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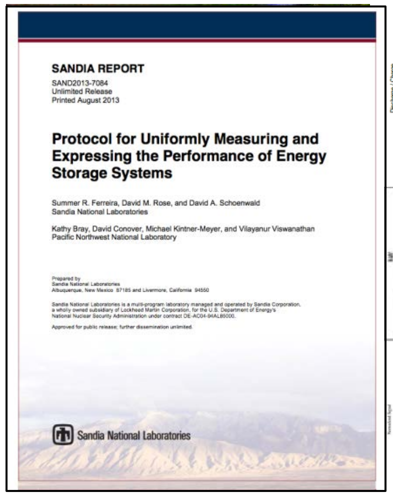

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Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems

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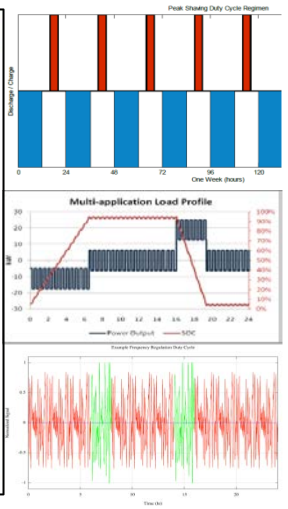

Energy Storage Systems Analysis Laboratory – ESTP Operations and Results

9/24/2015 David Rosewater, Summer Ferreira, Roy Lopez, Jacquelynne Hernandez, Lana Kimmel

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Project Overview: Purpose

- ***Industry Acceptance:*** There is significant uncertainty about how storage technology will be used in practice and how new storage technologies will perform over time in applications. Currently, systems operators have limited experience using deployed storage resources; stakeholder input suggests that development of algorithms to employ storage technology effectively and profitably could encourage investments.

"Industry adoption requires that they have confidence storage will deploy as expected, perform and deliver as predicted and promised." - Energy Storage Strategic Goal

Source – U.S. DOE Plan for Grid Energy Storage, December 2013

Project Overview: Infrastructure

The Energy Storage Systems Analysis Laboratory (ESSAL)

Providing reliable, independent, third party analysis and verification of advanced energy technologies for cell to MW systems

Cells and Modules

72V 1000A Bitrode (2 Channels)

Cell, Battery and Module Analysis

- **14 channels from 36 V, 25 A to 72 V, 1000 A for battery to module performance analysis**
- **Over 125 channels; 0 V to 10 V, 3 A to 100+ A for cell performance analysis**
- **Potentiostat/galvanostats for spectral impedance**
- **Multimeters, shunts and power supply for high precision testing**
- **Temperature chambers**

Fully Integrated Systems

Lab Analysis

Energy Storage Test Pad (ESTP)

- **Scalable from 5 KW to 1 MW, 480 VAC, 3 phase**
- **1 MW/1 MVAR load bank for either parallel microgrid, or series UPS operations**
- **Subcycle metering in feeder breakers for system identification and transient analysis**
- **Thermal imaging**
- **<u>System Safety Analysis (new)</u>**

Field Analysis (new)

Remote Data Acquisition System (RDAS)

- **Portable, Modular, Remotely Reconfigurable, and outdoor-ready**
- **Subcycle metering**
- **Tractable calibration**
- **Command Signal Ready for Grid Operator Simulation**
- **No control over grid conditions**

Project Overview: Scope (**Jet Analogy**)

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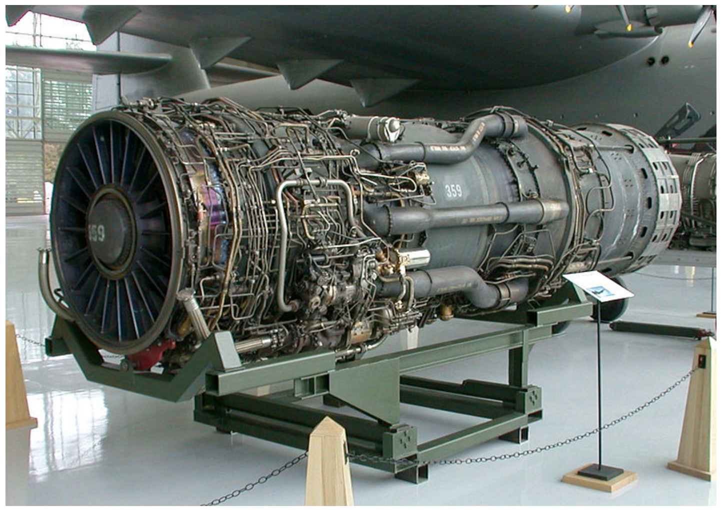
Activity

Cells and Module Analysis

System Laboratory Analysis

Demonstration and Field Analysis

Analogy



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Capability

Cells and Module Analysis:

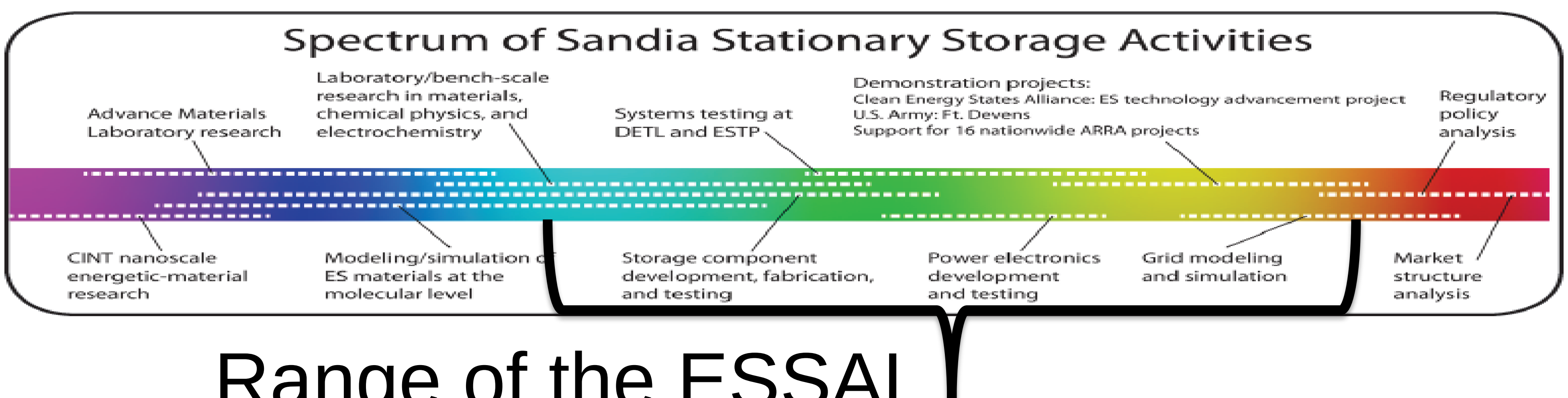
- Adjustable Environmental Conditions
- Control Signals and
- Components need to perform reliably

System Laboratory Analysis:

- Adjustable Grid Conditions
- Simulated Control Signals
- Components need to perform reliably

Demonstration and Field Analysis:

- Real World Grid and Environmental Conditions
- Real World Control Signals
- Interconnection Requirements
- Maintenance



Range of the ESSAL

FY15 Accomplishments

Publications

- D. M. Rosewater et al "**Modeling And Performance Analysis of a Grid-Scale Lithium-Ion Battery System**" – under review with IEEE Transactions on Power Conversion

- D. M. Rosewater, S. R. Ferreira "**Derivation of a Frequency Regulation Duty Cycle for Standardized Energy Storage Performance Testing**" under review with Journal of Energy Storage

FY15 Accomplishments

Projects

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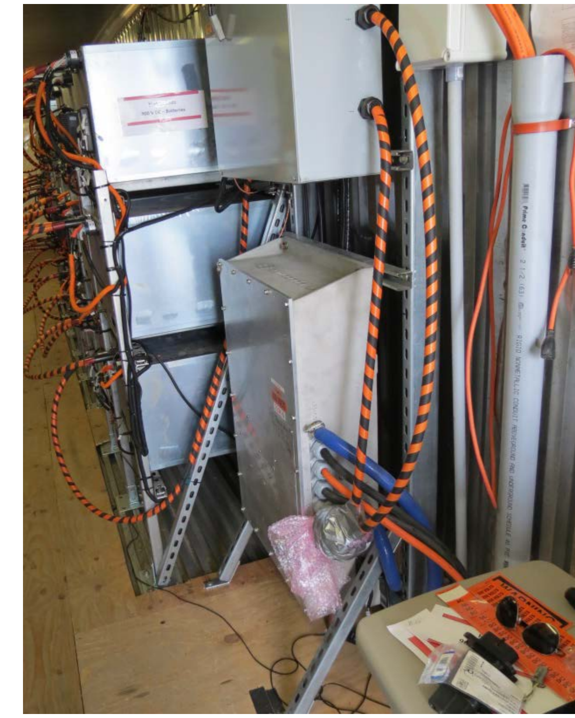
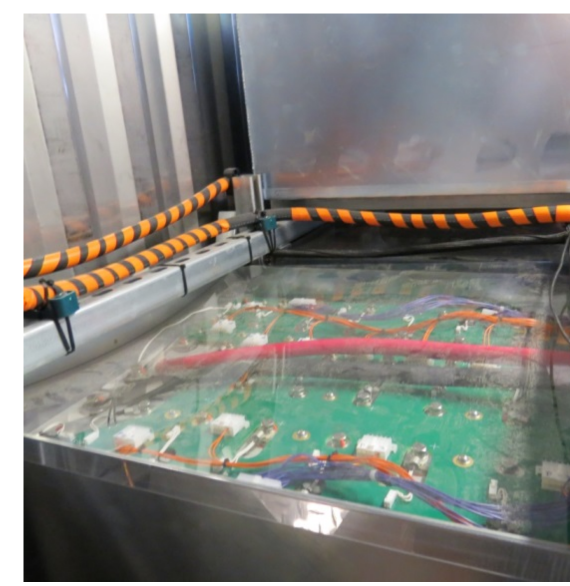
Installation of the Raytheon RK10 at ESSAL



Installation of TransPower Grid Saver at ESSAL

UET system in Washington (rendering)

String F in GridSaver

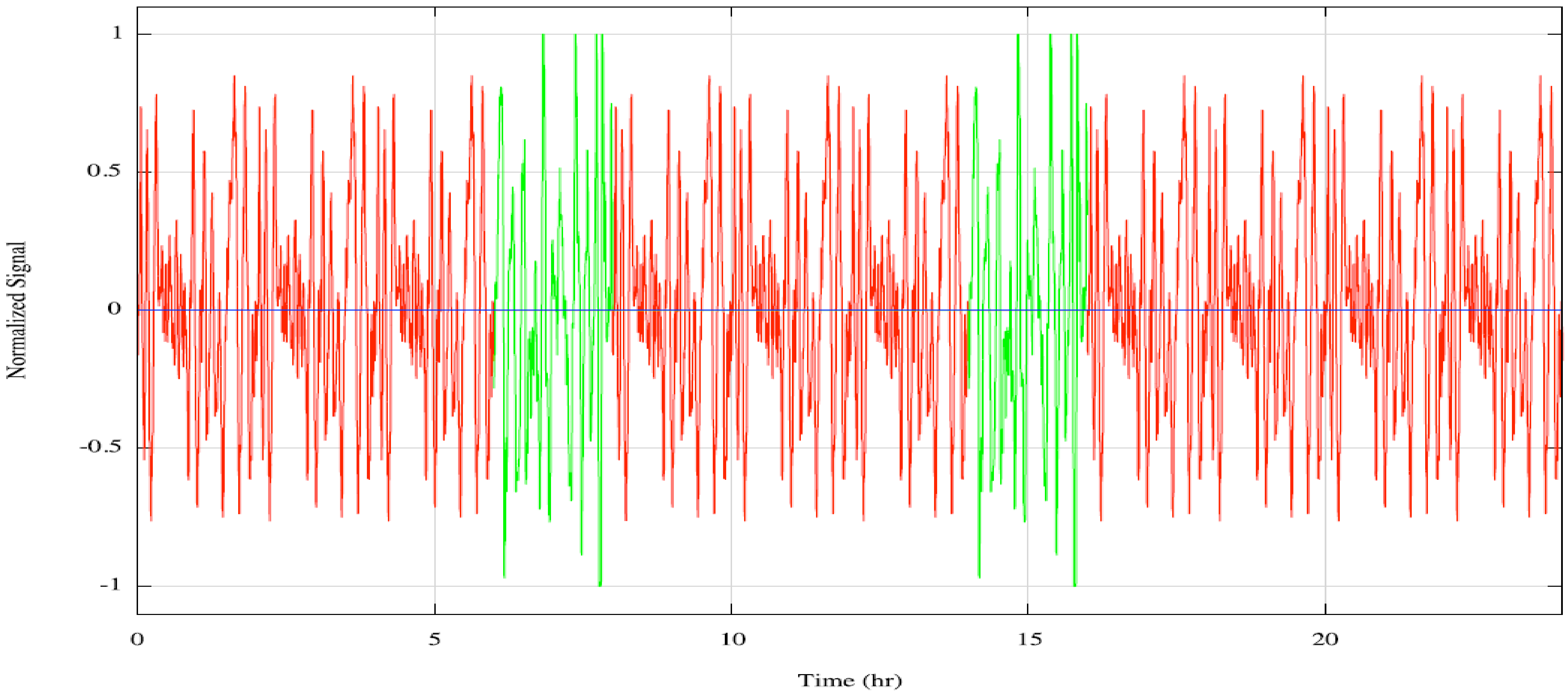


String E (top) and
D (bottom) in GridSaver

Results: Review of the DOE Protocol for Frequency Regulation

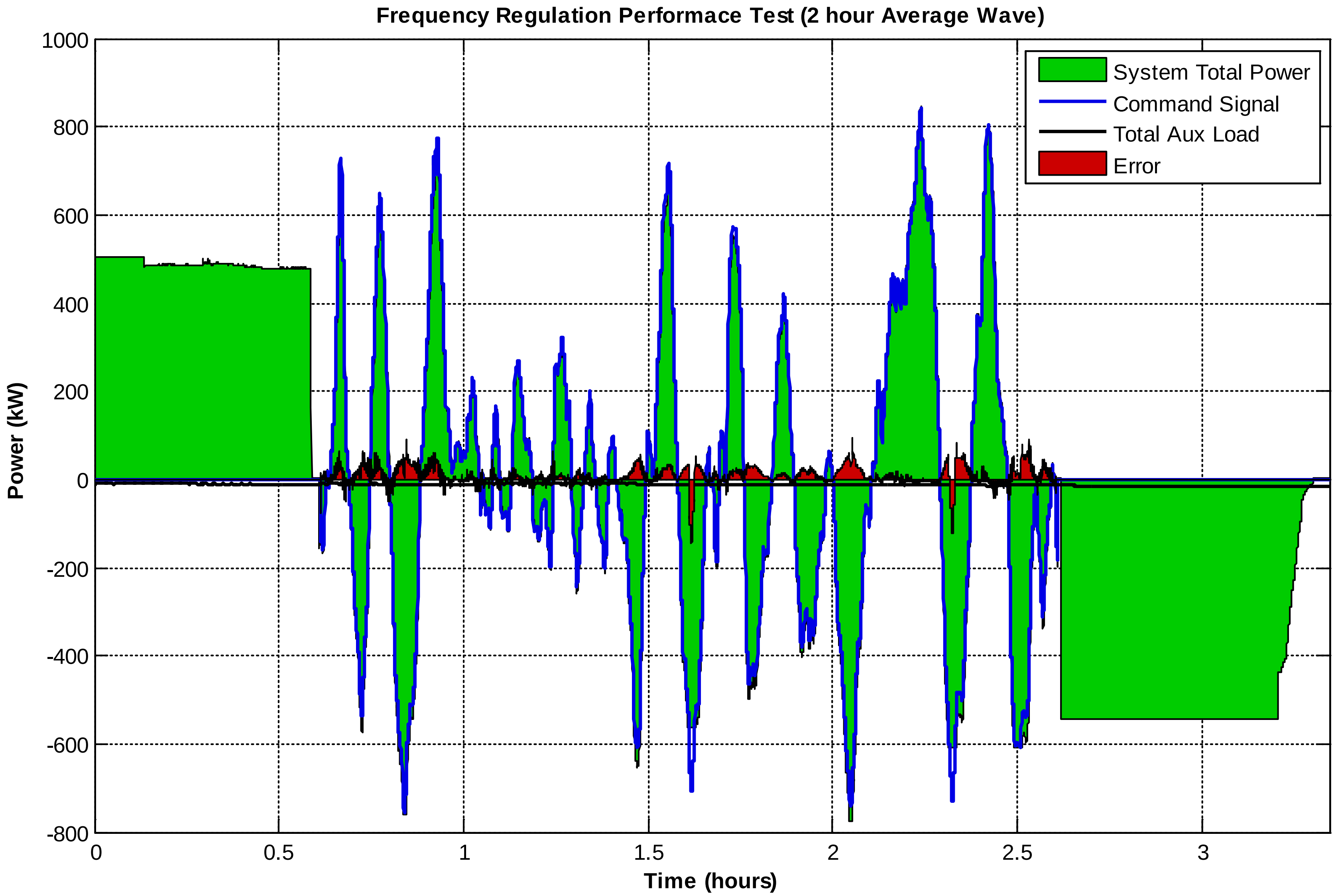
- 24 hour duty-cycle
- 12, two-hour sections
- 10, representative “average”
- 2, representative “aggressive”

Example Frequency Regulation Duty Cycle



Results: Review of the DOE Protocol for Frequency Regulation

- Comment 1: 24 hour profile is very difficult to apply to a prototype system for all the reasons discussed in the best practices for safe operations
- Comment 2: 2 hour profile generates half the data in 1/12 the time and so can be very useful



Results: Review of the DOE Protocol for Frequency Regulation

Metrics

- Sum of squared error

  $\Sigma\,(P_{signal} - P_{ess})^2$

- Sum of absolute error

  $\Sigma\,|P_{signal} - P_{ess}|$

- Sum of energy error

  $\Sigma\,|E_{signal} - E_{ess}|$

- % of time signal is tracked

  % of time of which $(P_{signal} - P_{ess})/P_{signal} < 0.02$

Transpower System

Metric	Performance
*Sum of squared error	3,646,416 kW^2
*Sum of absolute error	103,820 kW
*Sum of energy error	439,614,224 kWh
*% of time signal is tracked	24.5%

* From DOE Protocol

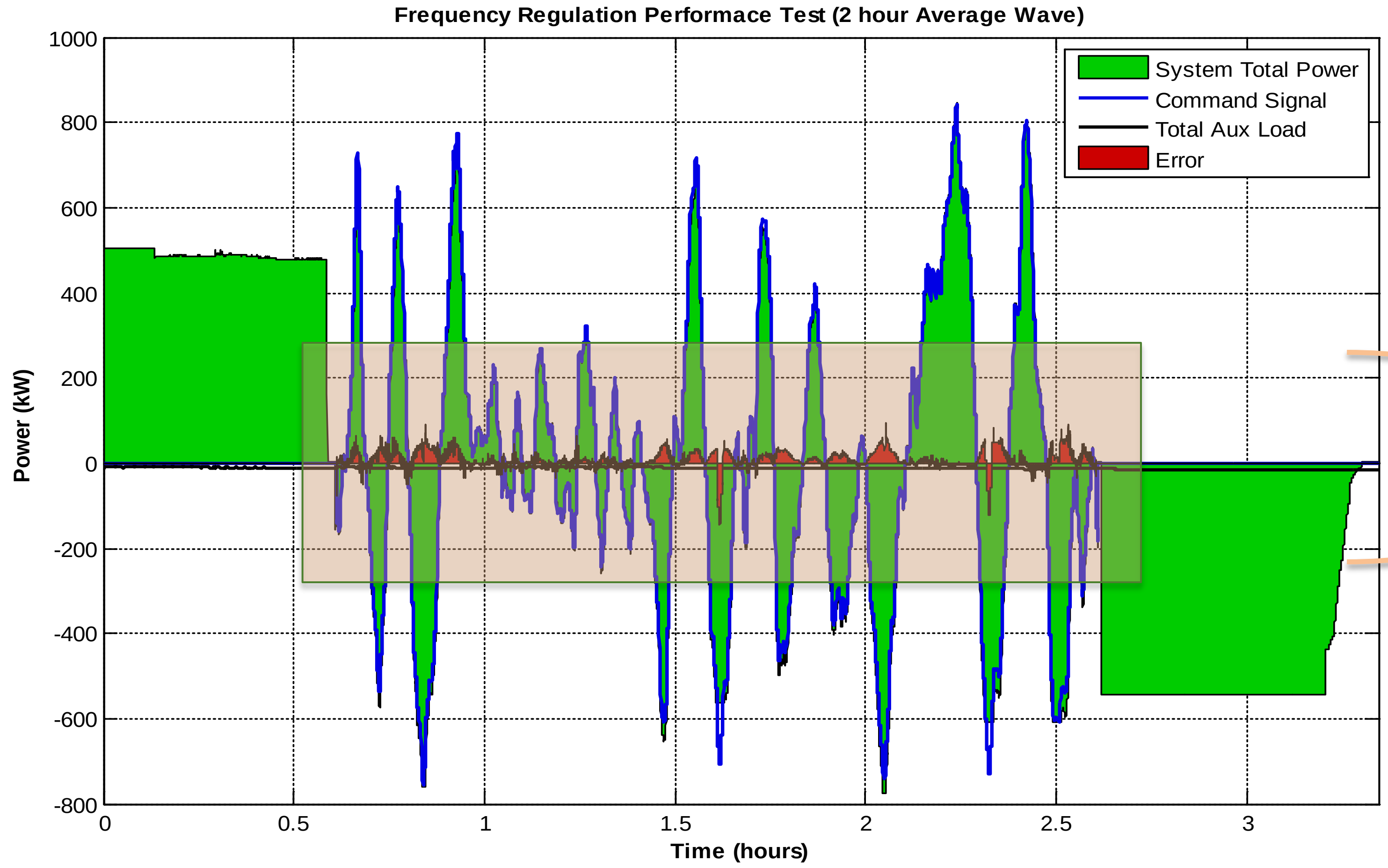
Comment 3: Non-normalized metrics produce meaningless performance values

Results: Review of the DOE Protocol for Frequency Regulation

Comment 4: Even highly accurate systems can have pore tracking accuracy because measurement becomes less accurate (as a %) at low power.

Power	Measurement Accuracy (%)	±kW
1000 kW	0.5 %	5 kW
500 kW	1.0 %	5 kW
250 kW	2.0 %	5 kW
100 kW	5.0 %	5 kW

* From DOE Protocol



Duty Cycle spends most of its time in the region within ±250kW, where measurement is less accurate than the protocol's requirement for tracking

Results: Review of the DOE Protocol for Frequency Regulation

Alternative Metrics

- Tracking Error RMS

  $$\Sigma\,(\mathrm{Psignal}-\mathrm{Pess})^2/\mathrm{N}$$

- Tracking Error RMS %

  $$\Sigma\,(\mathrm{Psignal}-\mathrm{Pess})^2/\mathrm{N}$$

- Alternate % of time signal is tracked

  % of time of which $(\mathrm{Psignal}-\mathrm{Pess})/\mathrm{RatedPower} < 0.02$

Transpower System

Metric	Performance
Tracking Error RMS	22.5 kW
Tracking Error RMS %	2.3 %
Alt. % of time signal is tracked	73.5%

Comment 5: There are better metrics to use when expressing performance.

- Tracking Error RMS and Tracking Error RMS % provide an intuitive measure of accuracy
- Alternate % of time signal is tracked accounts for measurement error at low power

Conclusion

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"There are three principal means of acquiring knowledge… observation of nature, reflection, and experimentation. Observation collects facts; reflection combines them; experimentation verifies the result of that combination." – Denis Diderot

Conclusion

Impacts

- Infrastructure and experience leveraged into publications
- Data collected to form the technical foundations for R&D, Standards, and Outreach
- Improved methods for industry acceptance

FY 16

- Continue to work with industry to collect valuable data, perform analysis, and conduct demonstration experiments which drive industry acceptance.
- Publish revised testing protocols based on lessons learned

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Questions?

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