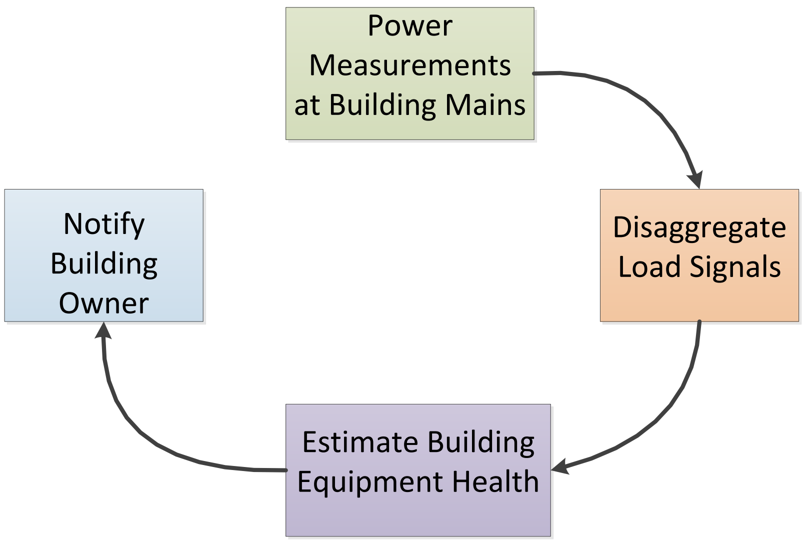
FY14 BEN FOA- ORNL – University – Industry Partnership to Improve Building Efficiency by Equipment Health Monitoring with Virtual Intelligent Sensing

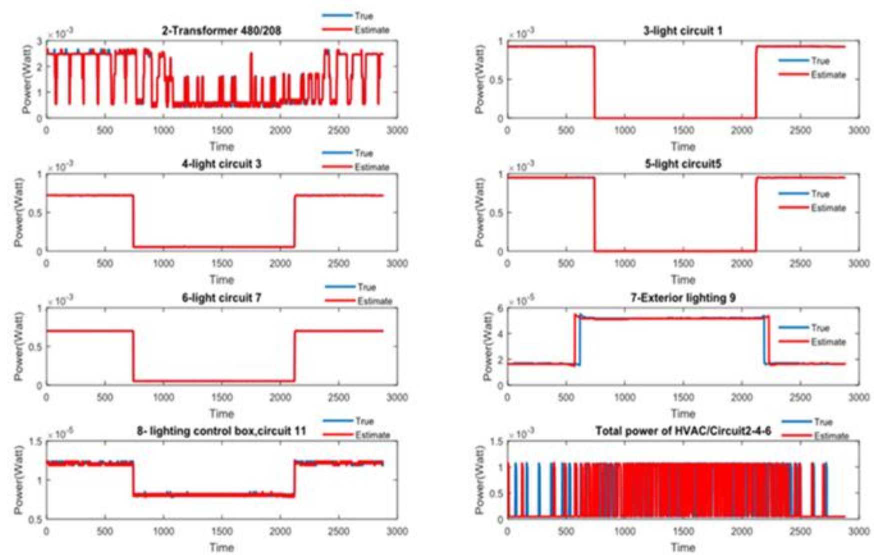
2016 Building Technologies Office Peer Review

Project Concept



Signal Unmixing of Power Measurement Data from ORNL Testing

Energy Consumption of Transformer, Lighting, HVAC



Oak Ridge National Laboratory

The University of Tennessee Knoxville

Richman Surrey
Alert, monitoring, and automation

U.S. Department of Energy | Energy Efficiency & Renewable Energy

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Oak Ridge National Laboratory

Project Summary

Timeline:

Start date: October 2014

Planned end date: September 2016

Key Milestones

1. Instrumentation installed; August 2015
2. Signal unmixing demonstrated; March-Dec. 2015
3. Equipment fault testing; Sept. 2015-March 2016

Budget:

Total Project $ to Date:

- DOE: $730.9k
- Cost Share: $74k

Total Project $:

- DOE: $996k (two years)
- Cost Share: $110.7k

Key Partners:

Richman Surrey	
Dr. Hairong Qi , the University of Tennessee	

Project Outcome:

Collaborate with small business and university partner to develop and deploy low cost nonintrusive building power measurement and fault detection system for commercial deployment.

Target enabling energy efficiency gains of 15~25% (0.4 quad) due to fault detection of building equipment. [S. Katipamula and M. R. Brambley, "Methods for fault detection, diagnostics, and prognostics for building systems—A review, part I," *HVAC&R Research*, 11(1), 3–25, January 2005.]

Note 1: Project supports DOE BTO MYPP S&C ETP strategy 1 (page 94) & goals "Automatic fault detection and diagnostics" page 89 & "virtual sensing" page 95.

Purpose and Objectives

Problem Statement: Building equipment faults are prevalent which negatively impacts building energy efficiency. (Note 1)

Building equipment faults consist of two categories.

1. Category one describes improper operation due to schedules and control.
2. Category two describes equipment degradation.

Category two fault examples:

1. HVAC evaporator flow is 15 to 25% less than optimal, 35% of dampers on commercial rooftop units fail within several years of installation, and 50 to 67% of HVAC units are improperly charged or have airflow issues. [J. Proctor, "Field measurements of new residential air conditioners in Phoenix, Arizona," *ASHRAE Transactions*, 103(1), 406–415, American Society of Heating, Refrigerating and Air-Conditioning Engineers 1997.]
2. Downey and Proctor tested 4,000 residential air-conditioning systems in California and found that only 38% had the correct refrigerant charge. [T. Downey and J. Proctor, "What can 13,000 air conditioners tell us?" *Proceedings of the American Council for an Energy-Efficient Economy (ACEEE) 2002 Summer Study on Energy Efficiency in Buildings*, vol. 1, 53–68, Washington, DC, 2002.]

Purpose and Objectives

Problem Statement: Building equipment faults are prevalent which negatively impacts building energy efficiency. (Note 1)

ORNL has developed a representative list of common building faults.

Category	Faults
Category 1: Operational Faults	Incorrect equipment schedules, improper cycling
Category 2: Impeded airflow in air handler	Dirty filter/evaporator fouling
	Condenser fouling
Category 2: Improper refrigerant charge	Condenser fouling
	Refrigerant overcharge
	Refrigerant undercharge
Category 2: Fan motor degradation	Condenser fan degradation
	Supply fan degradation
Category 2: Fan motor degradation Compressor motor degradation Degradation of heating and/or cooling efficiency	Return fan degradation
	Compressor degradation
	Decrease in SEER
Category 2: Compressor motor degradation	Capacity does not meet unit rating

Purpose and Objectives

Target Market and Audience: This project targets the retrofit of small and medium commercial buildings (<50,000 ft2) which account for 47% of commercial building energy costs and an HVAC energy consumption of 1.411 quads. [Commercial Building Energy Consumption Survey, Table A1, C2A, E1.A, 2003.]

Impact of Project: This project will lead to a commercial-product for retrofit automatic fault detection system for small/medium commercial buildings that can enable improved energy efficiency due by detecting common building faults. (Note 1)

1. The small business partner Richman Surrey (RS) has a market presence in monitoring electrical consumption, power factor, and harmonic distortion for buildings.
2. RS is planning to introduce versions of the system in 2017 with key partners and customers in five different U.S. cities.
3. RS intends to quality this approach for future utility incentive opportunities.

Approach

Approach: Nonintrusive load monitoring offers a low cost and retrofit-compatible installation. Load disaggregation and fault detection algorithms can provide automatic fault detection of building faults through virtual sensing.

1. Design and develop a commercial-ready instrumentation system.
2. Install and deploy the instrumentation system on ORNL assets.
   - Flexible Research Platforms (FRP's) and a research house.
3. Acquire data to develop load disaggregation algorithms with building main power measurements.
4. Perform fault testing of equipment to acquire data to develop fault detection algorithms.
5. Demonstrate algorithms with additional testing.

Approach

Approach: Install and deploy the instrumentation system on ORNL assets.

ORNL FRP's include a 1-story 2,400 ft^2 metal building and 2-story 3,200 ft^2 brick building. Each FRP has a variety of building equipment and is heavily instrumented.

Approach

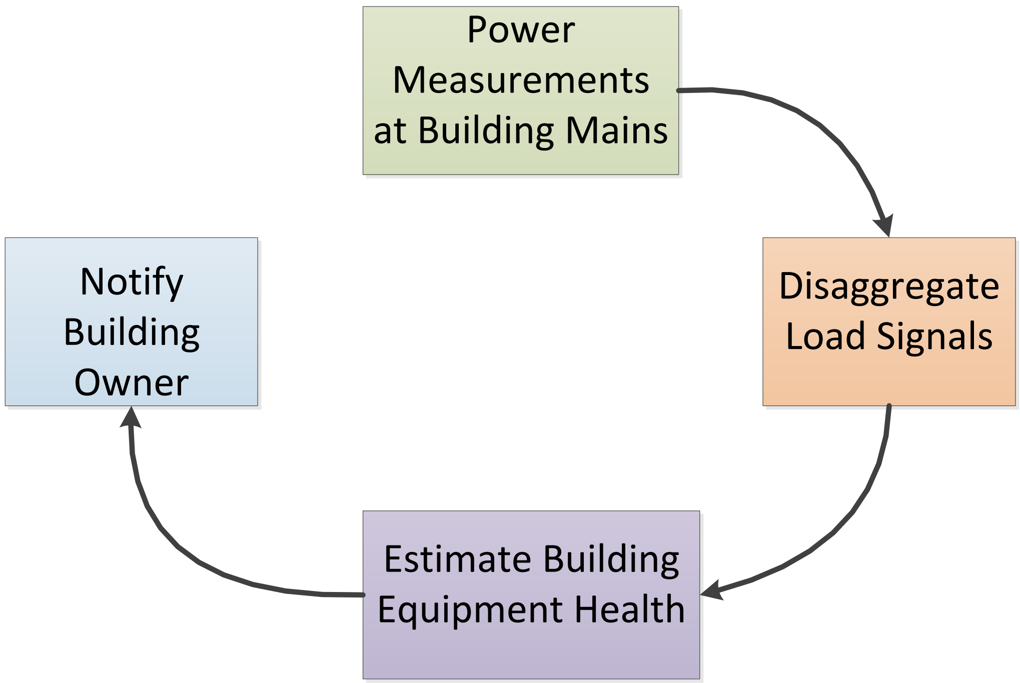
Key Issues: Most fault detection approaches require the installation of sensors on building equipment. These approaches are intrusive which drive up the installation cost to not be economical.

1. Today's commercial market offers expensive handheld instruments for technicians which are not suitable for widespread deployment.
2. Research efforts have identified approaches that require installing intrusive sensors directly on the building equipment which can cost $3k~$5k/HVAC unit.
3. The monitoring of electrical power and current has been applied to heavy industry but has not been commercially applied to building HVAC equipment.

Approach

Distinctive Characteristics: The project is utilizing a load disaggregation technique to enable a single measurement on the building power mains instead of measuring each building load. This reduced the hardware cost significantly (~50~75%) versus other approaches.

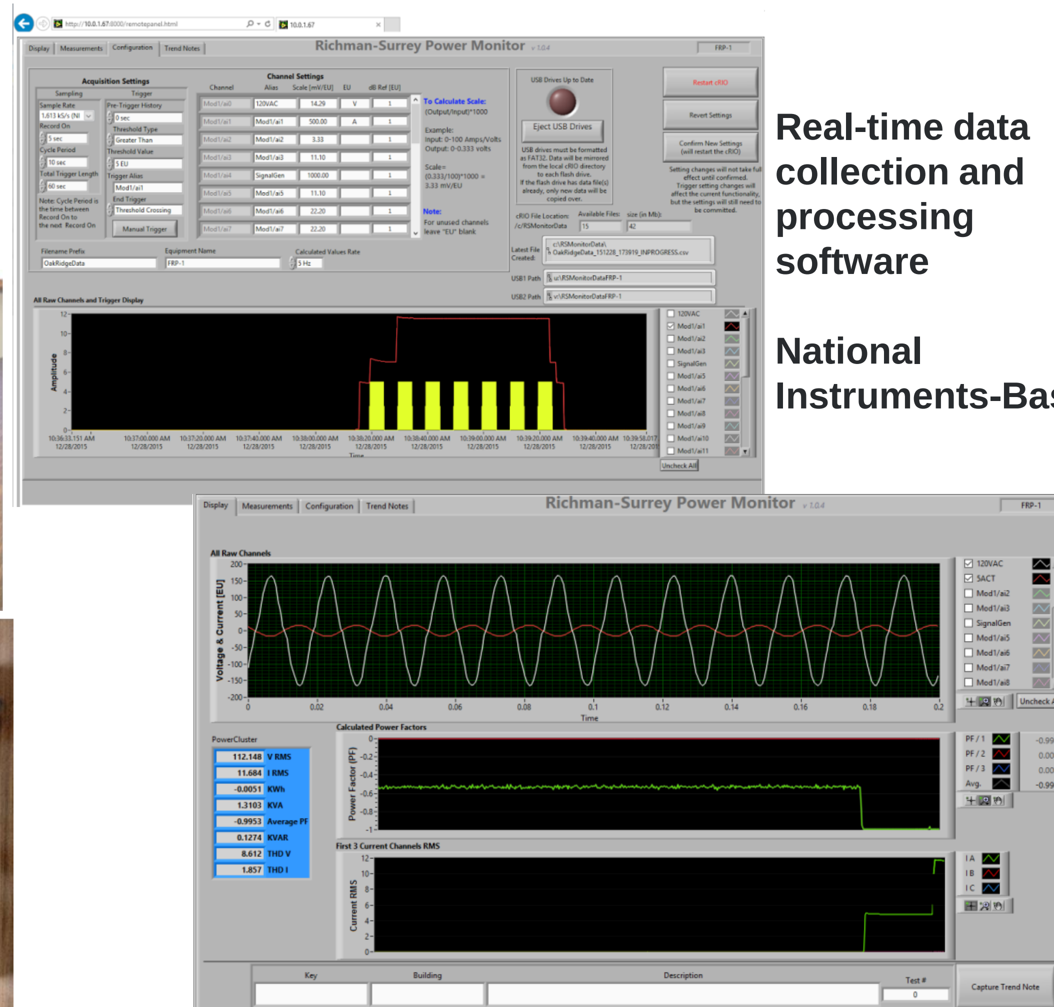
1. Perform building main power measurement.
2. Disaggregate various load signals (lighting, HVAC, other, etc.).
3. Apply fault signatures to the disaggregated building equipment power signals.
4. Estimate the building equipment health.
5. Notify the building owner.



Progress and Accomplishments

Accomplishments: A commercial-ready design instrumentation system has been installed on the ORNL FRP1, FRP2 and a research house. Collected data was used to disaggregate loads successfully and equipment fault testing was conducted.

RS power measurement equipment



Real-time data collection and processing software

National Instruments-Based

Progress and Accomplishments

Accomplishments: A commercial-ready design instrumentation system has been installed on the ORNL FRP1, FRP2 and a research house.

Experiment: Measure building mains for FRP1 which contains lighting, HVAC, air handling equipment, and other loads.

This required multiple disaggregation steps. Step #1 is the disaggregation of the HVAC load from the building load and Step #2 is the disaggregation of the HVAC compressor, condenser fan, blow fan, etc. from the HVAC total load.

1- Disaggregating Bldg_Power(1) to all the devices:

Bldg_Power(1) (Building Total) =

Bldg_Power(2) + Bldg_Power(3) + Bldg_Power(4) + Bldg_Power(5) + Bldg_Power(6) + Bldg_Power(7) + Bldg_Power(8) + HVAC_Power(1) (HVAC total)

Devices: 2-Transformer 480/208, 3-light circuit 1, 4-light circuit 3, 5-light circuit5, 6-light circuit 7,

7-Exterior lighting 9, 8- lighting control box,circuit11.

HVAC_Power1=Total power HVAC/Circuit2-4-6

2- Disaggregating the power signal of HVAC to its component:

HVAC_Power(1) (HVAC total) =

HVAC_Power(2) + HVAC_Power(3) + HVAC_Power(4) + HVAC_Power(5) + HVAC_Power(6)

Parts:

2-Nordyne=C1 compressor/NextAire=outdoor,circuit 2-4-6

3- Nordyne=C1 condenser fan/NextAire=AH1,circuit 10-12

4- Nordyne=C2 compressor/NextAire=AH2,circuit 16-18

5- Nordyne=C2 condenser fan/NextAire=0

6-Nordyne=Indoor blower/NextAire=0

Progress and Accomplishments

Accomplishments: A commercial-ready design instrumentation system has been installed on the ORNL FRP's and a research house.

Signal Unmixing (Load Disaggregation) Algorithm

1. Use Group Constrained Non-negative Matrix Factorization (GCNMF) problem to solve for the optimized disaggregation.

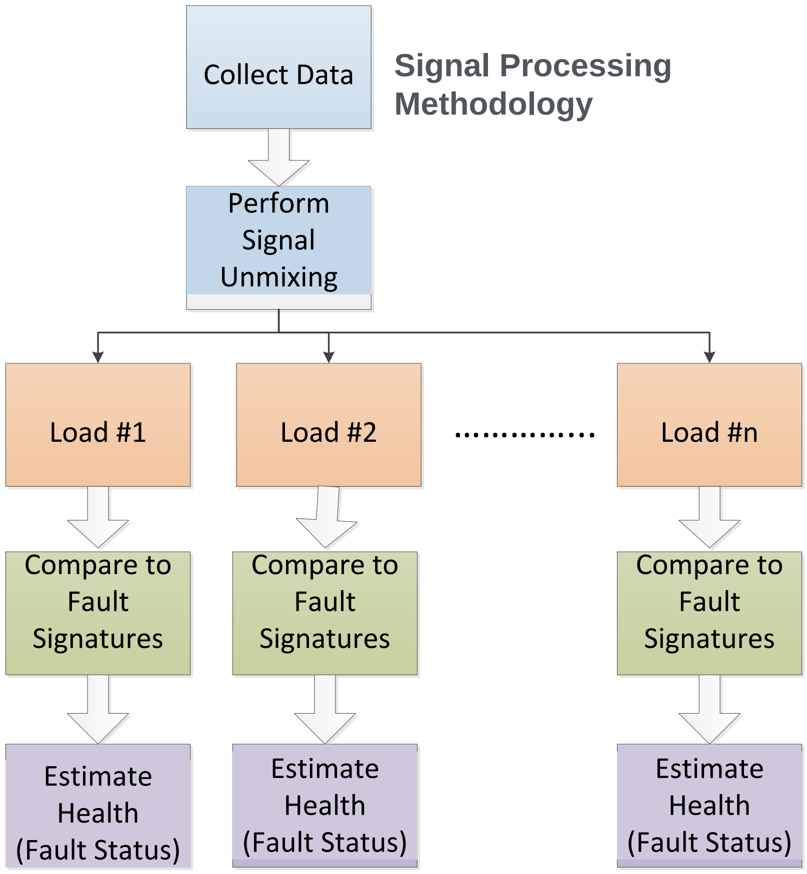
$$\bar{X} = \Psi A$$

$$\hat{A}_{1:k} = \underset{A_{1:k}}{\operatorname{argmin}} \left\| \bar{X} - [\Psi_1, \ldots, \Psi_k] \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_k \end{bmatrix} \right\|_2^2$$

2. Impose constraints for nonnegative energy and a sum-to-one constraint for the activation coefficients.

$$\hat{A} = \underset{A \geq 0}{\operatorname{argmin}} \left\| \begin{bmatrix} \bar{X} \\ \beta U \end{bmatrix} - \begin{bmatrix} \Psi \\ \beta Q \end{bmatrix} A \right\|_2^2$$

3. Use Root Mean Square Error and Disaggregation Error to train and evaluate the performance.



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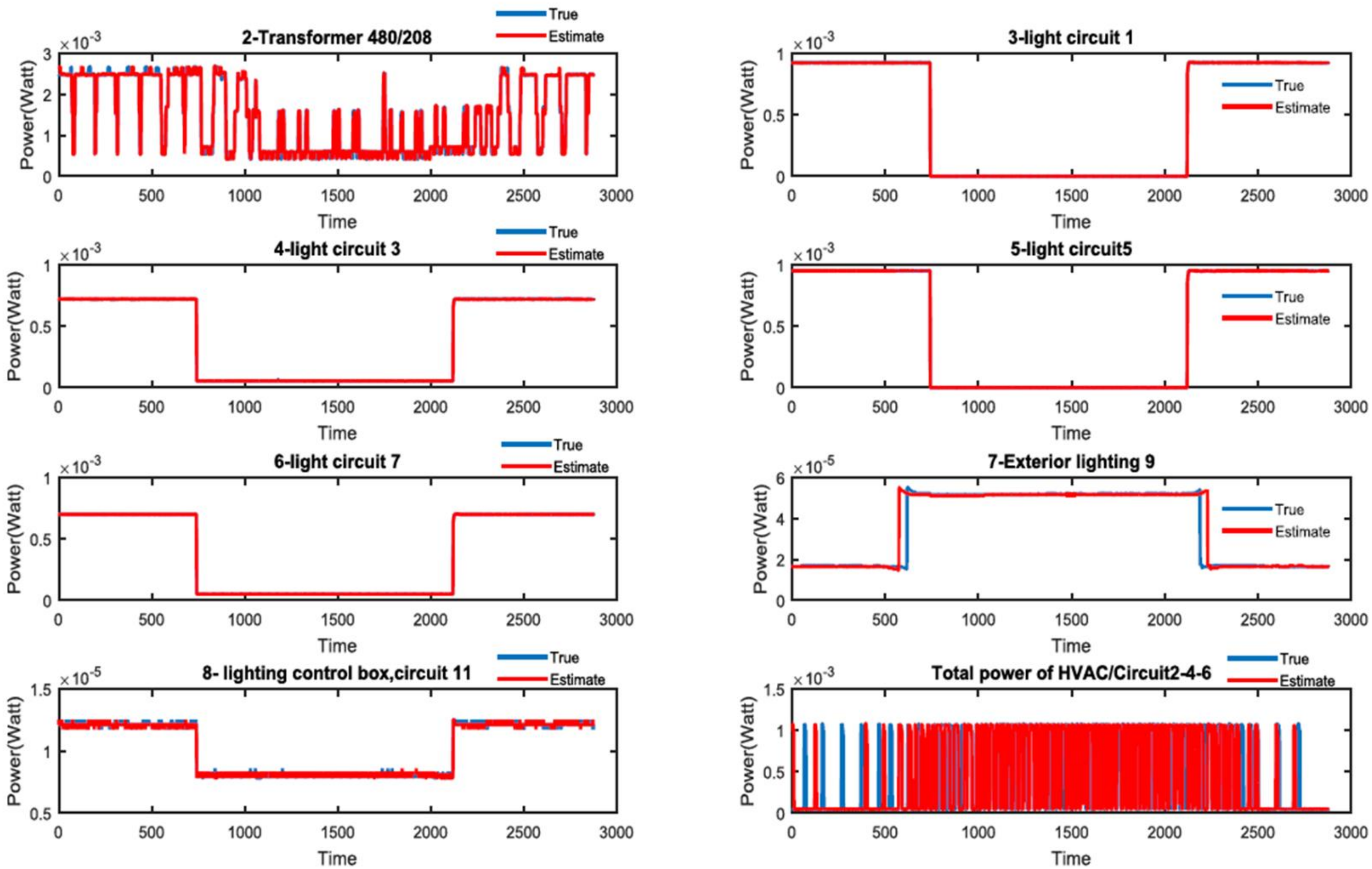
Progress and Accomplishments

Accomplishments: A commercial-ready design instrumentation system has been installed on the ORNL FRP1, FRP2, and a research house.

Signal Unmixing Algorithm Results of Disaggregating Individual Building Loads Over ~50 minutes of testing

- Disaggregated Power Consumption Error ranged from 0.5%~3% for the different loads
- Operation of individual loads was detected with 100% accuracy

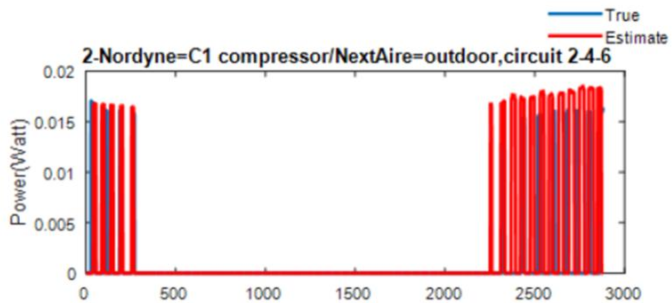


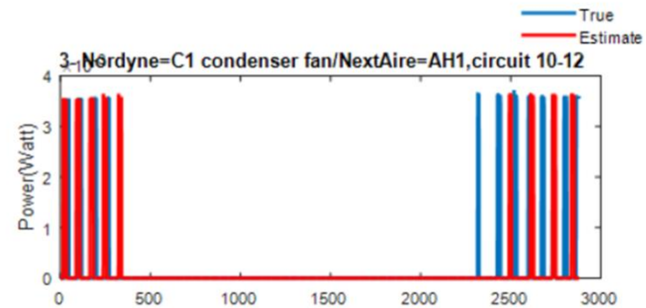
Progress and Accomplishments

Accomplishments: A commercial-ready design instrumentation system has been installed on the ORNL FRP1, FRP2, and a research house.

Signal Unmixing Algorithm Results of Disaggregating HVAC Components
Over ~50 minutes of testing

- Disaggregated Power Consumption of Blower Fan, Condenser Fan, and Compressors.
- Root Mean Square Error (RMSE) for different HVAC components





HVAC Components	Estimation RMSE
C1 compressor	0.0029
C1 condenser fan	0.00017
C2 compressor	0.00049
C2 condenser fan	0
Indoor blower	0

- **Equipment Fault Detection for Category 1 Operational Faults has been demonstrated on FRP1 and FRP2.**
- **Equipment Fault Detection for Category 2 Degradation Faults is in progress.**

Progress and Accomplishments

Market Impact: The detection of operational faults (Category 1) for disaggregated loads has been demonstrated using only the building mains measurements.

The small business partner (Richman Surrey) is planning on the commercial sale of the monitoring system to their customer base.

1. RS is planning to introduce versions of the system in 2017 with key partners and customers in five different U.S. cities.
2. RS intends to quality this approach for future utility incentive opportunities.

Awards/Recognition: UTK/ORNL submitted a paper "Non-Intrusive Load Monitoring of HVAC Components using Signal Unmixing" to 3rd IEEE Global Conference on Signal and Information Processing in Orlando, Florida, December 14-16, 2015, 1st International Symposium on Signal Processing Applications in Smart Buildings.

Lessons Learned: The electronic commercial market requirements for UL electrical safety testing and certification require significant schedule and budget considerations.

Project Integration and Collaboration

Project Integration: ORNL has regular meetings and teleconferences with the industry and university partners. Design reviews of the commercial-ready design instrumentation system were conducted.

Partners, Subcontractors, and Collaborators:
Richman Surrey has a market presence in monitoring electrical consumption, power factor, and harmonic distortion for buildings with energy bills in the range of $5–100K per month, which are ~70% of commercial buildings.

The university partner, Dr. Hairong Qi of the University of Tennessee, contributed signal unmixing algorithms based on source-signature extraction approach.

Communications: 3rd IEEE Global Conference on Signal and Information Processing in Orlando, Florida, December 14-16, 2015, 1st International Symposium on Signal Processing Applications in Smart Buildings.

Next Steps and Future Plans

Next Steps and Future Plans: During FY2016, additional Category 2 fault testing and algorithm development will occur to mature the fault detection algorithms.

1. RS will continue to develop their commercialization plans.
2. ORNL and UTK will pursue additional publication opportunities.
3. Algorithms, test data, and the hardware design will be published as an open-source project.

Potential Future Work: Additional future scope could include:

1. Examine the potential for applying these methods for nonintrusive load measurements (building mains) for buildings with large numbers of loads.
2. Examine the potential for applying these methods for nonintrusive fault detection (building mains) for buildings with large numbers of loads.

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REFERENCE SLIDES

Project Budget

Project Budget: $996k over two years.
Variances: None
Cost to Date: $730.9k

Additional Funding: None

Budget History					
October 2014– FY 2015 (past)		FY 2015 (current)		FY 2016 – Sept 2016 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$996k	$110.7k	$544k	$67k	$996k	$110.7k

Project Plan and Schedule

Project Schedule

Project Start: Oct 2014		Completed Work
Projected End: Sept 2016		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for missed
		Milestone/Deliverable (Actual) use when met on time

	FY2015				FY2016				FY2017			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Q1: Non-Disclosure Agreements, Contracting												
Q2: Functional Requirements												
Q3 Install Instrumentation on FRP's												
Q4: Demonstrate Category 1 Operational Fault Detection												
Q4: Submit Draft Market Strategy and Commercialization Plan												
Q1: Perform Category 2 fault testing on FRP's.												
Current/Future Work												
Q2: Install Instrumentation on Research House												
Q3: Demonstrate Category 1 & 2 fault detection on FRP's.												
Q4: Demonstrate Category 1 & 2 fault detection on research house.												
Q4: Submit updated Market Strategy and Commercialization Plan												