LPRDS – ETS 2009

Lafayette Photovoltaic Research and Development System
Energy Transfer Subsystem

Final Presentation
May 11, 2009
Lafayette College-ECE Dept.

LPRDS-ETS

Department of Electrical and Computer Engineering
ECE492 Spring 2009
Project Overview

- Project Overview
  - Total investment of $40,000 in solar infrastructure to support student projects
  - One semester team-based capstone senior design project
    - 22 student team
    - $4000 Budget (Not including Array cost and initial battery cost)
    - Subject to a 55 page requirements document
      - Technical Specifications
      - National Electric Code (NEC) Article 690 on PV systems
      - Reporting requirements (e.g. website, PDR reports, CDR reports, etc.)
      - General Project Requirements (Maintainability, Sustainability, Reliability, etc.)
      - Total of 104 requirements
Presentation Outline

1. Project Overview
2. ->**System Input – Solar Energy**
3. System level design
4. Subsystem design
   1. RPI
   2. ESS
   3. EDS
   4. SCADA
5. Conclusion
Why solar energy?

- Energy Consumption
  - Energy Consumption on the rise
  - Causes: Population growth and technological developments

- Energy Sources
  - Non-renewable resources such as Petroleum, Natural Gas, and Coal account for 85% of US energy consumption.
  - Solar energy accounts for less than 0.5% of total consumption. Why?

- Economic Analysis – A household system is not economical for Easton, PA
  - A 20yr system has been calculated to cost $72,400
  - 5.45 times cost of buying from the grid
  - Technology will continue to improve
  - Experts predict solar will play a role in the future energy market
System Input – Solar Energy

- 10 GEPBp-200-MS modules connected in series configuration.
- 5 degree tilt because of wind loading.
- Average of 4 kwh/m²/day
- We calculated an expected power of our system 4.2kwh/day

**Insolation Curve**

**IV Curve Provided by GE**
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Main Requirements

- Accept high voltage DC from the PhotoVoltaic Array.
- Output AC voltage @ 120 volts, 60Hz +/- 0.05%.
- Total Harmonic Distortion <= 3%
- An Energy Storage System
- Autonomous Safety Interface
- SCADA (monitoring, control and display)
Summary of Project Accomplishments

- Number of requirements satisfied = 100
- % requirements satisfied = 96.15%
  (note to senior management, that’s an A)
- Major Requirements that were met
  1) AC output at 120 volts RMS
  2) Energy Storage System
  3) Accepts DC high voltage from Photovoltaics
  4) Autonomous Safety Interface
- Requirements Missed
  1) AC output at 60Hz +/- 0.05%
  2) THD <= 3%
  3) Load Regulation <= 3%
  4) Transient Response <= 5%
The ‘illities’

- Manufacturability
  1) Mean Time To Repair less than 1 week
  2) Spare parts in storage as order time is about 2 weeks.
  3) System Tolerances
- Sustainability
  - Economic sustainability considered for a household PV system
  - Key components such as PVs and batteries considered for sustainability
- Ethical Considerations
  - Kant’s Categorical Imperative
- Maintainability
  1) MIL-HDBK-472 (Note 1) and MIL-STD-470B
  2) \[ \text{MTTR} = \frac{\sum_{i=1}^{n} \lambda_i \mu_i \tau_i}{\sum_{i=1}^{n} \lambda_i} \] gives a MTTR of 2.6 days
- Reliability
  1) MIL-HDBK-217 delivers MTBF of 1071 hrs. (1000 hr. requirements)
Design Tools and Features

- Tools used:
  - VTB
  - Simulink (ECE433)
  - PSpice (ECE323)
  - AVR studio (ECE212)
  - Linux (CS classes)
  - PHP
  - MySQL
  - C++ (CS205)
  - C (ECE212)
  - PADS
  - DxDesigner (ECE323)
  - Quick Circuit Milling Machine

- Features:
  - Commercial off the self (COTS)
    - Sensors (current, temperature, voltage)
    - Relays
    - PIC
    - Microcontroller
    - PC
  - Custom circuit design
    - 7 PCB boards
    - software
Safety Concerns

- Safety was an integral part of the design process
  - Safety Lecture
  - Safety plan (signed by all students)
  - Commercial GFI
  - Safety circuit
  - High voltage/low voltage isolation in all subsystems
System Design

- **Supervisory Control and Data Acquisition**
  - Monitors the system for safety issues
  - Controls the system states

- **Energy Storage Sub-System**
  - 64 LiFePO4 Cells
  - 205 Nominal Array Voltage
  - 10 Ah leads to 2.35 kWh

- **Energy Delivery Sub-System**
  - Provides proper load to the batteries
  - DC/AC conversion (Inverter)

- **Raw Power Interface**
  - Ground fault protection
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Raw Power Interface

- **Main Requirements:**
  - Disconnect from PV
  - Ground Fault Detection
  - Provide Sensor Data for PV Array
RPI Box Layout

- PCB with PIC
- 15A Fuse
- Current Transformer
- Solid-State Relay
- Output Blocks
- 30V+ & DC Indicators
- Safety Relay
- System Power
- *GFM Mounted on Box Door
- *Red Pattern Indicates Shielded HV Region
RPI Features

- Ground Fault Monitor- Bender RCMA420
  - Purchase for safety concerns
- Voltage, current and temperature sensors
  - Voltage from PV array
  - Voltage to EDS
  - Current sourced from PV array
  - Temperature inside enclosure
- PIC to perform data acquisition
  - 10-bit A/D converter
  - RS485 serial communication
- Separated into low and high voltage sides
RPI Sensor Designs

Custom Designed Sensors (Pictured):
• Voltage Sensors
• HV Indicator
• DC Power Indicator

C.O.T.S.: Sensors:
• Current Sensors
• Temp. Sensors

Temperature Sensor
400mv , +/- 19.5mv/C

Current Sensor
2.5V +/- 125mv/A
RPI Summary

- RPI was a complete success
- Viable Final Version
  - No revisions necessary
- Tested drawing power from the PV array
- Charged ESS batteries
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## Energy Storage System (ESS) Requirements

- 20 project requirement mapped to ESS
- Main requirements are listed below:

<table>
<thead>
<tr>
<th>Main Requirements</th>
<th>Specification</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>R002-01</td>
<td><em>Energy Accumulator</em> is required to store excess energy</td>
<td>Pass</td>
</tr>
<tr>
<td>R002-04</td>
<td>Discharge power capacity of the ESS shall be able to meet the power requirements of the system</td>
<td>Pass</td>
</tr>
<tr>
<td>R002-06</td>
<td>Shutdown switch required.</td>
<td>Pass</td>
</tr>
<tr>
<td>R002-12</td>
<td>Containers must have closable access ports for electrical probing of each extreme of the HV system.</td>
<td>Pass</td>
</tr>
<tr>
<td>GPR004-20</td>
<td>NiCd and Lead-Acid batteries may not be used.</td>
<td>Pass</td>
</tr>
</tbody>
</table>
ESS Design

- Parts Designed
  - PCB Layout (fabricated off-site)
  - PIC code
  - HV (>30V) Indicator
  - Voltage Sensors
  - Isolated Relay Control
  - PCB
  - Metal Case
  - Battery Technology Selection
  - Battery Mounting Mechanism

- Parts Purchased
  - DC-DC converters
  - Relays
  - Disconnect Switch
  - Temperature and Current Sensors
- 64 3.2V LiFePO4 Cells in series
- 205V nominal @ 10 Ah = 2KW of power
- Up to 70A discharge rate and 60A charge rate
- Clever and Safe Design
- When top is removed, there is no voltage greater than 14.8V in the battery compartment
- Makes maintenance easier – individual packs can be swapped out
Features:
• PIC
• RS485 communication to SCADA
• Indicator Lights
• Voltage, Current, and Temperature Sensors
• Low Voltage sources of 5V and 12V
• Relay Control
Batteries charging/discharging- Test Results

Charging

- **5A Rate**
  - Charging Time: 1.7hrs
  - Voltage: 3.65 V

- **10A Rate**
  - Charging Time: 0.8hrs
  - Voltage: 3.7 V
  - Overcharge: 3.3 V

Factory Curves

- **Charge Cycle**
  - Voltage: 3.30 V
- **Discharge Cycle**
  - Voltage: 2.75 V
- **Discharge Cycle**
  - Voltage: 3.3 V

Trickle Charging

- **10A Rate**
  - Discharging Time: 1.7hrs
  - Voltage: 3.3 V
  - Voltage: 2.75 V
- **5A Rate**
  - Discharging Time: 0.9hrs
  - Voltage: 2.57 V
ESS Summary

- ESS is a final part of the LPRDS-ETS
- Future Additions/Changes
  - Voltage Ramping Circuit
  - Battery Management System (BMS)
  - Redesign Voltage Sensors
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   3. **->EDS**
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Energy Delivery System-DC to AC Converter

- 23 Total Requirements
- Major requirements listed below:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>R003-02</td>
<td>Provide 120 V RMS AC sinusoidal at 60Hz for the load with a max sustained current of 15Amps RMS</td>
<td>Pass</td>
</tr>
<tr>
<td>R003-03</td>
<td>60Hz frequency is accurate to within 0.05%</td>
<td>Fail</td>
</tr>
<tr>
<td>R003-04</td>
<td>Total Harmonic Distortion is less than 3%</td>
<td>Fail</td>
</tr>
<tr>
<td>R003-05</td>
<td>The system can be modified to work at 50Hz</td>
<td>Pass</td>
</tr>
<tr>
<td>R003-06</td>
<td>Load regulation is better than 3% for a 100% step load change</td>
<td>TBD</td>
</tr>
<tr>
<td>R003-07</td>
<td>Transient Response is less than 5% for a 100% step load change</td>
<td>Pass</td>
</tr>
</tbody>
</table>

- Custom parts designed

<table>
<thead>
<tr>
<th>Parts designed</th>
<th>Parts purchased</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-Bridge/Inverter</td>
<td>Isolation Transformer</td>
</tr>
<tr>
<td>Differential Voltage measurement</td>
<td>12v DC-to-DC converter (hi-lo voltage isolation)</td>
</tr>
<tr>
<td>Filter</td>
<td>microcontroller</td>
</tr>
</tbody>
</table>

- One PCB board fabricated in-house with 2 revisions
- A copy-cat of the ESS board (fabricated off-site) for sensor values
- Budget spent- $1,020
EDS Design

- Filter design and PWM scheme driven by THD and frequency requirements
- H-Bridge design based on high voltage (120Vdc) and high current (15A) requirement
- Possible implementation of closed loop Inverter algorithm to meet voltage regulation requirement – new power algorithm downloadable
- High and low side voltage signals required opto-isolators
Features:
- 4 IGBTS
- 2 gate drivers
- 2 opto-isolators
- High voltage input goes through a 16A fuse
EDS- PWM Scheme

Unipolar Sine PWM

PSpice Simulation

Measured Result from Low Voltage Prototype

IGBT Drive Signals
EDS-Filter

- LC Filter
- 3dB at 684.2Hz (simulated)

Simulated AC Response of Filter
Measured data from the inverter

- 210v DC input / 124 RMS AC at 60.5Hz
- 50 ohm load

- 210v DC input / 124 RMS AC at 60.5Hz
- 25 ohm load
Interface of EDS to ESS (Batteries)

- Blew up!
- High Voltage to Low Voltage isolation worked!
- High Voltage parts destroyed
- Low Voltage survived
- Safety Plan (important)
- Possible cause: Current Surge

Future Work:
- Use a Start up Circuit
- Additional Simulations
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SCADA - Overview

- Supervisory Control and Data Acquisition
  - Monitor and log critical values in the system
  - Provide manual control of the system
  - Provide a useful interface for displaying the collected data

- Major components
  - Hardware (Custom PCB)
  - Software
    - PIC – C language
    - PC – C++, MYSQL, Linux OS, PHP, C
  - Communications protocol
    - RS232 and RS485
SCADA - Software Top Level Diagram

The different color boxes denote different processes.

V6

SSC001
Comm Interface

SSC002
Monitor

SSC003
Input Manager

SSC004
Database

SSC005
Database Interface C++

SSC006
System State Manager

SSC007
Demo Application

SSC008
Database Interface (PHP)

SSC009
System State Manager Interface (PHP)

SSC010
Website (Graphing)

To Network (Ethernet)

Intrachip calls
Files
PHP-MYSQL interaction
MYSQL++

API

SVN ver. Control (CS205)
Design principles (CS205)
SCADA - Software Operation Overview

- **Poll**
- **Check Values**
- **Store in database**
- **Update System State**

<table>
<thead>
<tr>
<th>part_number</th>
<th>pin_number</th>
<th>limit_max</th>
<th>limit_high</th>
<th>limit_low</th>
<th>limit_min</th>
<th>type</th>
<th>conv_factor</th>
<th>offset</th>
<th>units</th>
<th>description</th>
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</thead>
<tbody>
<tr>
<td>4</td>
<td>5</td>
<td>100</td>
<td>90</td>
<td>10</td>
<td>5</td>
<td>A</td>
<td>50</td>
<td>0</td>
<td>V</td>
<td>Voltage at battery 3</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>100</td>
<td>90</td>
<td>10</td>
<td>0</td>
<td>A</td>
<td>19.5</td>
<td>0.4</td>
<td>C</td>
<td>Temperature at battery 1</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>100</td>
<td>90</td>
<td>70</td>
<td>60</td>
<td>A</td>
<td>95.2</td>
<td>0</td>
<td>V</td>
<td>Voltage at battery 1</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>100</td>
<td>90</td>
<td>70</td>
<td>60</td>
<td>A</td>
<td>72.6</td>
<td>0</td>
<td>V</td>
<td>Voltage at battery 2</td>
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<tr>
<td>4</td>
<td>4</td>
<td>100</td>
<td>90</td>
<td>70</td>
<td>60</td>
<td>A</td>
<td>25.8</td>
<td>0</td>
<td>V</td>
<td>Voltage at battery 4</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>100</td>
<td>90</td>
<td>10</td>
<td>0</td>
<td>A</td>
<td>19.5</td>
<td>0.4</td>
<td>C</td>
<td>Temperature at battery 2</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>100</td>
<td>90</td>
<td>10</td>
<td>0</td>
<td>A</td>
<td>19.5</td>
<td>0.4</td>
<td>C</td>
<td>Temperature at battery 3</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>100</td>
<td>90</td>
<td>10</td>
<td>0</td>
<td>A</td>
<td>19.5</td>
<td>0.4</td>
<td>C</td>
<td>Temperature at battery 4</td>
</tr>
</tbody>
</table>
SCADA - Software Operation Overview

- Poll
- Check Values
- Store in database
- Update System State

- If values not within acceptable boundaries, a fault has occurred.
- System State manager is informed.
SCADA - Software Operation Overview

- Poll
- Check Values
- Store in database
- Update System State

<table>
<thead>
<tr>
<th>measurement_index</th>
<th>part_number</th>
<th>pin_number</th>
<th>time</th>
<th>value</th>
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<tbody>
<tr>
<td>80</td>
<td>4</td>
<td>5</td>
<td>2009-05-09 16:07:00</td>
<td>11.75</td>
</tr>
<tr>
<td>81</td>
<td>4</td>
<td>3</td>
<td>2009-05-09 16:07:00</td>
<td>20.512</td>
</tr>
<tr>
<td>82</td>
<td>4</td>
<td>5</td>
<td>2009-05-09 16:07:21</td>
<td>11.75</td>
</tr>
<tr>
<td>85</td>
<td>4</td>
<td>3</td>
<td>2009-05-09 16:07:21</td>
<td>20.512</td>
</tr>
<tr>
<td>86</td>
<td>4</td>
<td>5</td>
<td>2009-05-09 16:07:21</td>
<td>11.75</td>
</tr>
<tr>
<td>87</td>
<td>4</td>
<td>3</td>
<td>2009-05-09 16:07:21</td>
<td>20.512</td>
</tr>
</tbody>
</table>
SCADA - Software Operation Overview

- **Poll**
- **Check Values**
- **Store in database**
- **Update System State**

New state depends on:
- User requests
- Voltages at load and batteries
- Faults reported
SCADA Communication

- RPI PCB
- EDS PCB
- ESS PCB
- World Wide web
- PC
- SCADA PCB
- Display Board

Connections:
- RS 485
- RS 232
- Ethernet
- Ribbon Cable Connection
3 Types of Sensors (Voltage, Current, and Temperature)

- **RPI Sensors**: PIC
  - Rs 485
- **EDS Sensors**: PIC
  - Rs 232
- **ESS Sensors**: PIC

**Voltage Sensors**
- Linear voltage
- Calibrated using test data
- Sensor value = A/D value * 0.005v/bit * Scale factor

**Current Sensors**
- Bidirectional Hall effect type sensor
- Calibrated scaling factor and offset

**Temp. Sensors**
- Calibrated using test data
SCADA Board Schematic

Relay

PIC

Ribbon Cable Connector To Display Board
SCADA Board

Designed using PADs Software

Fabricated Board
SCADA – Features

- Website
  - URL: lprds.aec.lafayette.edu
  - Data history
  - Plots
  - Maintenance

- picoLCD Screen
- Display board
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Engineeering Management Results

- Budget

- Current Budget Cost $3400
- Andy Misc. Costs - $400

- $200 under BUDGET! – enough to order food rather than cook our own.
- ECE Dept absorbed $4400
Conclusion-Results

- Total of 5735 project hours or $172,059 (at $30/hr)
  - Developed 7 UNIQUE BOARDS! (RPI, SCADA, SCADA-555, ESS, EDS-ADAPTED-ESS, EDS-PROTO1, EDS-PROTO2). Almost one for every 3 students

- RPI tested and working correctly
- ESS tested and working correctly
  - Mechanical layout complete
  - Battery management system needed
- EDS with partial functionality
  - Proto-type completed with basic functionality
- SCADA with partial functionality
Conclusion – What is next?

- Buck Converter- increase power intake 12-15%
- Battery Current Control Algorithm – increase efficiency in storing energy in the batteries (LiFePo₄ has a complicated charging curve)
- Grid Tie – allow us to share electricity with the grid
- Motor control and electric vehicles
Thanks To

- Dr. Jemison
- Mr. Nadovich
- Andy Langoussis
- Nicolette Stavrovsky
- Doug Wood
- Chris Lett
Questions?