EDLC Modeling and Integration for Hybrid Electric Vehicles

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Presented to
“The 14th International Seminar on Double Layer Capacitors and Hybrid Energy Storage Devices”
Deerfield Beach, Florida
December 6-8, 2004
Objectives of This Presentation

- Update on NREL’s EDLC modeling and EDLC automated analysis program
- Update on EDLC roles in hybrid vehicles
- Overview of Heavy Hybrid EDLC initiatives
Outline

EDLC activities overview

• **Modeling Review**
  – The New Manual’s Modeling Implications
  – VBA Analysis Spreadsheet
  – Electrochemical Impedance Spectroscopy

• **Light Duty Hybridization Analyses**
  – Fuel Cell Efficiency Curve
  – Specific Fuel Cell ESS Requirements

• **Heavy Hybrid EDLC Efforts**
Equivalent Circuit Capacitor Model

- C - mapped as a function of temperature & current
- R - mapped as a function of temperature & current

Additional Attributes

- Coulombic efficiency accounted for
- Thermal model: temperature rise predictions & thermostat temperature control
- Maximum power limitations
- Series and Parallel configurations
Most of NREL’s Model Data is Generated from Standard Test Characterizations
There are Multiple Calculation Techniques used for obtaining Modeling Characteristics.

The graph shows a series of points marked with numbers 1 to 5. The graph is divided into two sections: Discharge and Charge. The x-axis represents time (seconds), ranging from 72 to 132 seconds. The y-axis represents current (A) and voltage (V), with current values ranging from -400 to 0 A and voltage values ranging from 1.25 to 2.55 V.

The graph includes two lines: I_BCap (current) and V_BCap (voltage). The I_BCap line is represented by a blue line with square markers, while the V_BCap line is represented by a magenta line with diamond markers.

The graph illustrates the transition from discharge to charge, with specific points marked at 72 seconds (point 1), 92 seconds (point 2), 102 seconds (point 3), 122 seconds (point 4), and 132 seconds (point 5).
Automated Analysis Program

Objective:

It is anticipated that the Excel VBA program will provide a simple, standard, user-friendly, and powerful tool to help industry perform automated test analyses and characterization for EDLC modeling.

Demonstration:
1st Screen – Choose Test to Analyze

National Renewable Energy Laboratory

FreedomCAR

Ultracapacitor Test Manual Modeling/Analyses Program

Step 1: Choose Test-Type to Analyze

- Reference Capacity
- Constant-Power Decah
- Load and Current
- Hybrid Pulse Power
- Efficiency Performance
- Constant Current
- Self Discharge
- Cold Cycling
- Efficiency I/III
2nd Screen – Choosing Data

NREL National Renewable Energy Laboratory

FreedomCAR
Ultracapacitor Test Manual Modeling/Analyses Program

Step 1: Select file for analysis at:
- Choose Constant Current File: 07222004_BCap77523_C0TestA2x300001.xls
- Back to "Main"
- Return to Test Selector Sheet

Step 2: Select data columns:
- Select Current (A) Data
- Select Voltage (V) Data

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Step 3: Data Analyses: Feedback
- Graph & Pick Pt.s
- Plot Results are located in file specified in step 1, and in tab ResultsPlot1
### 4th Screen – Analysis Results

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<th>t (s)</th>
<th>I (A)</th>
<th>V (V)</th>
<th>Dischg Capacitance (F)</th>
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**NREL** National Renewable Energy Laboratory
Electrochemical Impedance Spectroscopy (EIS) Applications

- Material Characterization & Modeling
- Battery SOC predictions
- Battery SOH predictions

Proposed:
- EDLC modeling
Rigorous Test Procedures are Required for Device-Level Modeling with EIS Data

• More rigorous test procedure details are to be included in the new testing manual:
  (1) Insure small AC amplitude injection signal.
  (2) Use true four lead measurement.
  (3) A low resistance, consistent, & repeatable connection must be made between the four leads and the cell under test.
  (4) Use equipment with adequate current drive rating.
  (5) Specify consistent and stable SOC(s) at which to perform readings.
  (6) Wait sufficient time to allow for device to equilibrate after charging to said SOC.
  (7) Connect “reference” leads directly to the cell under test (not “working” and “counter” leads) – If connectors don’t allow same location of connection point.
More Rigorous Definition of Details for EIS Analyses

The CNLS fitting method is not as straightforward as would be desired for a procedure outlined in a manual. It involves:

1. Evaluate quality of lab data for glitches/anomalies that will prevent proper fitting.
2. Estimate initial values from which to begin the fitting process.
3. Fix some values (necessary for high order circuits, like the 5-stage ladder) & iterate through by fitting different circuit sections.
4. Adjust weighting or the weighting method used between real & imaginary impedance values (depending on fitting software).
5. Simulate the model for comparison to the data.

Many steps need: (A) researchers’ heuristic feedback, (B) measurements iterations to obtain a working circuit diagram. Additionally, it may be difficult to provide a consistent basis by which fittings can be compared from different sources.
Modeling Summary

• We are looking for EDLC community feedback on:
  – Level of interest and those interested in Beta testing the automated analysis program for the FreedomCAR EDLC test manual
  – Level of interest for EIS based system modeling and feedback on consistent techniques to incorporate EIS into standardized device testing/modeling.
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• **Light Duty Hybridization Analyses**
  – Fuel Cell Efficiency Curve
  – Specific Fuel Cell ESS Requirements

• Heavy Hybrid EDLC Efforts
There are Various Vehicle Applications/Needs for Energy Storage

Addressing requirements of energy storage in vehicles with different strategies

<table>
<thead>
<tr>
<th>This Presentation’s Focus</th>
<th>42-Volt (Start/Stop, Mild HEV, Power-assist HEV)</th>
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<td>Fuel Cell Hybrids (Power)</td>
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<td>Battery EV</td>
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This Presentation’s Focus

- **42-Volt (Start/Stop, Mild HEV, Power-assist HEV)**
- **Power Assist HEV (Low Power, High Power)**
- **Fuel Cell Hybrids (Power)**
- **Battery EV**
Variability in Fuel Cell System Efficiency Will Affect FC-ES Hybridization, so System Design is Key
These fuel cells have the SAME net power.

Theoretical FC efficiency curves are based on DOE Targets.

Fuel Economy is Affected by the Position of FC Peak Efficiency.

Vehicle with fuel cell only (96 kW)
Drive Cycle Power Output Histogram Helps Explain 10% Peak Power Benefits

- 10% peak efficiency FC has the highest fuel economy because its peak efficiency is better aligned with the power requirements.

- Little fuel economy difference over US06 cycle.
  - wider power distribution
  - similar efficiency at $P_{avg}$

Vehicle with fuel cell only
The Benefit of Downsizing Tied to Fuel Cell Efficiency Characteristics
What kind of Energy Storage is Required for Minimum Supplementation of a Downsized FC?

<table>
<thead>
<tr>
<th>63 kW Fuel Cell</th>
<th>Peak Shaving FC Power (kW)</th>
<th>Warm-Up Time (s)</th>
<th>Ramp Rate 10-90% (s)</th>
<th>( P_{\text{req'd}} ) (kW)</th>
<th>( E_{\text{req'd}} ) (kWh)</th>
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- Minimal ESS roles require high power and relatively little energy.
- ESS needs significantly less energy in "2010 Target" fuel cell performance.
- The minimal control case results in little to no effect on ESS sizing.
Additional Fuel Cell Hybridization Work to be presented:

**Objective:** Evaluate Energy Storage System (ESS) Requirements for a Fuel Cell Vehicle with an Aggressively controlled ESS

Using 2010+ Vehicle and Fuel Cell Assumptions

@

EVS 21
MONACO
2 - 6 April 2005
Light-Duty Hybridization Summary

• Downsizing the fuel cell in a vehicle provides improvement in:
  
  – Fuel economy, especially for FC systems with peak efficiency as a high percentage of net power
  
  – Fuel cell costs
  
  – Has little to no affect on ESS sizing [in minimal control case].
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• Heavy Hybrid EDLC Efforts
DOE’s Advanced Heavy Hybrid Propulsion Systems Program

Program Goals:

– Next generation technologies for commercially viable heavy-hybrid vehicles

– Meet EPA’s 2007 emissions standards

Phase I - Underway

– 3-year Research & Development Effort (FY 03-05)

– 50%-50% Government / Industry Cost-Share

– Targeting Wide Range of
EDLC’s may be Well Suited to some Heavy Vehicle Applications

Demanding Vehicle Requirements:

- 8 to 12 hours of continuous stop-and-go duty cycle
- 34,500 lb vehicle, 17,000 lb payload
- Fully loaded highway speeds / grades
- Much higher traction / regen power requirements
- Durability, reliability, and cost are critical fleet concerns

Actual Heavy Vehicle Duty Cycle with > 1000 starts/stops
AHHPS EDLC
System Development Activities

**Vehicle Systems Modeling** (FY04)
- Fuel economy prediction, system sensitivity, optimization

**Technology Characterization** (FY04)
- Review / down-select of available technologies

**Reliability testing** (FY05)
- Bench testing of 3-4 selected technologies

**Thermal management** (FY04 – FY05)
- Conjugate thermal / flow analysis of module thermal management

**Model validation** (FY04 – FY05)
- Module and thermal management system bench tests
- Chassis dynamometer and field testing of vehicle
Acknowledgements

  – Energy Storage Program
  – Vehicle Systems Program

• We appreciate the support and technical guidance from USABC/FreedomCAR ES Technical Team
  – Harshad Tataria
  – Cyrus Ashtiani
  – Franco Leonardi

www.ctts.nrel.gov/BTM
www.ctts.nrel.gov/analysis