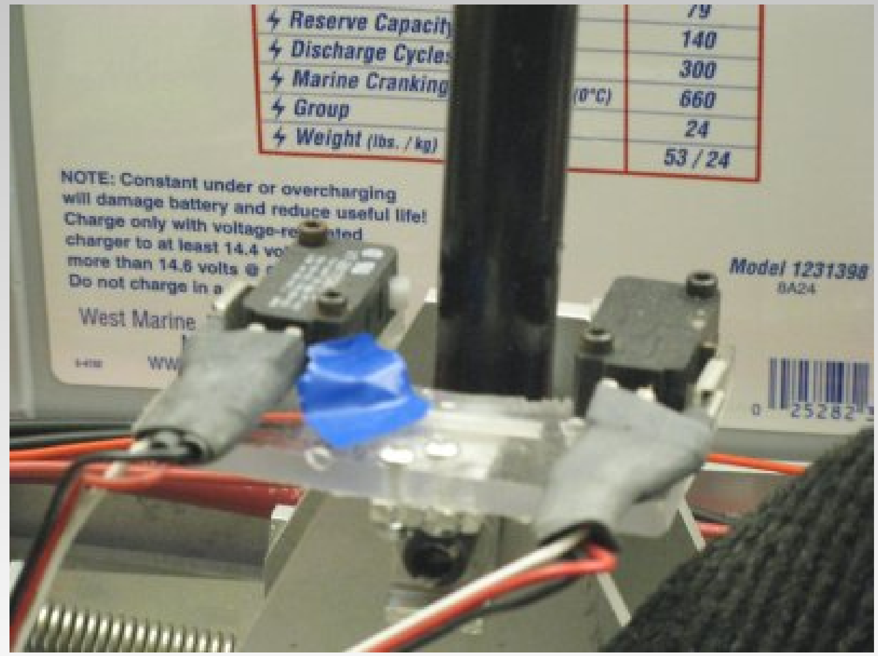


Isolators and Optical Couplers



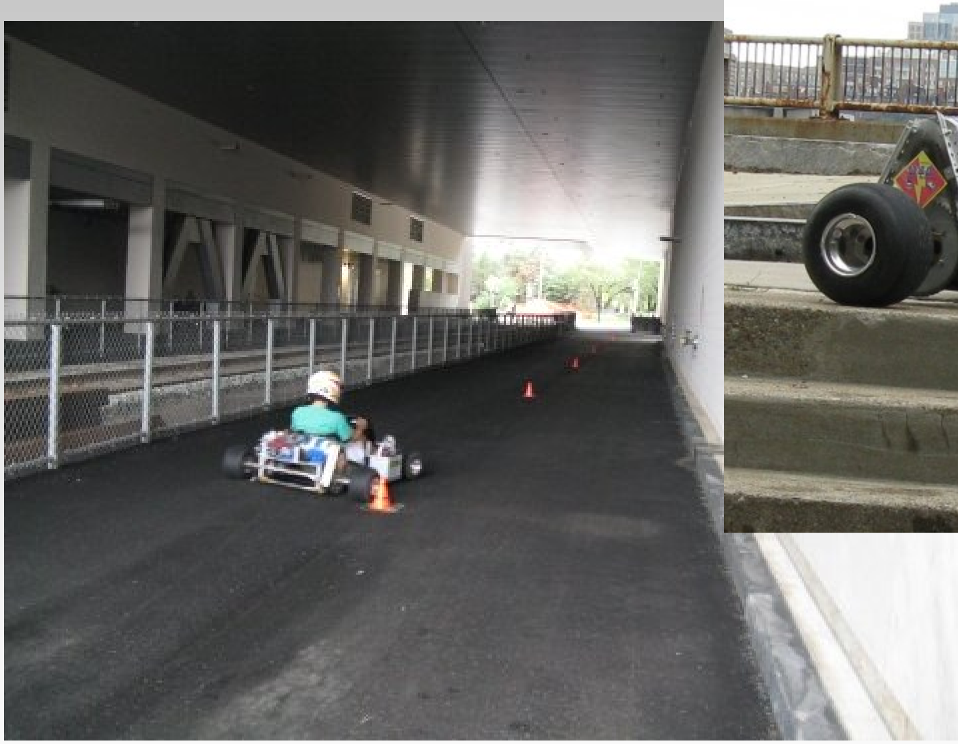
Armature and Field Drive Half-Bridges

Field Control



Electric Sequential “Gear” Shifter

Test Drives

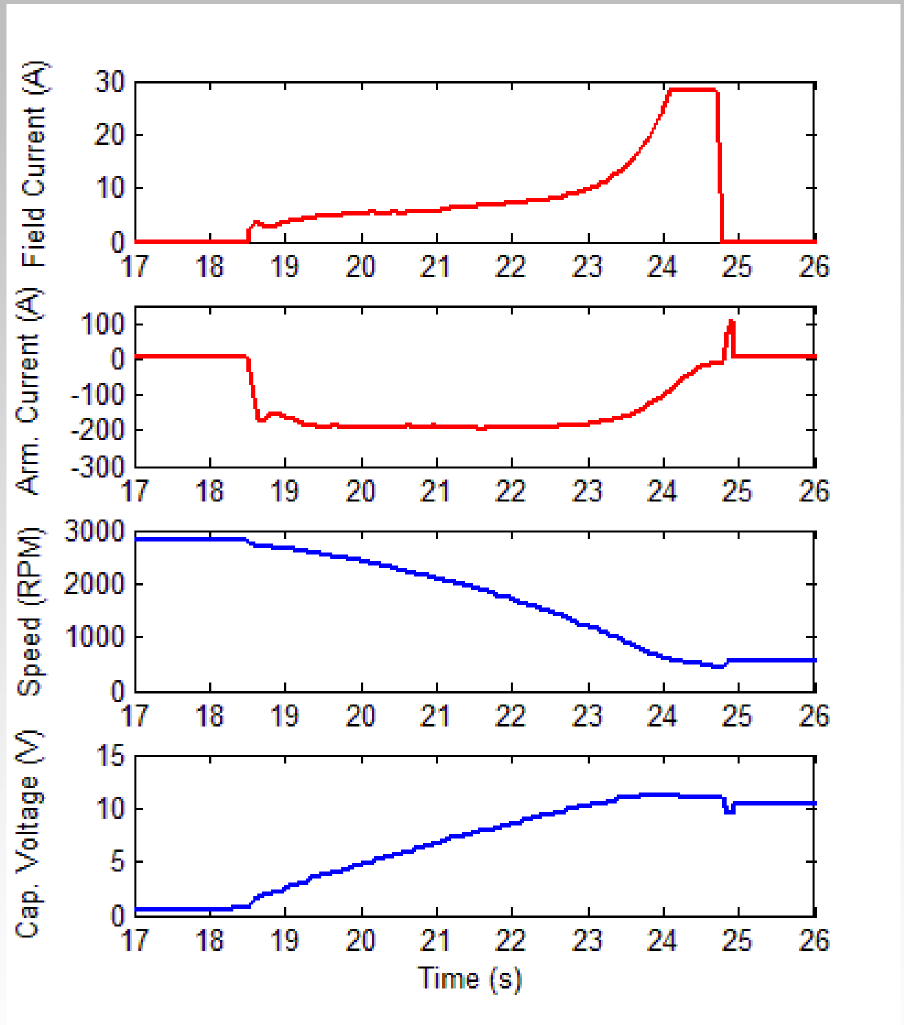


(Launch Video)

Flywheel Testing

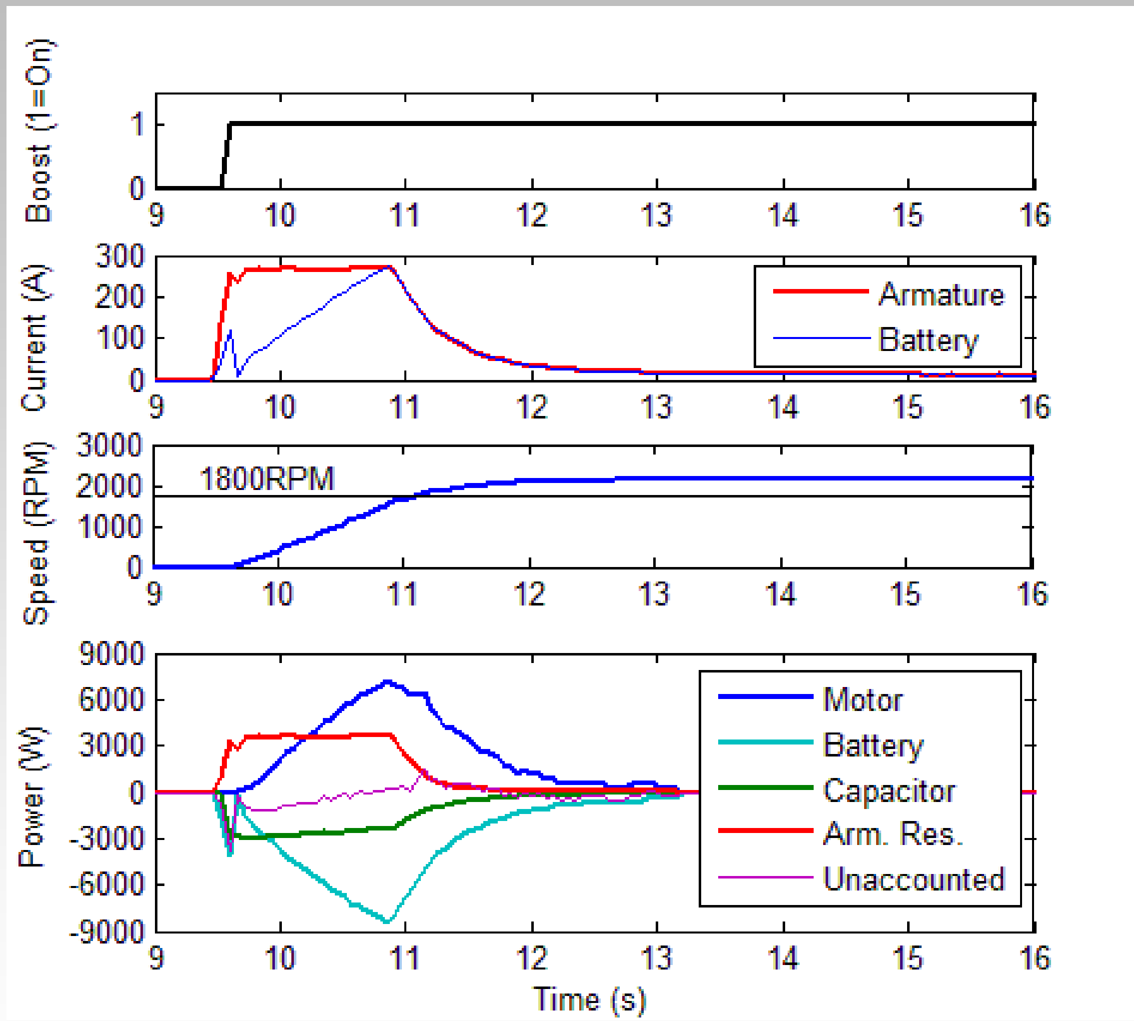
Effective inertial loads up to 250kg.

Flywheel Testing



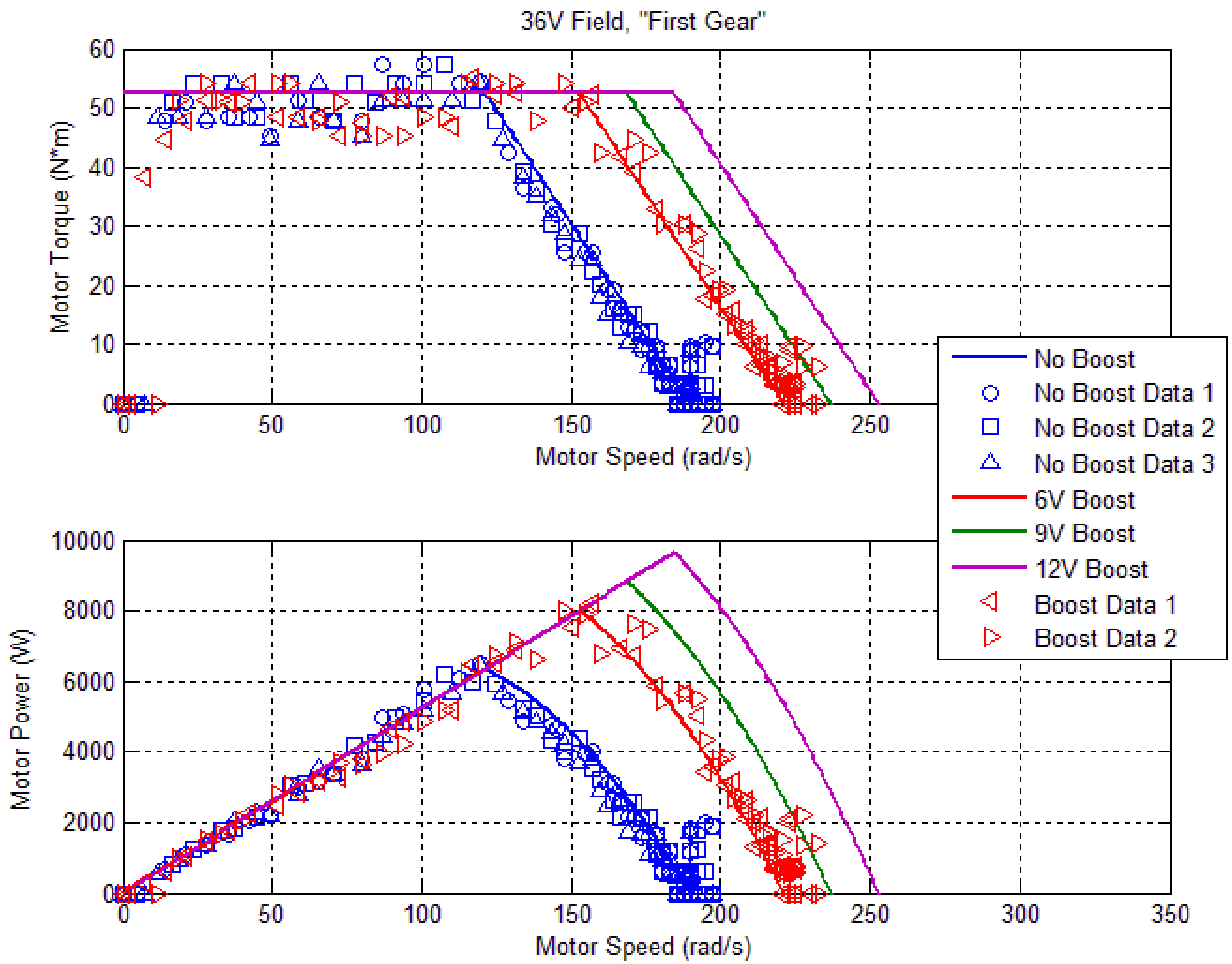
Example regenerative braking profile.

Flywheel Testing



Example acceleration assist profile.

Flywheel Testing



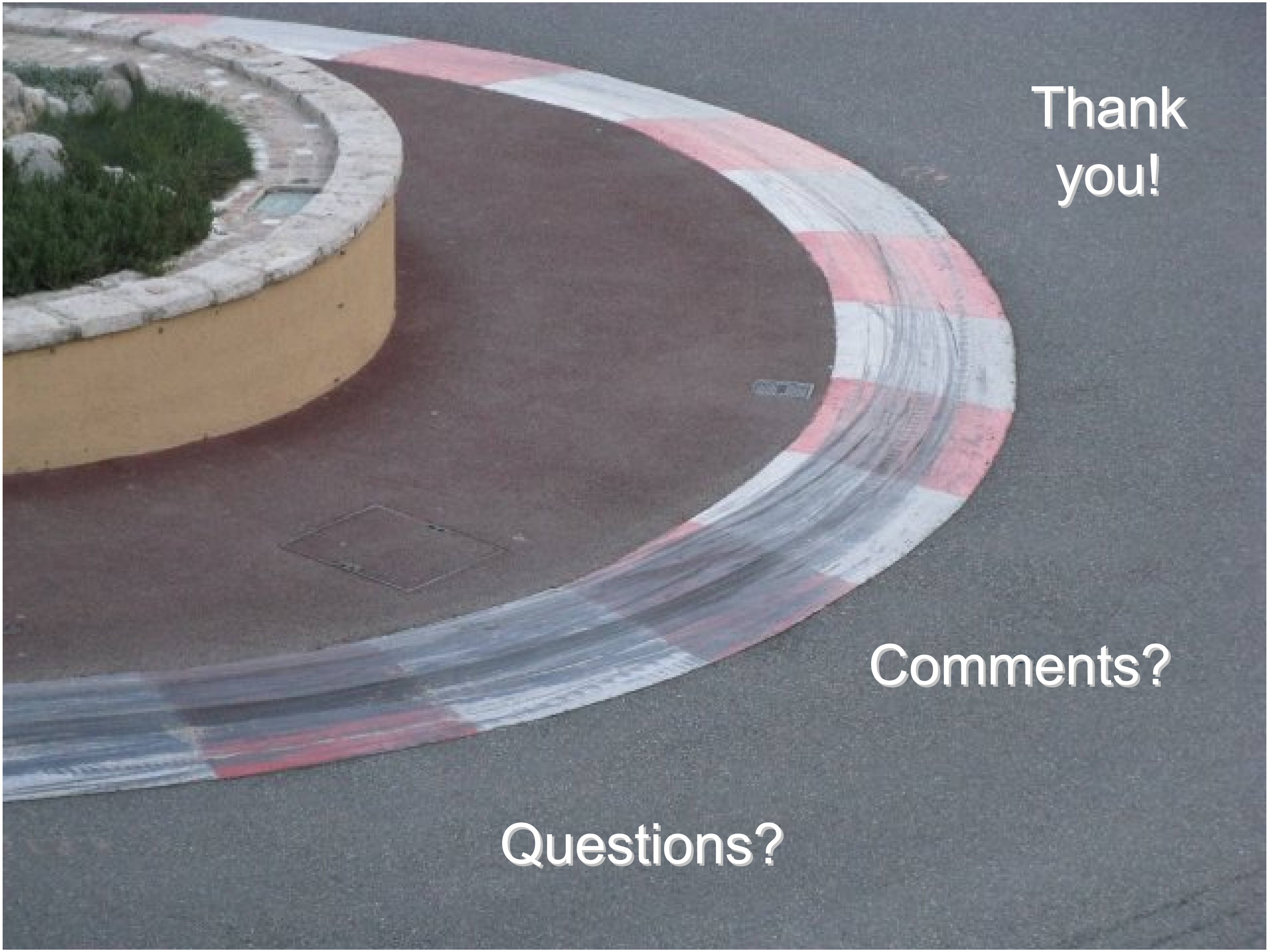
Capacitor assist on torque-speed and power-speed curves.

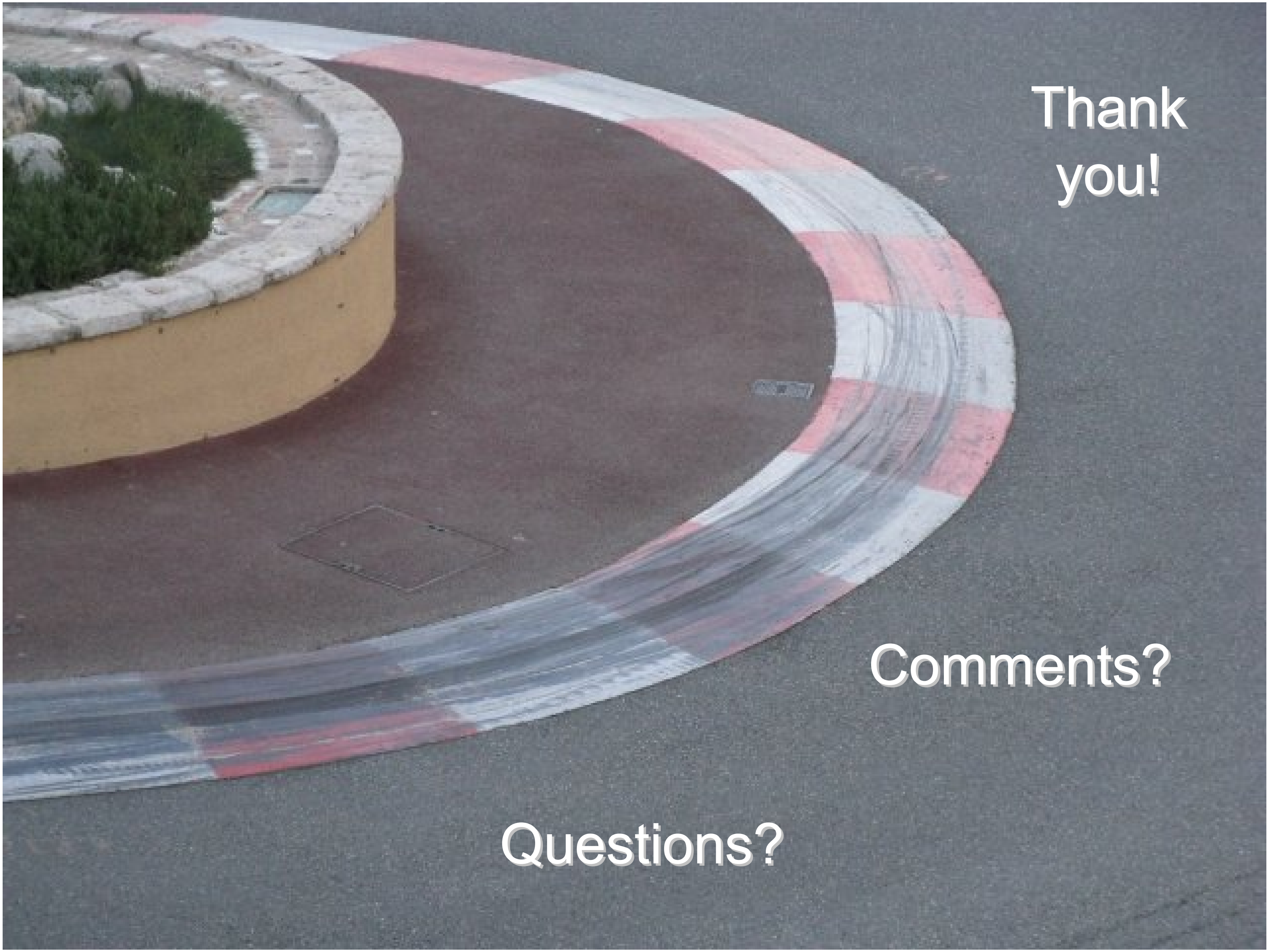
Conclusions and Future Work

- Series battery/ultracapacitor combination offers several advantages which make it well-suited for light DC-drive vehicles as an efficiency and/or performance enhancement.
- Experimental vehicle confirms the validity of the simple system model: Regenerative braking and capacitor assist efficiency predictable using armature resistance model.
- Simple system makes for an ideal educational project.

Future Work:

- Track testing.
- More work on merging regenerative and mechanical brakes.
- Extension to AC drive system?


Thank
you!
Comments?
Questions?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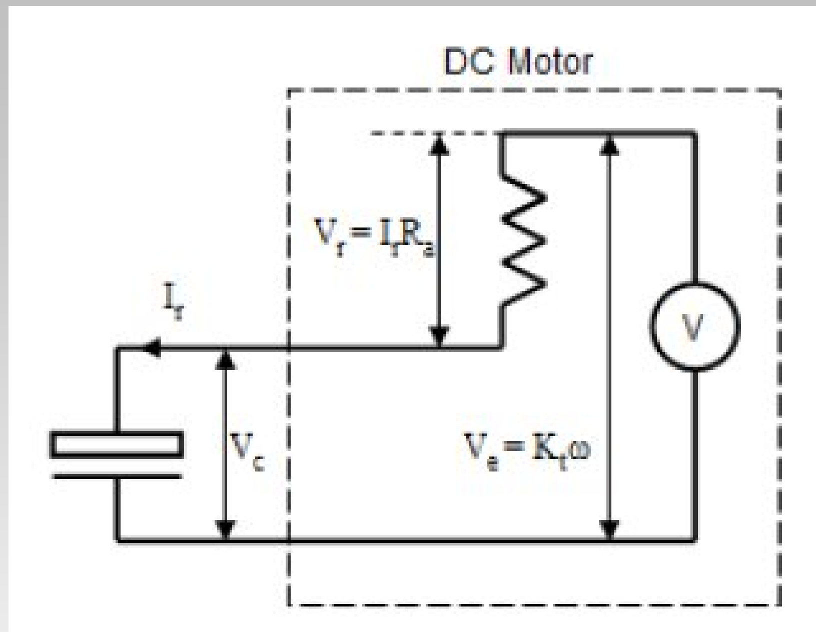
Regenerative Braking Model



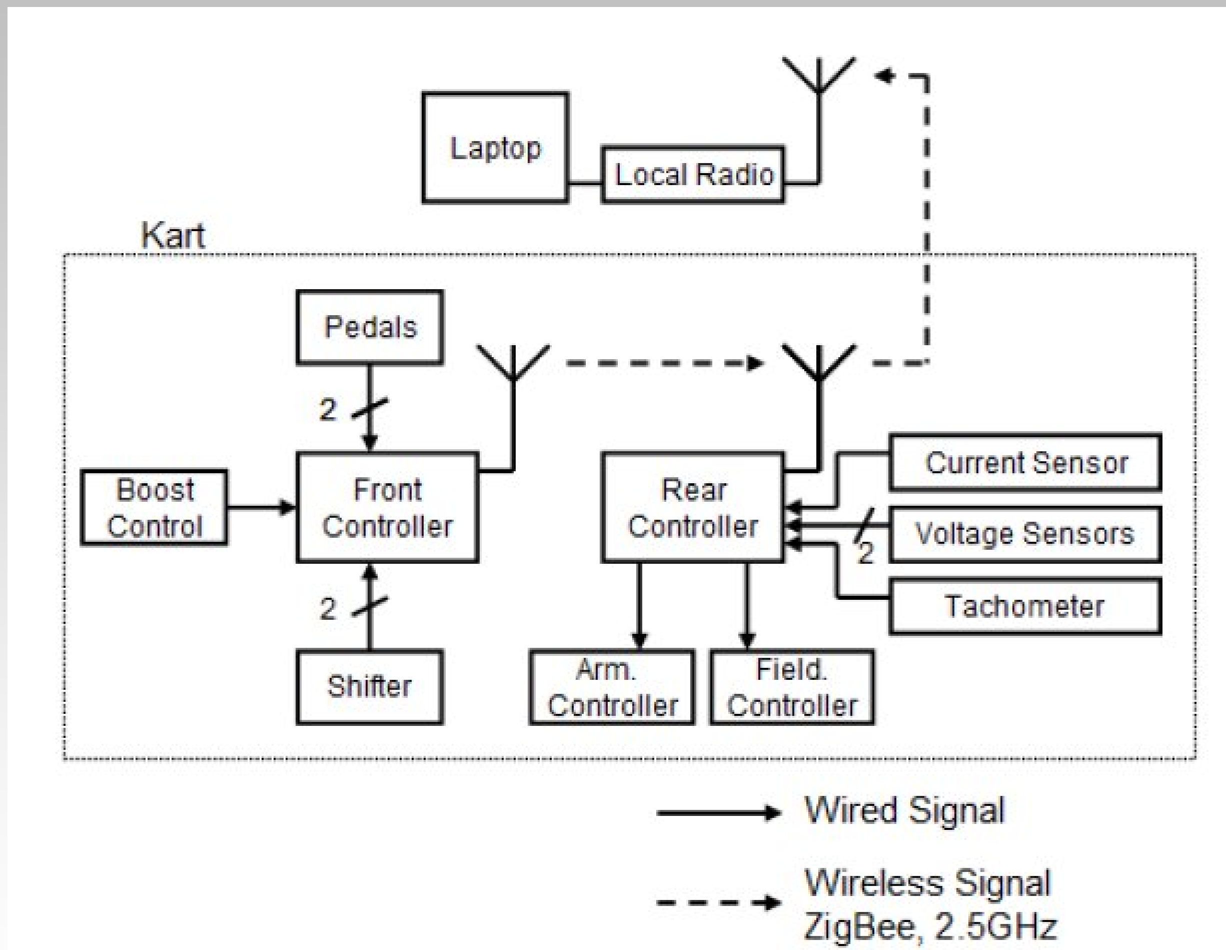
$$P_{cap} = \tau_b \varpi - I_r^2 R_a = I_r V_c \, , \qquad (5)$$

Experimental Vehicle Specifications

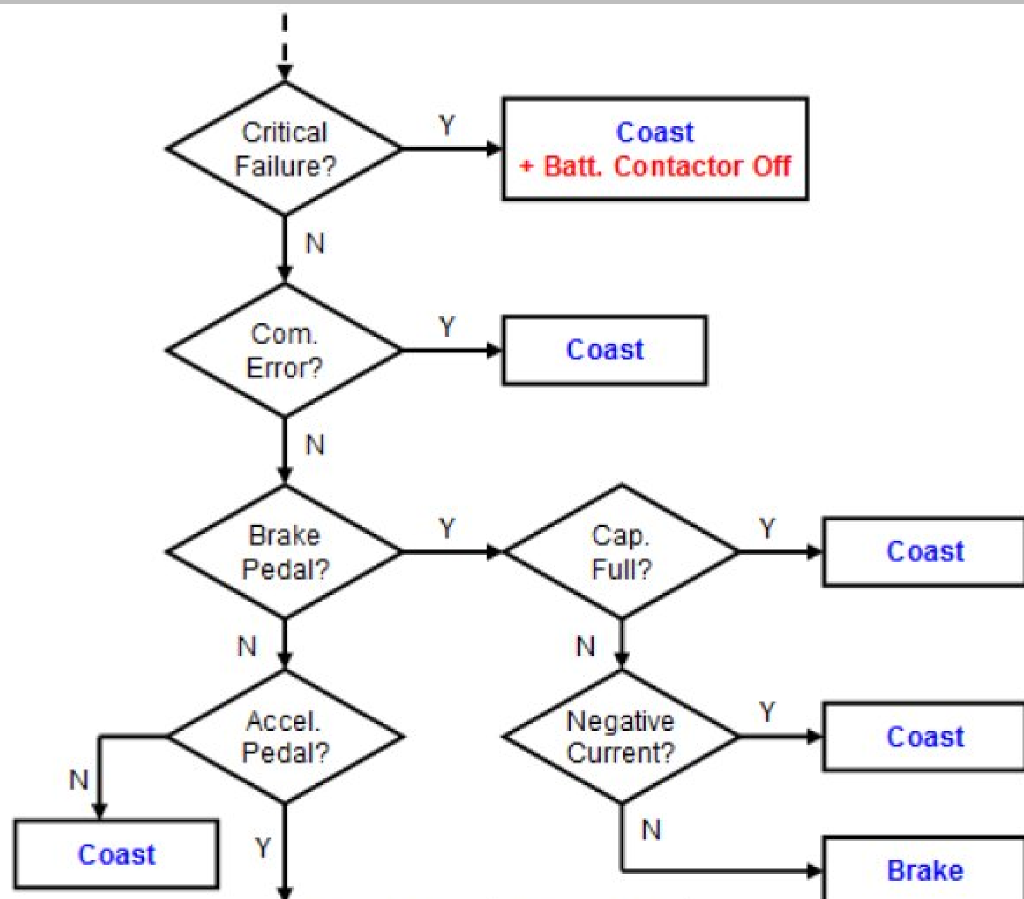
Table 1: Experimental Vehicle Components and Specifications

Batteries	12V, 79Ah sealed AGM Pb-Acid from SeaVolt, 24kg ea, ~5mΩ ea.
Ultra-capacitor	Maxwell 16V (6-cell), 110F with active balancing, 3kg, ~3mΩ
Motor	D&D SepEx brushed DC, 10kW peak, 23kg
Mass (no driver): 160kg **Peak Current:** 300A **Peak Acceleration:** 0.6g **Top Speed:** 16m/s (58km/hr)	

Experimental Vehicle Signal Architecture



Experimental Vehicle Program Loop



	Boost On	Boost Off
Shifter Low	1st Gear Boost	1st Gear
Shifter High	2nd Gear Boost	2nd Gear