LAFAYETTE PHOTOVOLTAIC RESEARCH AND DEVELOPMENT SYSTEM – BATTERY MANAGEMENT SYSTEM (LPRDS-BMS-2010)
CDR OUTLINE

- Introduction to the System 8:30am
- Project Goals 8:35am
- Top Level Overview 8:45am
- System Software 10:35am
- Raw Power Interface (RPI) 11:40am
- Lunch 11:50am
- Energy Storage System (ESS) 12:30pm
- Switch Controller (SC) 1:35pm
- Filter Inverter Box (FIB) 2:40pm
The project is a solar power energy conversion system.

- PV panels are a 2kW system.
- Converts DC solar power to 120V AC.
- Monitors energy usage and provides data acquisition.
- Second year of the project.
PV ARRAYS

× 10 panels on the roof
× 54 poly-crystalline cells connected in series
× 20-year limited warranty on power output
× Peak power of 200 watts at 26.3 volts

ELECTRICAL PERFORMANCE

Typical IV Curve for GEPVp-200-MS Module

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power (Wp)</td>
<td>Watts</td>
<td>200</td>
</tr>
<tr>
<td>Max. Power Voltage (Vmp)</td>
<td>Volts</td>
<td>26.3</td>
</tr>
<tr>
<td>Max. Power Current (Imp)</td>
<td>Amps</td>
<td>7.6</td>
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<tr>
<td>Open Circuit Voltage (Voc)</td>
<td>Volts</td>
<td>32.9</td>
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<tr>
<td>Short Circuit Current (Isc)</td>
<td>Amps</td>
<td>8.1</td>
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<tr>
<td>Short Circuit Temp. Coefficient</td>
<td>mA/°C</td>
<td>5.6</td>
</tr>
<tr>
<td>Open Circuit Voltage Coefficient</td>
<td>V/°C</td>
<td>-0.12</td>
</tr>
<tr>
<td>Max. Power Temp. Coefficient</td>
<td>%/°C</td>
<td>-0.5</td>
</tr>
<tr>
<td>Max. Series Fuse</td>
<td>Amps</td>
<td>15</td>
</tr>
<tr>
<td>Max. System Voltage</td>
<td>Volts</td>
<td>600</td>
</tr>
<tr>
<td>Normal Operating Cell Temperature [NOCT]</td>
<td>deg. C</td>
<td>45</td>
</tr>
</tbody>
</table>
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PROJECT GOALS

- Dozens of project requirements with an emphasis on system integration
- Main requirements include:
  - Automatic charge and discharge the LiFePO$_4$ batteries
  - Deliver 120V RMS, 60Hz +/- 0.05% AC electricity
  - Monitor, store and display real time temperature, voltage, and current data from all subsystems
  - Safety precautions will be implemented to safely shut down the system if a fault is detected
  - Install an LCD display in the system to show a demo
2009 SYSTEM

Raw Power Interface: Accepts high voltage DC from the roof-mounted PV array and delivers it to the rest of the system.

Energy Delivery System: Accepts high voltage DC and converts to 120V RMS signal of 60 Hz.

Supervisory Control And Data Acquisition: Gathers and displays voltage, current, and temperature readings from the system.

Energy Storage System: Stores excess energy from PV to deliver energy to the load.

Transformer
2009 PROBLEMS

- Did not achieve complete system integration
- Did not achieve desired output frequency specified in the statement of work – which is why we are not reusing the inverter
- They did not protect against voltage or current spikes in the switching – issues with high power switching
2009 PROGRESS (ITEMS BEING REUSED)

- Data Acquisition Boards
- Safety

![Diagram Graphic]

**Raw Power Interface:**
Accepts high voltage DC from the roof-mounted PV array and delivers it to the rest of the system.

**Energy Storage System:**
Stores excess energy from PV to deliver energy to the load.

**Transformer**
2010 SYSTEM (ADDITIONS)

**SCADA INTERFACE BOX**
Gathers data from all subsystems, contains FIT PC, controls monitor display and dataflow to the website.

**SWITCH CONTROLLER**
Regulates the high voltage path between the PV, batteries (ESS), and the filter/inverter (FIB).

**FILTER INVERTER BOX**
Contains the DC to AC inverter as well as the filter to output 120V AC 60 Hz.

**SNUBBER CIRCUITS:**
A safety precaution to prevent current spikes from damaging the system.
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Raw Power Interface (RPI):

- Accepts high voltage DC from the roof-mounted PV array and delivers it to the rest of the system.

### Diagram Description:

- **Raw Power Interface**: Manages high voltage DC from the PV array.
- **SCADA Interface Box**: Connects to the monitoring and control systems.
- **Switch Controller**: Controls power distribution.
- **Energy Storage System**: Stores excess energy.
- **Filter Inverter Box**: Converts energy for distribution.
- **Xfmr (Transformer)**: Converts voltage levels as needed.

### Key Connections:
- **HV** (High Voltage): Inputs high voltage DC from the PV array.
- **120V AC Out**: Outputs 120V AC power.
- **USB** and **Ethernet**: Communication links.
- **Digital**: Digital signal lines.
- **Wall Supply**: 125V AC supply for wall outlets.

The diagram illustrates the flow of electrical power through these components, ensuring efficient and safe power delivery throughout the system.
ENERGY STORAGE SYSTEM (ESS)

Energy Storage System:
Stores excess energy from PV to deliver energy to the load
FILTER & INVERTER BOX (FIB)

FILTER INVERTER BOX
Contains the DC to AC inverter as well as the filter to output 120V AC 60 Hz
SWITCH CONTROLLER (SC)

Regulates the high voltage path between the PV, batteries (ESS), and the filter/inverter (FIB)
SCADA INTERFACE BOX
Gathers data from all subsystems, contains FIT PC, controls monitor display and dataflow to the website
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SAFETY INTERFACE REQUIREMENTS

- Allows system to be quickly and reliably shut down to a safe, un-energized state should a fault be detected
- All subsystems will be connected to the safety interface
- Breaking the safety interface → all subsystems:
  + enter a fault state
  + disconnect HV from their outside terminals
- The RPI is the safety hub; other systems comply with its interface
EXISTING SAFETY INTERFACE

- **Ground Fault**
  - Monitor opens the safety loop

- **High Temperature**
  - Normally closed T-dependent switch opens at high T

- **Subsystem Fault**
  - Subsystem Data Acquisition board controls a relay

- **Isolation Relay**
  - Normally open; needs 12V to close
SAFETY ADDITIONS

- RPI and ESS are currently in safety loop
- SC, SIB, and FIB will be added
- SC will be added as part of DC Load Integration
- FIB and SIB will be added as part of System Integration
SAFETY FAULTS

- **Ground Fault**: Ground Fault Monitor opens the safety loop.
- **High Temperature**: Normally closed T-dependent switch opens at high T.
- **Subsystem Fault**: Subsystem Data Acquisition board controls a relay.

**Subsystems**:
- **ESS**: HV Isolation Relay
  - HV from PV & to FIB via SC
- **FIB**: HV Isolation Relay
  - HV from PV & ESS via SC
- **SC**: HV to/from ESS
- **SIB**: Temp Controlled Switch
  - Controllable Relay

**Relays**:
- **Isolation Relay**: Normally open; needs 12V to close.
- **Fault Indicator**: Safety 12V
- **Safety Relay**: HV Isolation Relay
- **System 12V**: from ESS
- **HV to ESS via SC**:HV Isolation Relay
- **Safety Reset Button (Green)**: HV from PV
- **Shutdown Button (Red)**: “Safety 12” 12V
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PLAN OF ATTACK (ROADMAP)

✓ Read data off Data Acquisition boards
  + We can accurately read voltage, temperatures and current out of the boards using algorithms
✓ SCADA is able to read sensor data and set outputs with the Data Acquisition Board – Basic Maintenance App
  + Using terminal user interface
  + Uses algorithms to calculate sensor values
❌ DC Load Integration
❌ Demonstrate per cell battery management
❌ System Integration
❌ Final Demo
DC LOAD INTEGRATION: RISKS TO BE RETIRED

- Snubber, high power switching, and charge control
- Correctly assembling and testing SC
- Charge Battery Pack from PV array
- Run DC Load from Battery Pack
- Software communicating with all systems through Data Acquisition Boards except FIB
- Displaying Information online/completed database
- Integrate the Safety Loop in all related subsystems
DC LOAD INTEGRATION PREREQUISITES

- The DAQ board must be controllable and understandable
  - Input/output pins must be identified
  - We must be able to communicate with the board
- RPI must be safe and able to communicate with SCADA
- ESS must be safe and ready to test
  - Fix broken relay
  - Battery voltage, current, and temperature measurements must be accurate when asked for
DC LOAD INTEGRATION PREREQUISITES

- SC must be operable to control PV-ESS interface
  - Switches must be placed inside box along with DAQ board
  - Proper cabling between SC and other subsystems must be completed
  - Software must be able to control SC switches to regulate the flow of high voltage throughout the system
  - Snubber Circuits must be installed and tested to show proper functionality and shown to be safe
- SCADA must have working database
  - Display voltage, current, and temperature measurements on the LPRDS 2010 website
Figure out how to fix SC DAQ and connectors needed for SC 3/4/10
Order the missing parts of DAQ, broken ESS relay, Snubber stuff and connectors 3/5/10
Finish Charge/Discharge Curves 3/5/10
Test RPI to ensure safety and communicate with DAQ inside RPI 3/10/10
Test ESS to ensure safety and communicate with DAQ inside ESS 3/12/10
Assemble SC, snubbers, and fix DAQ board 3/12/10
DC Load integration Test plan complete 3/12/10
Spring Break 3/13/10-3/21/10
Software controlling switches 3/24/10
Test SC and snubbers 3/24/10
SCADA database ready to display information on LPRDS 2010 website 3/26/10
Interconnect SC, ESS, RPI, Safety Loop and DC Load with proper cabling 3/26/10
Test safety loop 3/30/10
Perform Tests on entire DC Load Integration and declare functional 4/3/10
DC LOAD INTEGRATION TESTING EXAMPLES

- Test Plan to be completed: 3/12/10
- ESS Subsystem Tests
  - Cycle ESS in smaller packs at low voltage
  - Cycle ESS in single pack at low voltage
  - Cycle ESS in smaller packs at high voltage
  - Cycle ESS in single pack at high voltage
  - Cycle ESS in single pack with PV source
- SC Subsystem Tests
  - Test SC operation at low voltage manually
  - Test SC operation at low voltage under SW control
  - Test SC operation with HV DC source and ESS manually
  - Test SC operation with HV DC source and ESS under SW control
  - Test SC operation with PV source and ESS manually
  - Test SC operation with PV source and ESS under SW control
Expected Date of Completion: 04/01/10
To be demonstrated as a demo first by this date and will hopefully be integrated by May 7th if time permits
Be able to charge each cell to maximum capacity without overcharging other cells

Requirement of demonstrating per cell battery management can be done with LPRDS
SCHEDULE FOR PER CELL BATTERY DEMO

- Make a list of what need to be ordered (cells, chips, boards) 3/8/10
- Order cells, chips, boards 3/10/10
- Spring Break 3/13/10-3/21/10
- Per Cell Management Test Plan Complete 3/24/10
- Design and Create board to hold chips and monitor battery cells 3/26/10
- Demo per cell battery management 4/1/10
Expected Date of Completion: 4/30/10
SYSTEM INTEGRATION: RISKS TO BE RETIRED

- Correct Filter/Inverter output of 120V RMS 60Hz.
- Completed Safety Loop
- Software can talk to Data Acquisition Board in the FIB
- Correctly assembling and testing of FIB and SIB
- LCD Display working and Demo mode made
SCHEDULE TO COMPLETE SYSTEM INTEGRATION

- A list of cables, connectors, boxes, subsystem BOM's, anything to order: 3/8/10
- Order connectors, cables and anything else: 3/10/10
- Spring Break: 3/13/10-3/21/10
- Assemble SIB: 3/26/10
- DC Integration complete: 4/3/10
- Test SIB: 4/9/10
- Test Plan for System Integration Complete: 4/9/10
- Connect SIB to system with proper cables and test with the DC Load: 4/14/10
- Install LCD Display: 4/14/10
- FIB running off power supply: 4/17/10
- Demo App finished: 4/21/10
- Test Safety Loop with FIB and SIB incorporated: 4/23/10
- System Integration with FIB tested and declared done: 4/30/10
May 7th

Using George Foreman Grill to serve Hamburgers
ACCEPTANCE TEST PLAN: REQUIREMENTS

R001: Raw PV Power Interface (RPI)

R002: Energy Storage System (ESS)

R002b: Legacy ESS Requirements

R003: Energy Delivery System (EDS)

R004: SCADA-2010

R006: API and SDK

R008: Demonstration Application

R010: Power Input Independence

R011: Safety Interface

R012: SCADA Interface
Acceptance Test Plan Summary

- **Requirement:** Deliver 120V, 60Hz AC to a load
  - **Test:** Run the system with a load and use an oscilloscope to verify that the filter and inverter meet their specs

- **Requirement:** Do not over-charge or over-discharge the ESS; do not charge the ESS at extreme rates
  - **Test:** Cycle the ESS, verify that SC controls charging/discharging safely

- **Requirement:** SCADA must automatically initialize
  - **Test:** Restart and observe SCADA

- **Requirement:** All subsystems connected to working safety interface
  - **Test:** From each subsystem, break the safety loop (by overheating and via the subsystem DAQ) and verify that system enters the fault state and disconnects HV

- **Requirement:** Standalone, self-powered operation
  - **Test:** Run LPRDS for at least 24 hours without external input or power
BUDGET OVERVIEW

- Initial Budget: $3000
- Budget Estimates:
  - FIB: $1200
  - SIB: $862
  - ESS: $630
  - Safety Cables: $140
  - Misc.: $100
- TOTAL: $2932
SCADA INTERFACE BOX (SIB)
GOALS & REQUIREMENTS

- Periodically read and store sensor data
- Control system operations
- Create API for application development
- Log events, faults and changes
- System demonstration
- Website
SOFTWARE FUNCTIONAL DIAGRAM

System Controls
- On/Off/Reset
- Operation Change
- Smart Charge

System Sensors
- Voltage
- Current
- Temperature
- State

Database
- RPI Voltage Sensor
  3:59:01 2/21/10 200.3 V
  4:00:01 2/21/10 201.5 V
  4:01:01 2/21/10 199.4 V

Apps
- Maintenance
- Batt. Mgmt.
- Safety
- Demo

Website
- Data Plots
- Current State
- System Controls

API
MILESTONES SCHEDULE

- Basic Sensor Reading + System Control
  - Completed - February 22\textsuperscript{nd}

- Full LPRDS Sensor Reading + System Control
  - April 4\textsuperscript{th}

- Application Development
  - April 5\textsuperscript{th} – April 21\textsuperscript{th}

- Website Development
  - April 21\textsuperscript{st} – April 25\textsuperscript{th}

- System Completion
  - April 30\textsuperscript{th}
Existing Hardware
- FIT PC
- Switches & Relays
- Sensors
  - Voltage, Current, Temperature
- Data Acquisition Boards
- Sunny Boy Grid Tie Inverter
FIT PC

- Located in AEC 401.
- Accessible via SSH
- Will be running:
  - Core software
  - Database
  - Web server
  - Applications
DATA ACQUISITION (DAQ) BOARDS

- Designed by 2009 LPRDS team
- Microcontroller with working firmware
- 4 total in various subsystems
  - Raw Power Interface (RPI)
  - Filter and Inverter Board (FIB)
  - Energy Storage System (ESS)
  - Switch Controller (SC)
SOFTWARE TOOLS

- C++
  - Core Software
  - Applications
- MySQL
  - Database
- PHP/HTML
  - Website
- XML
  - Hardware Description file
COMMUNICATION PROTOCOLS

- RS-485
  - DAQ to SCADA Interface Board (SIB)
- USB
  - SCADA Interface Board (SIB) to FIT PC
- VGA
  - FIT PC to Display
I/O Hardware

- Data Acq: reads sensor data and controls relays
- Sunny Boy: grid tie info and controls
- Misc:
  - Safety Loop Relays
  - Alarm Buzzer
  - Alarm Silence/Reset
  - Demo Lights
LPRDS Software Architecture

- Apps *
- Commercial Product
- API Interface
- C++ Code *
- Hardware
- XML File

* Developed by SCADA team

rev. 4 (22-02-2010)
**Hardware Description XML**

- List of system devices
  - Sensors, Relays, Ports
- Loaded at system startup
- Allows new devices to be easily added
Hardware Description XML

- **Sensor Parameters**
  - Sensor name, board number, channel number
  - Scale, offset, min, max, type

- **Port Parameters**
  - Port name, board number, pin number, type

- **Relay Parameters**
  - Relay name, relay number, type
LPRDS Software Architecture

- **Apps**: Complete
- **Commercial Product**: In Progress
- **API Interface**: Data Signals
- **C++ Code**: Control Signals
- **Hardware**: XML File

- **XML File**: Developed by SCADA team

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- **Data Acq.**
- **Sunny Boy**
- **Misc.**

- **SIB**
  - usb-serial
  - xcr.h
  - iomgr.h
  - kernel.h

- **Hardware Desc. XML**
  - sensors.xml

- **XML Parser**
  - parser.h

- **Kernel**

- **MySQL++**
  - SQL - C++ wrapper

- **MySQL Database**

- **C++ API**

- **SQL API**

- **Apache2**
  - web server

- **Website**
  - PHP

- **Display**

**Revision**: 4 (22-02-2010)
XML Parser

- Extracts device information from XML
- Outputs map of device names and objects
SCADA Interface Board (SIB)

- Interface between software and:
  - Data Acquisition Boards
  - Sunny Boy Inverter
  - Misc. hardware

- Contains relays for system control
  - Alarm
  - Alarm reset
  - Display on/off
USB-Serial Transceiver (XCR)

- Receives data from the USB port
- Sends data to the USB port
I/O Manager

- Interprets data packets from hardware
- Generates commands sent to hardware
  - To get data
  - To control switches/relays
Kernel

- Interface between software and applications
- Provides system control functions
- Handles automated data polling
- Calibrates sensor data
MySQL Database

- Stores up to 1 year of sensor data
- MySQL++ wrapper for interaction with C++
  - Free commercial library
SQL API

- PHP methods
- Allows website to access MySQL database
SQL API Functions

- `mysql_connect( localhost, $username, $password )`
- `mysql_select_db( $database )`
- `mysql_query( $query )`
- `mysql_numrows( $result )`
- `mysql_result( $result, $i, "data" )`
- `mysql_close( )`
Website

• Apache2 web server
• Shows system status
• Access to system control
  – Authorization required
• Plots of system data
  – Organized by hour, day, month, year
C++ API

- Interface between applications and kernel
- Provides useful methods for app development
- Protects lower level system operation
C++ API Functions

- updateDeviceList()
- getSensorList()
- getPortList()
- getRelayList()
- getValue(string sensorID)
- getUnits(string sensorID)
- getPollingInterval()
- setPollingInterval(int seconds)
- setPort(string portID, int level)
- setRelay(string relayID, int level)
- getLog(string logID)
- writeLog(string logID, string errMsg)
Applications

• C++ programs using API
  – Safety
  – Battery Management
  – Maintenance
  – Demo
Safety App

- Automatically monitors critical sensor data
- Trips safety loop if sensor value exceeds a threshold
- Sounds alarm upon fault
Battery Management App

- Implements smart battery charging algorithms
- Uses data from database
- Uses API system controls
Maintenance App

• Terminal user interface
• Allows access to system controls over the network
• Displays sensor data
• View system logs
***************LPRDS Maintenance******************

---------- Current LPRDS State: Running    ----------
---------- Current Sunny Boy State: Off     ----------

Main Menu

A. System Controls
B. Sensor Data
C. System Logs

X. Exit App

Choose a Menu (A,B,C,X) :  A
***************LPRDS Maintenance******************

-------- Current LPRDS State: Running --------
-------- Current Sunny Boy State: Off --------

Main Menu> LPRDS Control Menu

A. System Startup
B. System Shutdown
C. Switch to Sunny Boy Mode

D. Simulate Fault
E. Clear Fault
F. Disconnect Load
G. Disconnect Solar Panels
H. Disconnect Battery Bank

S. View Sensor Data
X. Exit Control Menu

Choose an Option: C

Are you sure you want to Shutdown? (y/n): y

--Switching to Sunny Boy Mode...
Main Menu> Sensor Data Menu

Data Time Stamp- 3:31:55  2-21-2010

Photovoltaic Array
  Voltage: ___ V            Current: ___ A
  Power : ___ W

Raw Power Interface
  Voltage: ___ V            Current: ___ A
  Temperature: ___ °C      State: No Faults

Energy Storage System
  Voltage: ___ V            Current: ___ A
  Charge State: ___ %      Discharge Rate: ___ A/hr
  Temperature: ___ °C      State: No Faults

Energy Conversion System
  Voltage: ___ V            Current: ___ A
  Phase: ___

Press any key to return
Demo App

• Graphical display of system data and current state
• Controls AC outlet with relay for demo purposes
• Displayed on LCD monitor
• Simple user interaction
  – Startup/navigation via touch sensitive buttons
LPRDS is a self-monitoring solar energy system...

4.2 kWh/day

2 kW Solar Panel Array

Acopian Roof

Acopian Room 401

LPRDS

120 V ac 60 Hz

Power Grid

www.
10 solar panels collect 2kW of energy...

4.2 kWh/day

2 kW Solar Panel Array

Acopian Roof

Acopian Room 401

LPRDS

120 Vac 60 Hz

Power Grid

LPRDS Demo

Touch to Navigate
the energy is converted to AC and fed to the power grid
everything can be monitored and controlled via a website
LPRDS contains four major hardware systems

- Solar Panel
- Raw Power Interface (RPI)
- Switch Controller (SC)
- Filter Inverter Box
- Energy Storage System (ESS)

Connections:
- DC
- DAQ signals
- DAQ
- 204.8 V
- 64 - 3.2v LiFePO4 batteries in series

Touch to Navigate
Raw Power Interface

Connects the solar panel high voltage to the system

Real Time Solar Panel Voltage: 204.75 Vdc
Real Time Solar Panel Current: 3.83 A
LPRDS is currently in the battery discharge mode

Solar Panel
High Voltage

Raw Power Interface (RPI)

Danger
High Voltage

Switch Controller (SC)

Energy Storage System (ESS)
64 × 3.2V LiFePO4 batteries in series

DAQ

Filter Inverter Box

120 Vac 60 Hz

DAQ Signals

DAQ

DC

Prev

Next

LPRDS Demo

Touch to Navigate
LPRDS Energy Savings

At this moment, LPRDS has saved...

1000000000 kW·h

That’s equivalent to:

2056 tons of CO₂

56 houses for 130 days
$500 Allocation

Purchases:

- LCD Display < $400
- AC Relay Kit $23
- Touch Sensor Kit $25
- Demo Lights $30
ACCOMPLISHMENTS: TO DATE

- Complete system design
- Functional critical path
- Reading sensor data from DAQ to terminal
- Sending commands to DAQ from terminal
- Preliminary app development
Use terminal to read a DAQ port voltage

1. Issue command using terminal interface
2. Receive data packet from DAQ
3. Calibrate value for accuracy
4. Display value in terminal
DAC BOARD COMMAND PACKETS

- **Commands**
  - 0 = Get Analog Value
  - 1 = Get Digital Value
  - 2 = Set Pin High
  - 3 = Set Pin Low

- **Channels**
  - 1-3 = Temperature Sensors
  - 4-7 = Voltage Sensors
1. **Maintenance App** - issue read command using C++ API
   ```
   getValue(string sensorID)
   ```

2. **Kernel** - receive command via a pipe and pass the requested sensor object to I/O Manager
3. **I/O Manager** - create command to read voltage from sensor object and send to XCR

   Dest=4  Src =5  Bytes=6  Cmd=0  Chan=7  ChkSum

4. **XCR** - forward command via USB to the SIB and DAQ
5. **Data Acquisition** - sends sensor data back to XCR via USB

| Dest=5 | Src =4 | Bytes=7 | Error=0 | MSB = 0x00 | LSB =0x08 | ChkSum |

6. **XCR** - reads USB and passes data to **I/O Manager**
5. **I/O Manager** extracts data and passes value to kernel
   
   \[ x = 0008 \text{ (hex)} \]

6. **Kernel** calibrates sensor value using scale and offset
   
   \[ \text{Voltage} = 0.4848x + 1.0991 = 4.977 \text{ (V)} \]

7. **Kernel** returns adjusted value to the maint. app via a pipe
1. *Maintenance App-* issue control command using C++ API 
   `setPort(string portID, int level)`

2. *Kernel-* Receive command via a pipe and pass *port* or *relay* object and the level (H/L) to I/O Manager
3. **I/O Manager** - create command from the object and level and send to XCR

```
Dest=4  Src =5  Bytes=6  Cmd=2  Chan=13  ChkSum
```

4. **XCR** - sends command via USB to the SIB and DAQ

5. **SIB/DAQ** - set the corresponding output pin logic high
# Detailed Schedule

## April 2010

<table>
<thead>
<tr>
<th>Sunday</th>
<th>Monday</th>
<th>Tuesday</th>
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<td>Project Completion</td>
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CONCLUSION

- SCADA software will provide control and monitoring of LPRDS
- API will allow further application development
- Hardware expansion made easy with the hardware description XML

Questions?
SIB THINGS DONE AND THINGS TO DO

✓ The USB I/O board was ordered (02/18/10)
✓ The interface for the box was decided

✗ Install the Linux package to interface with USB I/O
✗ Build box and install in LPRDS tower
✗ Test subsystem
SIB TESTING

Test RS-485 connectivity
- Tested by connecting USB I/O board between FIT PC and a data acquisition board
- Test low level software commands to ensure connectivity
- Test using API commands
SIB TESTING

- Test digital inputs
  - Tested by inputting a dc voltage (5-12V) on the correct pin of the USB I/O board
  - Software test to detect an input
  - Software test to detect a falling edge on an input

- Test electromechanical relays
  - Software test for the control of the relays on the USB I/O board
SIB TESTING

- Test overall functionality of SIB
  - Test system shutdown button, alarm, & alarm acknowledge button
  - Test interactions with safety loop
SIB BUDGET

- $350 Total
  - $212 – USB-IIRO4-2SM (I/O Board)
  - $138 – Enclosure box and connectors
CDR OUTLINE

- Introduction to the System 8:30am
- Project Goals 8:35am
- Top Level Overview 8:45am
- System Software 10:35am
- Raw Power Interface (RPI) 11:40am
- Lunch 11:50am
- Energy Storage System (ESS) 12:30pm
- Switch Controller (SC) 1:35pm
- Filter Inverter Box (FIB) 2:40pm
RAW POWER INTERFACE (RPI)

- Main hub of safety loop
- Accepts high voltage DC from the roof-mounted PV array and delivers it to the rest of the system
CDR OUTLINE

- Introduction to the System 8:30am
- Project Goals 8:35am
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</tbody>
</table>
ENERGY STORAGE SYSTEM (ESS)
BATTERY STACK

One Cell Pack

One Cell

3.2V LiFePO4 Battery

- +

3.2V LiFePO4 Battery

+ -

One Cell Pack

One Cell

3.2V LiFePO4 Battery

- +

3.2V LiFePO4 Battery

+ -

V_BATT+

One Cell Pack

One Cell Pack

One Cell Pack

One Cell Pack

One Cell Pack

One Cell Pack

One Cell Pack

One Cell Pack

One Cell Pack

One Cell Pack

One Cell Pack

One Cell Pack

One Cell Pack
Purpose of the ESS: To store excess energy from the PV panels

The ESS must be capable of standalone operation

The ESS must incorporate per-cell battery monitoring

The ESS must allow for per-cell battery management
BATTERY CELL SPECIFICATIONS

- Manufacturer: General Electronics Battery (China)
- Supplier: Falcon-EV

“Green Square Cells LiFePO₄” – 10Ah, 8C Rated Cont., $39.00
  + Internal Resistance: < 8mΩ
  + Discharge Protection Voltage: 2.3V
  + Charge Protection Voltage: 3.65V
  + Continuous Discharge: 10C (100A)
  + Pulse Discharge Rate: 15C (5sec.)
  + Charging Current: 6-50A
  + Weight: 16oz.
  + Life: 1500 cycles w/ DOD @ 80%
2009 Battery Cell Characterization Curves

**CHARGING**

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

- **10A Rate**
  - Single Cell Charging @ 10A
  - Voltage: 3.70V
  - Time: 0.8hrs

**DISCHARGING**

- **5A Rate**
  - Voltage: 3.30V
  - Time: 1.7hrs

- **3.30V**
  - Voltage: 2.75V
  - Time: 0.9hrs

- **OVERCHARGE**
  - Voltage: 3.30V
  - Time: 2.57V
2009 TEST RESULTS

- Charging 10Ah battery cell @ 5A (1/2C) took 1.7hrs to reach maximum charge protection voltage
  - Initial battery voltage was 3.35V (78% charged)
- Charging 10Ah battery cell @ 10A (1C) took 0.8hrs to reach maximum charge protection voltage
  - Initial battery voltage was 3.30V (74% charged)
- Discharging 10Ah battery cell @ 5A (1/2C) took 1.7hrs to reach 2.75V
  - Initial battery voltage was 3.30V (74% charged)
  - Test did not run battery to maximum discharge protection voltage
- Discharging 10Ah battery cell @ 10A (1C) took 0.9hrs to reach maximum discharge protection voltage
  - Initial battery voltage was 3.3V (74% charged)
PRELIMINARY DISCHARGE TEST

- Verify internal resistance of battery cell
- Adjust discharge load across 15A range and observe battery voltage
- Disconnect and reconnect 15A load, observing changes

LeCroy Oscilloscope

TEST SETUP DIAGRAM

Adjustable Discharge Load Box

LiFePO₄ Battery

Battery Cell: S-69

HV Probe Adapter

High Voltage Probes
PRELIMINARY DISCHARGE TEST

Batt. V vs. Load I

\[ y = -0.0186x + 3.2761 \]
**PRELIMINARY DISCHARGE TEST**

Measured Battery Cell Internal Resistance = 0.02V/A = 20mΩ

+ Spec. sheet read 8mΩ
BATTERY CELL CHARACTERIZATION

TEST PLAN

- Measure Thevenin Resistance of 64-cell battery stack
- Charge cell @ 1C w/ initial charge @ 20% (2.56V) until a final charge @ 100% (3.65V)
  + Verify 10Ah charge capacity
  + Generate characteristic charge curve
- Discharge cell @ 1C w/ initial charge @ 100% (3.65V) until a final charge @ 20% (2.56V)
  + Verify 10Ah discharge capacity
  + Generate characteristic discharge curve
- Disconnect and reconnect a load current ranging from 5-20A on cell w/ charge @ 20% (2.56V)
  + Verify SC algorithm voltage thresholds
- Connect several cells in series and repeat charge and discharge tests monitoring each cell’s voltage
  + Generate characteristic charge and discharge curve for individual cells in battery stack
  + Determine the priority for per cell battery management (cell balancing)
PER CELL BATTERY MONITORING/MANAGEMENT

- To be demonstrated as a demo first then integrated if time permits using PCB board
- Demo will be created in two phases
- Utilizing the Linear Technology Multicell Battery Stack Monitor (LTC6802-1)
ABOUT THE LTC6802-1

- Multiplexed measuring of up to 12 Li-Ion cells
- Two temperature monitoring inputs
- On-chip passive cell balancing switches
- Stackable architecture via daisy chaining
PHASE 1

- One monitor chip & 8 LiFePO4 cells (~25.6 V battery stack)
PHASE 1 TESTS

- Send commands to and read voltages from chip
- Ensure temperature monitoring works
- Monitor voltage across each battery while charging
- Test passive cell balancing switches by charging one cell out of the circuit and reinserting it into the stack
- Monitor temperature while cell balancing
PHASE 2

- Two monitor chips daisy chained together & 8 LiFePO4 cells (~25.6 V battery stack)
PHASE 2 TESTS

- Send commands to chip 1 and ensure the commands are sent to chip 2 through daisy chain interface
- Read voltages & temperatures off of cells from both chips
FINAL STEPS - PCB M

- Prepare a final circuit design & PCB
- Redesign tower to allow room for circuit boards on top of the batteries
- Design a PCB to lay across two cell packs (8 cells)
- This creates a ~24V cell that will be monitored by one LTC6802-1 chip
PER-CELL BATTERY MANAGEMENT DESIGN

One Cell Pack

One Cell

3.2V LiFePO4 Battery

3.2V LiFePO4 Battery

3.2V LiFePO4 Battery

3.2V LiFePO4 Battery

To next board via daisy chain

SPI OUT

SPI IN

To previous board via daisy chain

LTC6802-1

TEMP Monitoring Pack 2

VBATT7

VBATT8

VBATT5

VBATT6

VBATT4

VBATT3

VBATT2

VBATT1
Test the existing data acquisition board to ensure it is fully functional

Test “maintenance” power mode (where system power is delivered from the main power)

Test the “fuel gauge” monitoring of the batteries
ESS THINGS DONE AND TO DO

- System remains unchanged from last year
- Chips selected for battery management
- Characterization of batteries
  - Create “fuel gauge” monitor & display that information
  - Demo of per-cell battery management
ESS BUDGET

- $630 Total
  - $50 LCD Display
  - $100 “Fuel gauge” monitoring circuitry
  - $100 Modifications to existing ESS
  - $140 Extra battery cells for per-cell management
  - $140 Per-cell management chips/evaluation board
  - $100 PCB Fabrication
SWITCH CONTROLLER (SC)
SWITCH CONTROLLER (SC) REQUIREMENTS

- Direct power between the RPI, ESS, and FIB
- First priority: RPI \(\rightarrow\) FIB
  - Additional energy from the PVs  RPI \(\rightarrow\) ESS
  - Not enough energy from the PVs  ESS \(\rightarrow\) FIB
  - Not enough energy from the PVs + ESS  Disconnect the FIB
Charge Mode
switch A closed and B open

Solar Panel
High Voltage
\(~205 \text{ V}_{dc}\)

Raw Power Interface (RPI)

Switch Controller (SC)

Energy Storage System (ESS)
64 - 3.2\text{v LiFePO}_4 batteries in series

DAQ
GFI

Fit PC
DAQ Signals

Filter Inverter Box
120 \text{V}_{AC}
60 Hz

-DANGER-
HIGH VOLTAGE

DAQ

DC
Battery Mode
switch A open and B closed
Fault State
switch A and B open
SWITCH CONTROL (SC) ALGORITHM

Battery Discharge

V_{batt}
Models are the same for both PV > Load and Load > PV except the constants change.
SC SIMULATIONS: LOAD > PV

Switch Position

time (s)

Battery Voltage

Voltage (V)

time (s)

Battery Current

Current (A)
SC SIMULATIONS: PV > LOAD

- **SWA**: Switch Position
  - Time (s): 0 to 4.5
  - Values: 0, 1

- **SWB**: Switch Position
  - Time (s): 0 to 4.5
  - Value: 1

- **Battery Voltage**: Voltage (V)
  - Time (s): 0 to 9
  - Values: 11.5 to 13

- **Battery Current**: Current (A)
  - Time (s): 0 to 9
  - Values: 0 to 0.1
SNUBBER CIRCUITS

- Switching high power causes voltage & current spikes due to inductance
- Can exceed ratings of switches, other components
- Especially important with inverter, filter
SNUBBER CIRCUITS

- They are going on all switches in the system to prevent unwanted spikes in current and voltage.
- These will prevent last year's problems with regards to the explosions.
- Limit current to 28A (IGBT switches).
- Tune for 1ms time constant for current.
SNUBBER SIMULATION

205V LiFePO4

IGBT

5 mH

10 ohm

10 uF

Load

Snubber

Load
SNUBBER SIMULATION-GENERIC LOAD

Current through IGBT/load:

Without Snubber (>1000A)

With Snubber
SNUBBER SIMULATION-GENERIC LOAD

Voltage across IGBT

Without Snubber
(>300V)

With Snubber
SNUBBER SIMULATION-INVERTER MODEL

Switching Inverter, No Snubber

Switching Inverter, Snubber

Without Snubber
(~1000A max)

With Snubber
(~22A max)
Diode
- Must handle moderate currents (~10-20A)
- Large reverse voltage rating (>200V)
- Fast recovery
- Vishay 20ETF04FP
  - 400V reverse, 20A
  - Fast recovery (60ns)
**SNUBBER-COMPONENTS**

- **Inductor**
  - Must handle current spikes/load current (~30A)
  - Large inductors (5mH) are expensive
  - Look into purchasing core and winding inductor
SNUBBER THINGS TO DO

- More simulations
- Need more details on where they will be used/currents & voltages to snub
SC TESTING

- Test SC operation at low voltage manually
- Test SC operation at low voltage under SW control
- Test SC operation with HV DC source and ESS manually
- Test SC operation with HV DC source and ESS under SW control
- Test SC operation with PV source and ESS manually
- Test SC operation with PV source and ESS under SW control
SC THINGS DONE AND TO DO

✓ Box with most of the connections re-designated to the SC
✓ Relays and DAQ board exist

✗ Write controller software
✗ Subsystem testing
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FILTER INVERTER BOX OUTLINE

- Inverter
  - H-Bridge
  - Microcontroller
  - Simulation
- Filter
  - Structure
  - Simulation
- Transformer
BASIC FIB TOPOLOGY

HV DC → H-Bridge → Low-pass Filter → Isolation Transformer

PWM
**FIB OUTLINE**

- Inverter
  - H-Bridge
  - Microcontroller
  - Simulation
- Filter
  - Structure
  - Simulation
- Transformer
SIMULINK MODEL

Discrete, Ts = 5.144e-006 s.
INVERTER REQUIREMENTS

- 120V RMS, sinusoidal 60Hz
- 10A RMS max current to any power factor
- 60Hz ±.05%
- 3% Load regulation
  + With 5% overshoot
  + Settling time within 2% of less than 33ms
- 3% THD
INVERTER DESIGN CONSIDERATIONS

- IGBT’s – Using the IGBT’s defined in the specification
  - 600V, 15A continuous
- IGBT Half bridge Drivers
  - Be able to drive high side over 250V
- PWM generation
  - Single sided PWM was decided upon last year, and we will stick with the same modulation scheme
PWM GENERATION

Show PWM generation waveform

Show sine waves along with triangle waves to generate PWM
PWM WAVES

Transient Analysis, 27 deg C

Voltage (V)

0 50 100 150 200

Time (s)

0 5m 10m 15m 20m

tran1.v(input1)
tran1.v(input2)
IGBT DRIVERS
- Atmel Atmega128
- Will drive H-bridge at 10kHz with 2 PWMs

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<td>Brown-out Detection</td>
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<td>Fully Static Operation</td>
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<td>On-Chip Debug support via JTAG port</td>
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<td>IEEE 1149.1 (JTAG) Boundary Scan</td>
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<td>Timer/Counters (8-bit)</td>
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<td>Watchdog Timer with On-chip Oscillator</td>
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<td>Real Time Counter</td>
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<td>Timer/Counters (16-bit)</td>
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<td>Analog Comparator</td>
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<td>Analog-to-Digital Converter (10-bit)</td>
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<td>Analog Gain Stage</td>
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<th>Programming Modes</th>
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<td>In-System Programming via SPI Port</td>
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<td>High Voltage Parallel Programming (12V)</td>
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<tr>
<td>Self-Programming via on-chip Boot Program</td>
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<td>In-System Programming via JTAG port</td>
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<tr>
<td>Full Duplex Serial Peripheral Interface (SPI)</td>
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<tr>
<td>2-wire Serial Interface (I2C compatible)</td>
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<tr>
<td>Full Duplex USART</td>
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</table>
LARGE INPUT CURRENT IN SIMULATION

- Input current of >1000A seen in simulation
LARGE INPUT CURRENT FIX

- Added resistor with a switch to limit the input current
- 10ohm resistor will allow at most 20A from the battery while H-bridge is off
- Switch will short out resistor to eliminate current drop while under load
- Have a delay circuit that will delay the switch until the capacitor is charged
LAST YEAR’S PROBLEMS

- 60.5Hz output
  + Used a sine table with half of a waveform
  + Will fix by using 3 full waveforms to get even 60Hz

- No feedback controller
  + Feedback designed, but never implemented
  + Will implement using HV differential amplifier and ADC

- And.....
DEATH AND DESTRUCTION
FEEDBACK CONTROL

- HV differential amplifier
- Optically isolated output
- Will produce a 1V-4V sine wave at output of optical isolator, sensing up to 340Vp-p
- Attached to microcontroller ADC
Algorithm

- Algorithm not yet designed
- Focus was on hardware initially, software can be designed while hardware is on order
- Controller designed last year met requirements, but was not implemented
PHASE DETECTION

- Use 0V crossing from the voltage and current to generate an 8-bit value for the phase angle, then feed that into an DAC that will be connected to the DAQ board.
- Still need to analyze use of optical isolators to get values for outputs to be able to connect to the DAQ.
- This will be done with software, so we can decide on values while hardware is being ordered.

**ANALOG DEVICES**

2.7 V to 5.5 V, Parallel Input Dual Voltage Output 8-Bit DAC
AD7302
H-BRIDGE SCHEMATIC
FIB OUTLINE

- Inverter
  - H-Bridge
  - Microcontroller
  - Simulation
- Filter
  - Structure
  - Simulation
- Transformer
SIMULINK MODEL

Discrete, \( T_s = 5.144 \times 10^{-6} \text{ s} \)

H-Bridge

Filter

XFMR

Battery

Ideal Switch

Pulse

IGBT1

IGBT2

IGBT3

IGBT4

Rdc

Cdc

VS1

VS2

R3

R4

C1

Linear Transformer

Pulses

Discrete PWM Generator

Constant

Idc-Scope

Iac-Scope

VS1-Scope

VS2-Scope

Idc

Iac

Battery-Scope

Constant1

XPFR

<Voltage (V)>

<Current (A)>

<Voltage (V)>

<Current (A)>

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<Switch current>

<Switch voltage>

<Switch current>

<Switch voltage>

<Switch current>

<Switch voltage>

<Switch current>

<Switch voltage>

<Switch current>

<Switch voltage>

<Switch current>
FFT W/O FILTER (SIMULATED)

× THD = 25%
FCC CONDUCTED EMISSION REGULATIONS

- Class A digital device
- Frequency measurements must use 50 μH/50 ohms LISN (Line Impedance Stabilization Network).
- Frequencies between 150kHz and 30MHz must meet the following requirements:

<table>
<thead>
<tr>
<th>Frequency of Emission (MHz)</th>
<th>Conducted Limit (dBμV)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Quasi-peak</td>
</tr>
<tr>
<td>0.15-0.5</td>
<td>79</td>
</tr>
<tr>
<td>0.5-30</td>
<td>73</td>
</tr>
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</table>
RADIATED EMISSIONS

- Can not be simulated, but will take measures to reduce
- All parts will be contained in metal casings to reduce radiated emissions.
- At a distance of 10 meters:

<table>
<thead>
<tr>
<th>Frequency of Emission (MHz)</th>
<th>Field Strength (microvolts/meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-88</td>
<td>90</td>
</tr>
<tr>
<td>88-216</td>
<td>150</td>
</tr>
<tr>
<td>216-960</td>
<td>210</td>
</tr>
<tr>
<td>Above 960</td>
<td>300</td>
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</tbody>
</table>
THINGS TO CONSIDER IN SELECTING CORES

- Maintaining constant inductance relative to current
- Temperature Rise
- Physical Size
- Number of turns and gauge of wire
- Power Loss
- Price
<table>
<thead>
<tr>
<th>Core Part Number</th>
<th>Price</th>
<th>AL nH</th>
<th>Turns</th>
<th>Wire AWG</th>
<th>% Fill</th>
<th>Rdc Ohms</th>
<th>Bac Gauss</th>
<th>% Perm</th>
<th>Core Loss Watts</th>
<th>Copper Loss Watts</th>
<th>Temp Rise deg C</th>
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<td>1.07</td>
<td>155</td>
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<td>2.20</td>
<td>28.7</td>
</tr>
<tr>
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<td>104</td>
<td>69</td>
<td># 13</td>
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<td>0.77</td>
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<td>28.4</td>
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<tr>
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<td>155</td>
<td>62</td>
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<td>19.7 m</td>
<td>10091.3</td>
<td>171.5</td>
<td>3.60</td>
<td>1.97</td>
<td>25.4</td>
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<td>42.2 m</td>
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<td>0.77</td>
<td>4.22</td>
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<td>96</td>
<td>72</td>
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<td>79</td>
<td>81</td>
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<td>23.7 m</td>
<td>10943.1</td>
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<td>Wire</td>
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<td>Height in.</td>
<td>Ac sq cm</td>
<td>Lm cm</td>
<td>Turns</td>
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</table>
AC Analysis, 27 deg C

- **ac2.db(v(rtop) - v(rbot))**
  - $X = 611.04$
  - $Y = 3.3766$

- **ac2.db(v(rtop) - v(rbot))**
  - $X = 9.9484K$
  - $Y = -47.37$
SIMULATION WITH MINIMUM CURRENT

AC Analysis, 27 deg C

\[ \text{ac4.db}(v(r\text{top}) - v(r\text{bot})) \]

- X = 669.3,
- Y = 28.42

\[ \text{ac4.db}(v(r\text{top}) - v(r\text{bot})) \]

- X = 10.031K,
- Y = -47.506
SIMULATION WITH FOREMAN GRILL LOAD

AC Analysis, 27 deg C

ac3.db(v(rtop) - v(rbot))
X = 636.86,
Y = 6.6981

ac3.db(v(rtop) - v(rbot))
X = 9.9484K,
Y = -47.365
NONLINEAR INDUCTANCE

CURRENT IN AMPERES

CORE: 1250-2200
0.7 Turns, 507.3 uH @ 10.0 Amperes RMS
MAX INDUCTANCE
FILTER FROM LAST YEAR
PROBLEMS WITH FILTER

- Filtered PWM frequency well, but...
- Nonlinearities caused much distortion
  - Simulink model with hysteresis model showed similar effects with random hysteresis model
  - We are trying to simulate with correct hysteresis model
- Design consisted of someone bringing some random inductors and a filter was designed around them at the last minute
FFT W/ FILTER (SIMULATED)

THD = 1.52% < Requirement: 3%
HYSTERESIS

BH curve for the core we selected

Our Simulink Model
THINGS TO DO

- Continue to simulate hysteresis with our inductor using either Simulink or SmartSpice
  + Part of a model working
- See if we can make the inductors smaller to reduce size and cost while still meeting requirements
FIB OUTLINE

- Filter
  + Structure
  + Simulation
- Inverter
  + H-Bridge
  + Microcontroller
  + Simulation
- Transformer
1:1 Isolation Transformer

- Measured at 35mH and 2.6Ω
- Used to reference the output wave to ground
- 2kVA
- 120/208/240/277 primary
- 120/240 secondary
- Wired for 120V to 120V
1:1 Isolation Transformer
- Measured at 35mH and 2.6Ω
- Used to reference the output wave to ground
- 2kVA
- 120/208/240/277 primary
- 120/240 secondary
- Wired for 120V to 120V
INVERTER SAFETY

- **Over Current**
  + Comparator in high voltage will check the output of a current sensor that will turn the microcontroller off if too much current is supplied

- **Under Voltage – HV DC**
  + Turn on circuit to limit inrush current can also serve as under voltage on the DC input, so if the DC is too low to allow for 120V rms output, the inverter will turn off

- **Over Voltage - AC**
  + Controller will decrease duty cycle if there is an over voltage on the AC output
Ease of removal of the PCB
  + Remove top and bottom

Filter mounted to the side

Internal connections to the board
  + Quick disconnects

Grounded metal box as required by safety plan

Cooling fan with thermostat
  + IGBT HS
  + Switch HS
DATA ACQUISITION BOARD

- Same design as used in the ESS and SC boxes
- Used to measure voltage and current of the AC and DC
- Also will record the phase angle of the output
- Wanted to put all onto one board, but decided that it would be more expensive to make one large board
- Also wanted to try to use FIB microcontroller instead of the data acquisition board, but decided that would be easier to use the existing board since it has known operation
- SCADA can talk to microcontroller via RS-485 if we have time in the future
TESTING

- Filter distortion can be tested by running of building mains and measuring harmonics.
- Test startup circuit for switch and PWM by feeding a voltage into the input of a comparator.
- H-Bridge will be tested with lower voltages to confirm operation, then progressive increase voltage with power supply to make sure it will run at rated voltage.
- Test with relay and power supply to test the step response of the inverter.
- Test whole inverter off the power supply before connecting to the batteries.
- Final test of FIB with batteries.
TO-DO LIST

- Analyze power dissipation from IGBT and switches
  + Was not done yet because existing inverter worked and we can use the same setup as last year

- Draw schematics to facilitate PCB design
BUDGET

$1200 total
+ Filter - $350
+ H-Bridge - $300
+ Box/PCB - $350
+ Connectors - $55
+ DAQ - $115
+ Slush Fund - $30

Already Own
- Microcontroller and JTAG programmer
- Filter Capacitor
- Isolation Transformer
SCHEDULE

- Today – CDR!
- 5 March – Hand schematic over to PCB design
- 8 March – FIB ordering deadline, except PCB – all requisitions handed to department secretary
- 12 March – Last day to order PCB
- 26 March – Have all software written and tested
- 17 April – Subsystem running off power supply
- 30 April – Integration Complete
- 7 May – Final Demo
*Burgers may not be as big as they seem