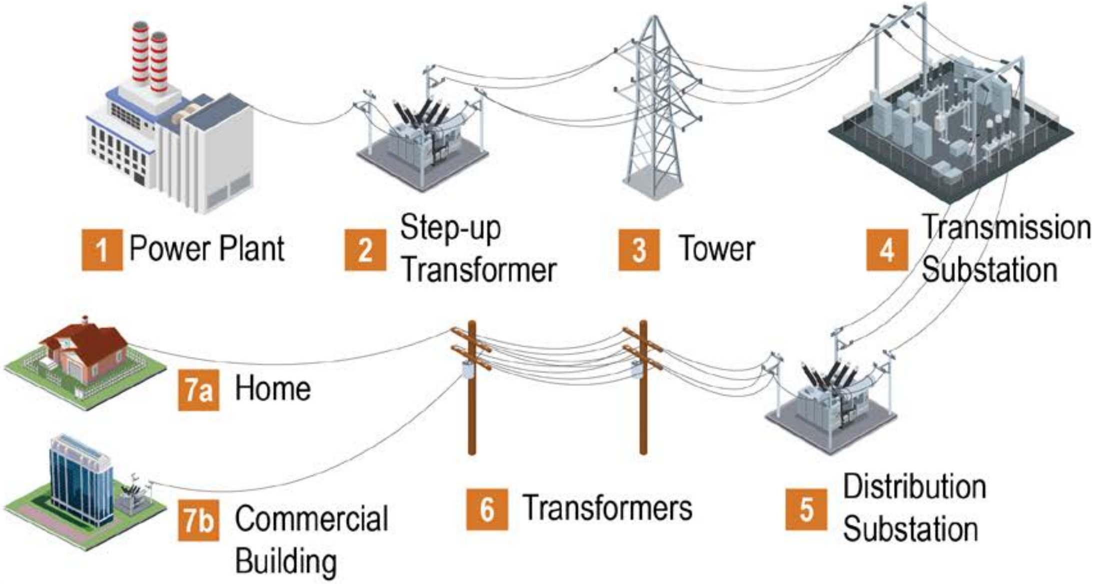
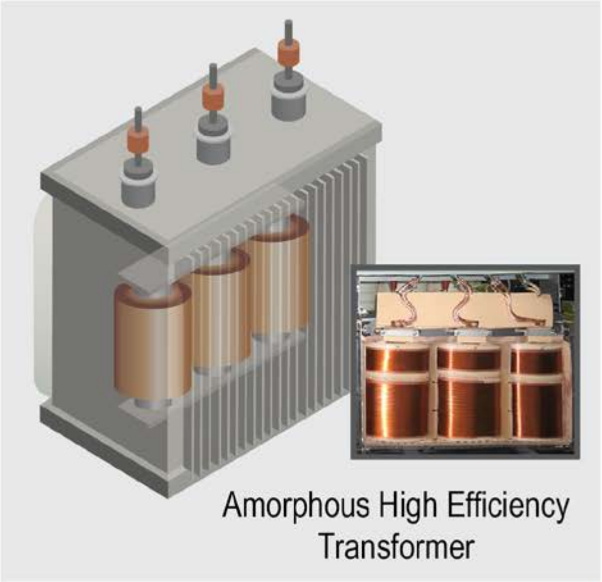
Improving Transformer Efficiency and Lifetime through Product Selection, System Integration and Dynamic Control





DISTRIBUTION TRANSFORMERS ARE THE SUBJECT OF THIS PROJECT

Pacific Northwest National Laboratory
Jianming (Jamie) Lian, Ph.D., Staff Engineer
(509) 372-4504
Jianming.Lian@pnnl.gov

Savannah River National Laboratory
Klaehn Burkes, Senior Engineer
(803) 725-2459
Klaehn.Burkes@srnl.doe.gov

Project Summary

Timeline:

Start date: April, 2016

Planned end date: December, 2018

Key Milestones

1. Transformer control method design complete (4/30/18)
2. Transformer testing and data summary complete (6/15/18)
3. Transformer control method implemented & initial validation complete (7/31/18)
4. Transformer control method validation complete (12/31/18)

Budget:

Total Project $ to Date:

- DOE: $1,200K
- Cost Share: $0

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Key Partners:

Pacific Northwest National Laboratory (PNNL)
Savannah River National Laboratory (SRNL)
Santee Cooper
Clemson University
ERMCO

Project Outcome:

Advance the state-of-the-art technologies of transformers with novel approaches

Provide proven guidance for the U.S. concerning the opportunities to reduce transformer losses and to prolong transformer lifetime

- No-load loss reduction from the adoption of amorphous metal core transformers leads to efficiency improvement
- Lifetime improvement from the adoption of transactive coordination and control for transformers and their loads

Team

- PNNL (lead)
  - Design dynamic control for distribution transformers and associated loads to manage transformer lifetime
  - Develop large-scale distribution system simulations using GridLAB-D™ to assess the cumulative impacts
  - Conduct hardware-in-the-loop experimental studies using VOLTTRON™ platform on full-scale transformers
- SRNL
  - Perform side-by-side testing of distribution transformers with different magnetic core materials
  - Assess the impact of test results to confirm the overall opportunity for energy savings in the U.S.
  - Characterize transformer performance for simulation model calibration in GridLAB-D™
- Santee Cooper
  - Support the development of transformer testing plan
  - Share 25 years of field performance and cost data for transformer testing and cost analysis
- Clemson University
  - Provide lab facilities for full-scale transformer testing
- ERMCO
  - Provide Totally Integrated Grid Energy Router

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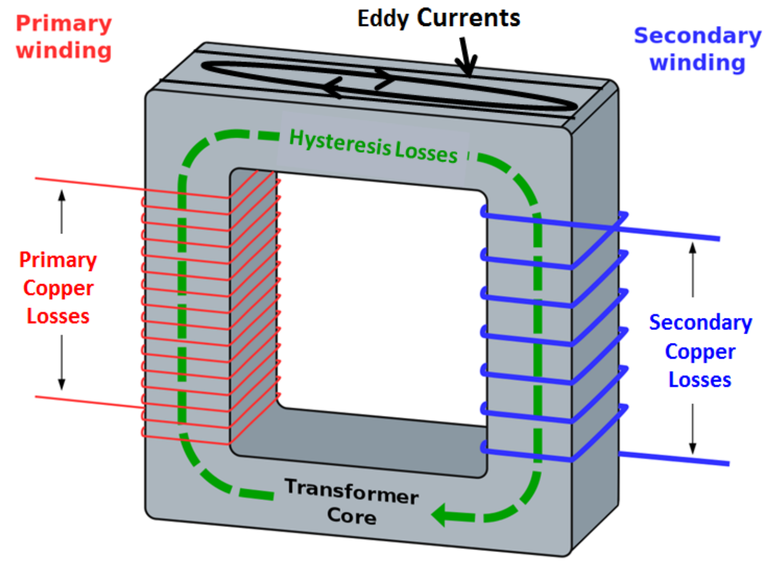
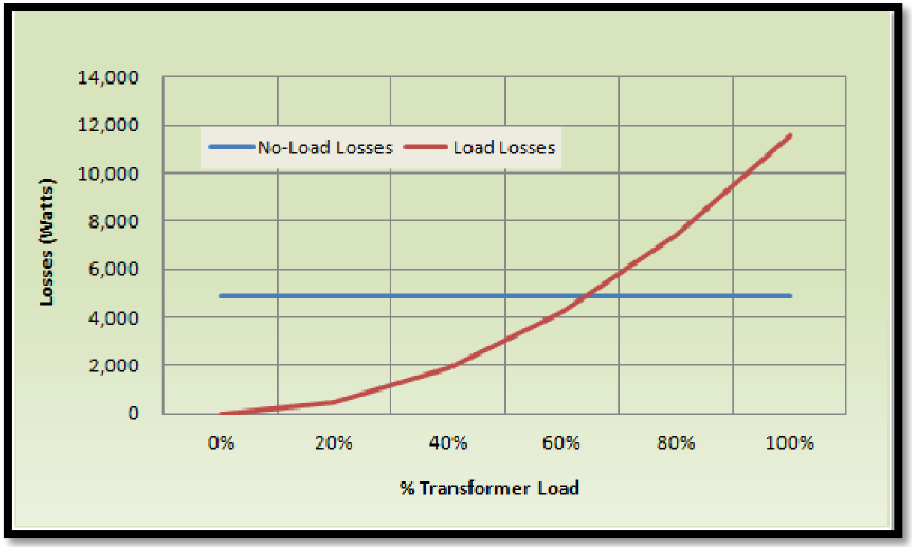
Challenge

- Distribution transformer losses consume 2–3% of U.S. generated electricity, losing $25 billion dollars each year
  - Hysteresis losses
  - Eddy current losses
  - Copper losses
- No-load losses alone from distribution transformers are estimated to account for about 25% of all the energy that is lost in the electric power grid
  - Need new technologies based on high-efficient core materials
- Transformer overloading during peak demand period significantly contributes to transformer loss of life
  - Need new dynamic coordination and control strategies to reduce the variability of transformer loading throughout the day by peak shaving and load shifting



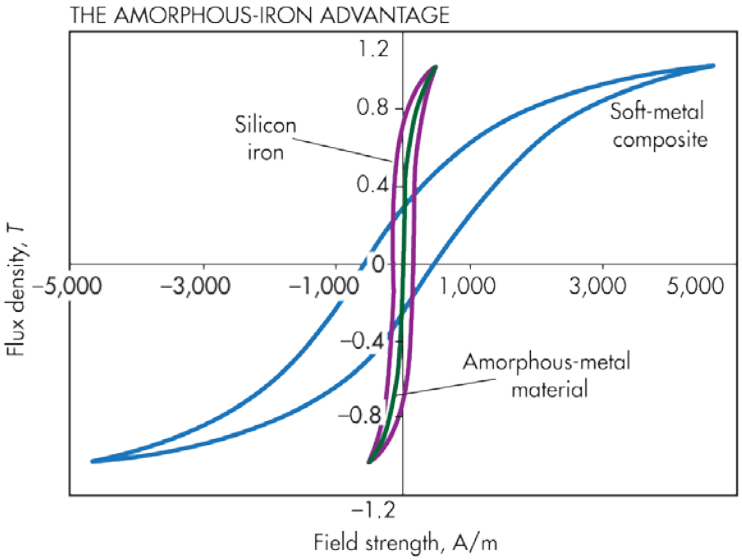


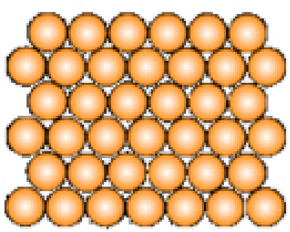
Approach

- Process utility data on distribution transformers purchases based on capacity, phase, and core material (Amorphous vs Silicon Steel)
- Perform distribution transformer testing for performance characterization in order to calibrate simulation model in GridLAB-D™
- Develop dynamic coordination and control strategies for distribution transformers (substation, feeder, building) and associated loads to manage/increase transformer lifetime
- Validate the effectiveness of developed dynamic coordination and control in increasing transformer lifetime
  - Design large-scale distribution system simulations using GridLAB-D™ to assess the cumulative impacts of control deployment
  - Conduct hardware-in-the-loop experimental studies using VOLTTRON™ platform on full-scale transformers by leveraging existing work under transactive building and campus

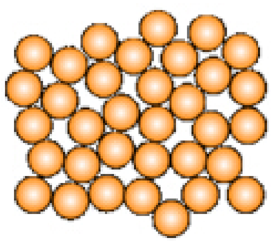
Amorphous vs. Silicon Steel Transformer Cores

- **Amorphous metals don't have crystalline structure so they magnetize with less energy**
  - Creates a very thin hysteresis curve and reduces amount of magnetization losses
- **Amorphous metals saturate at a lower flux density**
  - This requires more material (i.e. larger core sizes) to match the magnetic flux of silicon iron
- **Amorphous Transformer use in America is limited**
  - They have an increased cost versus Silicon Iron because of increase in size and more complex manufacturing processes
- **Amorphous Metal Distribution Transformers (AMDT) have mainly been used in China and India**
  - Higher electricity costs give a better return on investment





Atomic structure of crystals



Atomic structure of amorphous alloys

Approach: Analysis of Utility Data

<u>Processing over 25 years of utility data on transformer purchases based on capacity, phase, and core material – Amorphous vs Silicon Steel.</u>

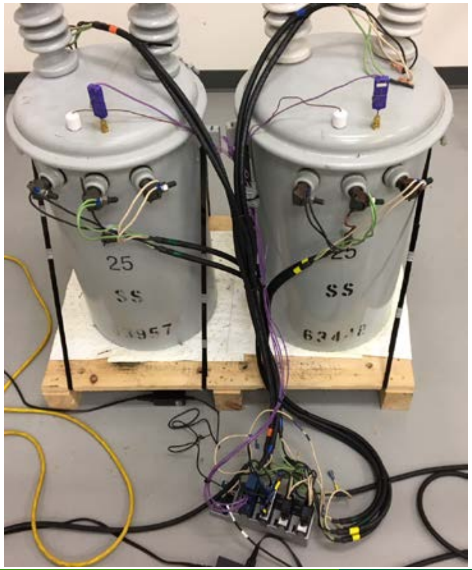
- Polled many utilities partners between SRNL and PNNL and only Santee Cooper had record of purchasing Amorphous Metal Distribution Transformers
- Worked with Santee Cooper to categorize their distribution transformers by size and secondary voltage and determined cost to replace entire fleet of distribution transformers with AMDT
- Utilized information to determine value and energy savings for the nation through advanced core material utilization.

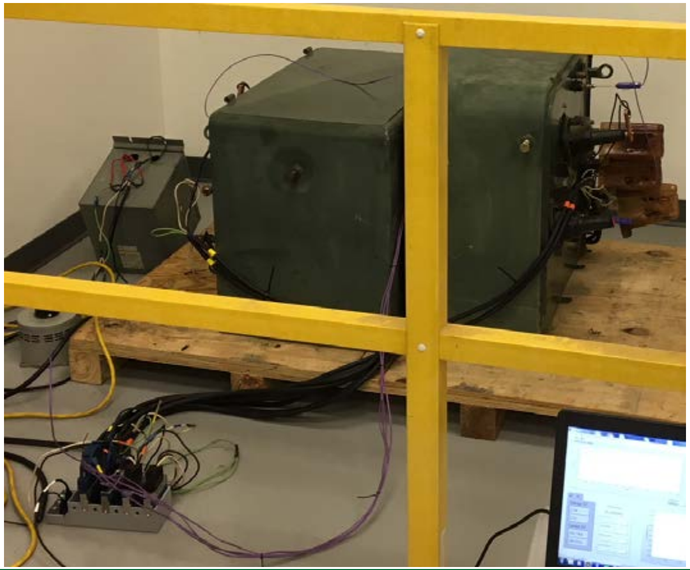
Most Common Distribution Transformer Sizes					
1-Ph Pole		3-Ph Pad 120/208		3-Ph Pad 277/480	
kVA	%	kVA	%	kVA	%
25	43	75	21	500	20
50	23	150	20	300	15
15	17	112.5	19	75	12

Approach: Distribution Transformer Testing

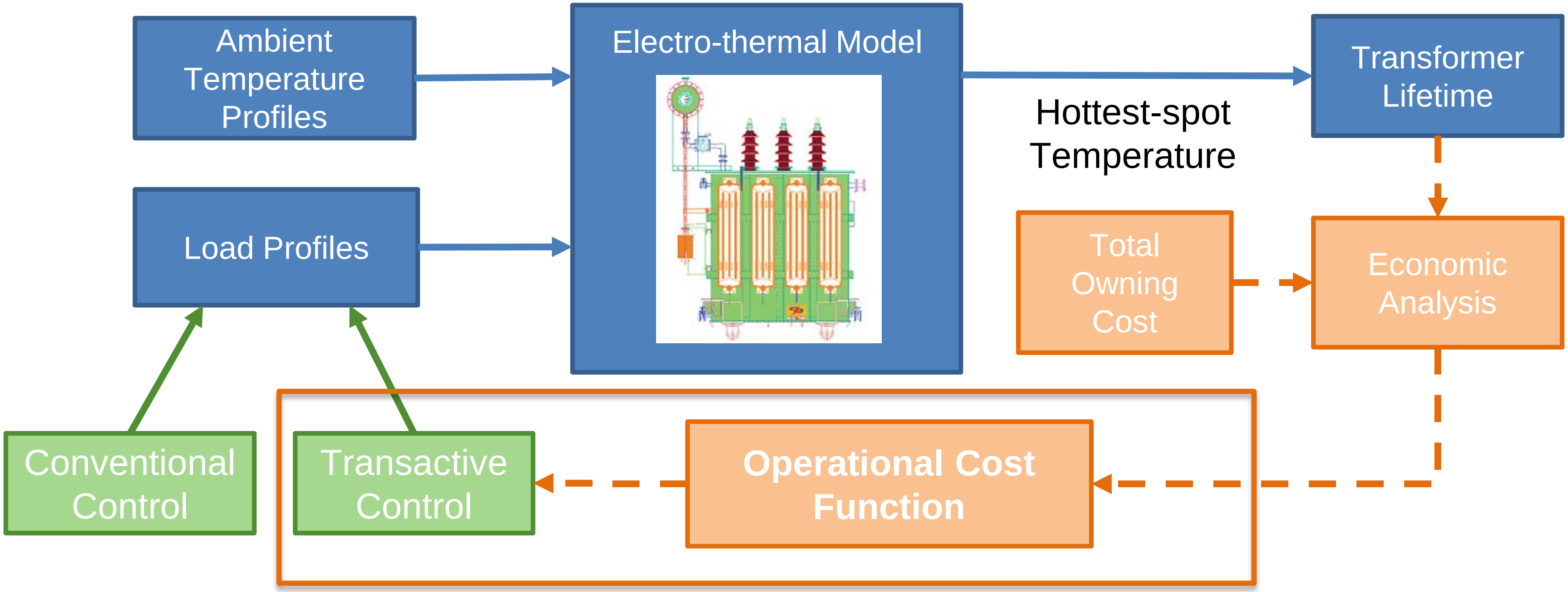
Comparing Distribution Transformers performance based on different core material – Amorphous vs Silicon Steel.

- Transformers were removed from Santee Cooper's distribution system for testing and have been installed over 25 years.
- Testing to DOE Standard: evaluates efficiency at 50% load through open and short circuit tests.
- Evaluate efficiency over power rating at rated voltage.
- Compare Core performance in presence of harmonics, over and under voltage and frequency, and bidirectional operation.





Approach: Lifetime Improvement



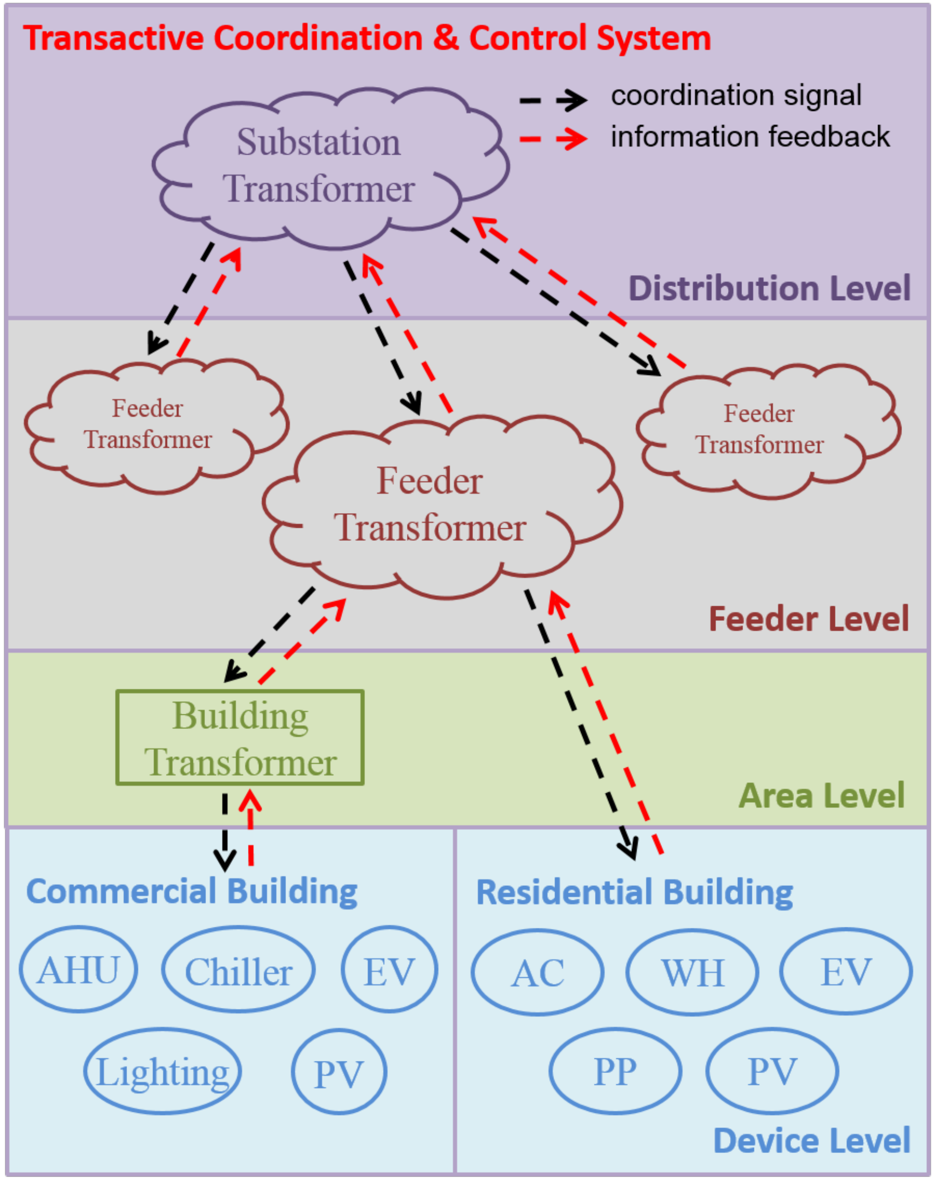
Step one: open-loop assessment

- Consider transformer capacity limit as a pre-defined hard limit
- Compare transactive load control to conventional control in improving the transformer lifetime

Step two: closed-loop co-optimization

- Derive operational cost function for transformer lifetime loss
- Optimize system operational cost with transformer lifetime loss by treating capacity limit as a decision variable

Approach: Transactive Load Control



- Customer – Building loads

$$\begin{aligned} \max_{p} \quad & U_i\left(p_i, \theta_i\right) - \lambda p_i \\ \text{s.t.} \quad & P_{i,\min} \leq p_i \leq P_{i,\max} \end{aligned}$$

- Supplier – Transformer

$$\begin{aligned} \min_{D} \quad & T(D) - \lambda D \\ \text{s.t.} \quad & D_{\min} \leq D \leq D_{\max} \end{aligned}$$

- Coordinator – Load aggregator

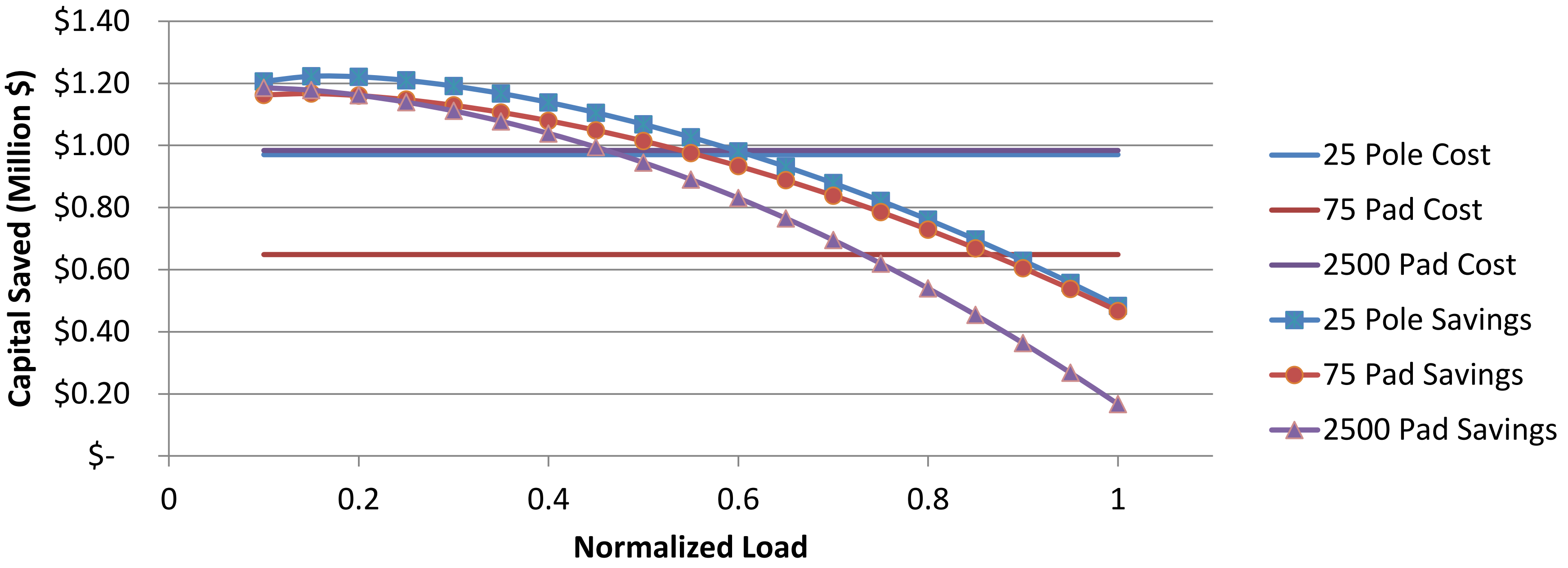
$$\begin{aligned} \max_{p_i, D, V} \quad & \sum_{i=1}^{N} U_i\left(p_i, \theta_i\right) - C\left(\sum_{i=1}^{N} p_i\right) - T(D) \\ \text{s.t.} \quad & \sum_{i=1}^{N} p_i(V) + p_{\mathrm{uc}}(V) \leq D \\ & P_{i,\min} \leq p_i(V) \leq P_{i,\max} \\ & D_{\min} \leq D \leq D_{\max} \\ & V_{\min} \leq V \leq V_{\max} \end{aligned}$$

Impact

- Target market: distribution and building transformers
- Target audience: transformer manufacturers, utilities
- Impacts of project
  – Informs the DOE and utilities of the achievable efficiency improvements and their incremental costs
  – Influences the setting of target efficiency levels for transformers and also utilities' likelihood of adopting new transformer technologies
  – Offers increased reliability and resiliency to not only the transformers, but also the entire distribution systems
  – Contributes to Building Technologies Office and Grid Modernization Initiative goals under "Devices and Integrated System Testing "
    - Task 2.1.5: Develop innovative grid infrastructure technologies that improve electrical grid efficiency and reliability by 10%

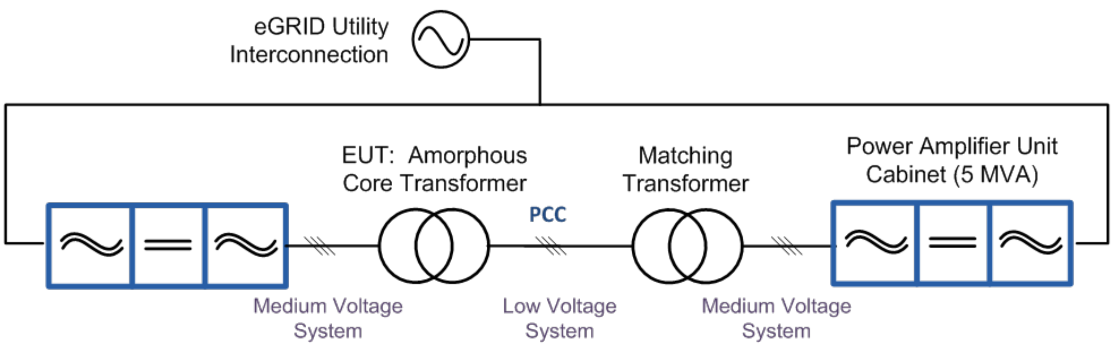
Progress: Analysis of Utility Data

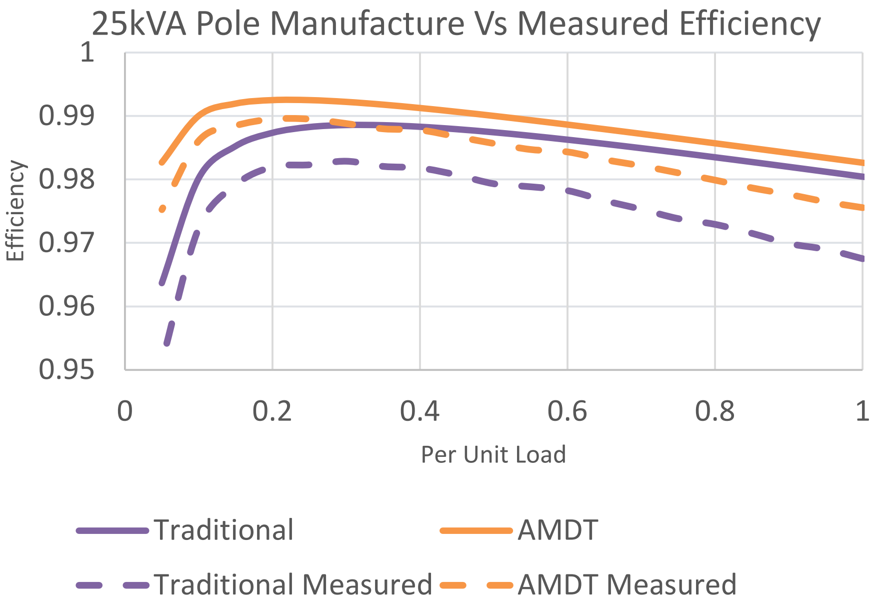
- Analysis is complete and a report has been issued to BTO
- Transformer efficiency is a function of normalized load and isn't constant
  - During transformer age loading profile changes and therefore costs savings for different transformers are different in the load profile
  - Savings are a function of efficiency, population size, and unit costs
  - Comparison of 30-year costs saving for replacing fleets of transformers shows there is a point when replacement cost is less than savings

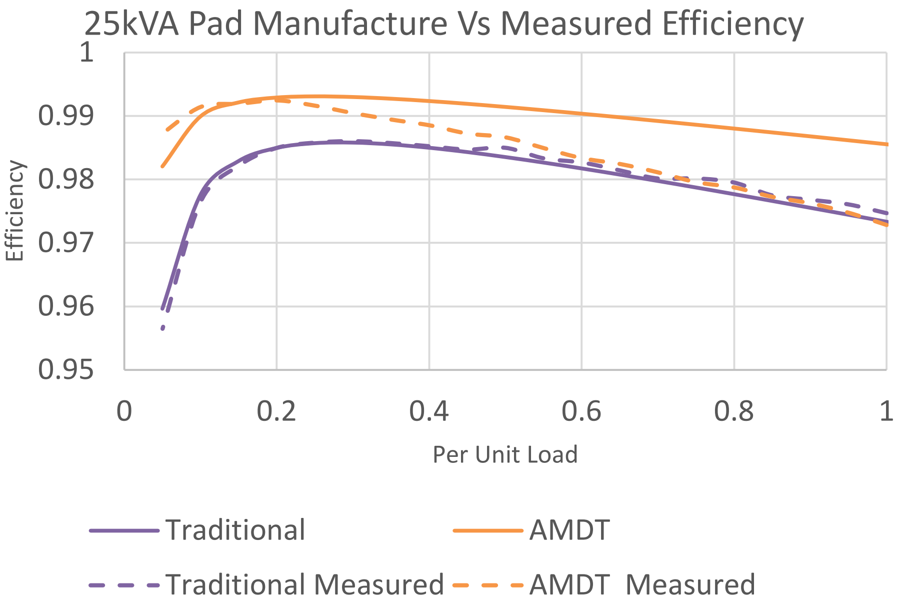


Progress: Distribution Transformer Testing

- Distribution Transformer measured efficiency tracks calculated efficiency from manufacturer-provided data with small reduction due to aging
- Actively testing performance evaluation of distribution transformers



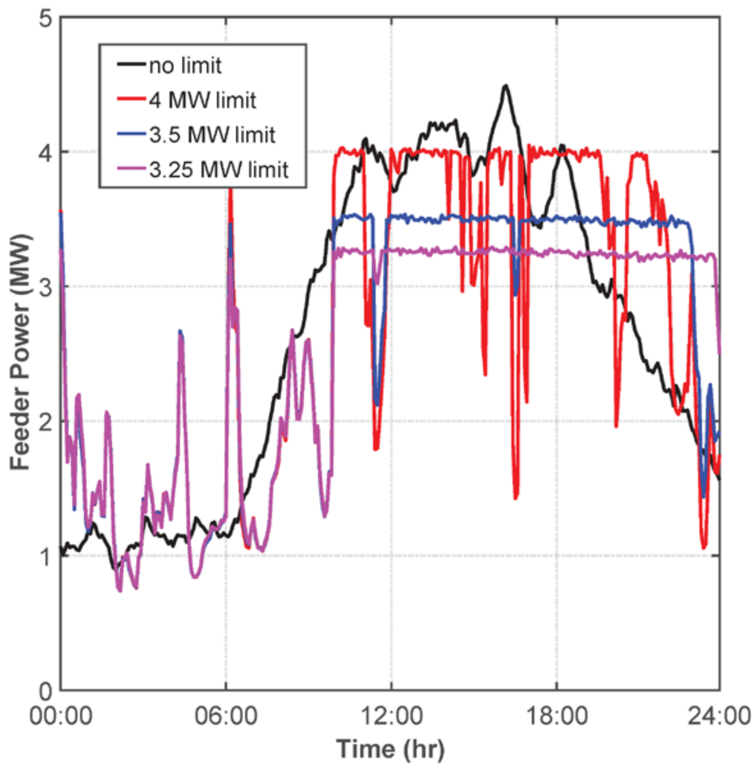




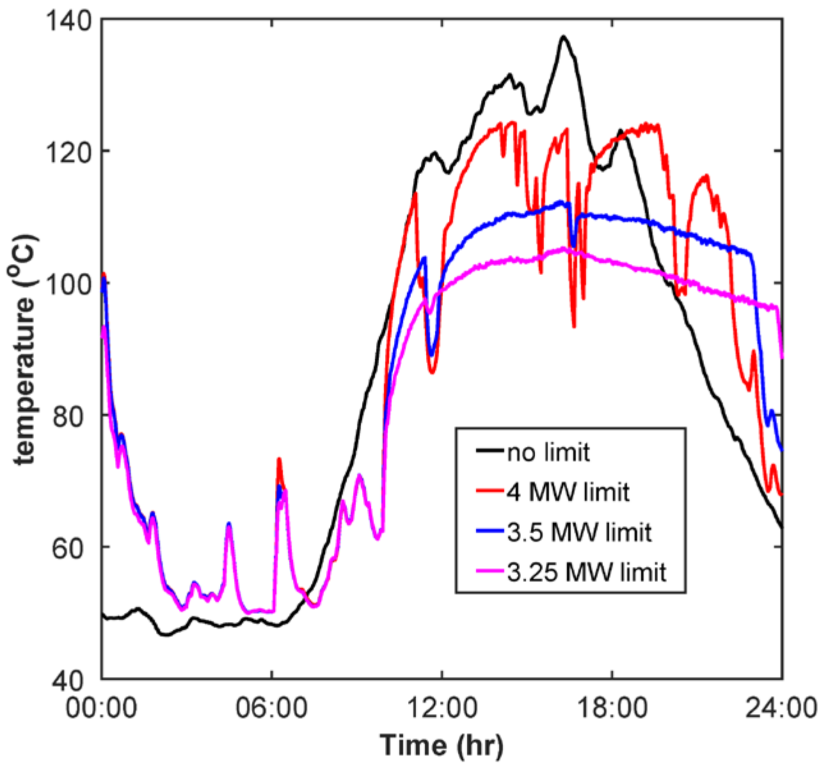
Progress: Open-loop Assessment

- Consider a feeder system with 1000 controllable residential ACs
- Feeder transformer has a nominal capacity of 3.6 MW (no-load loss is 0.3% of rated capacity and load loss is 1% at full load)
- Select three different capacity limits (4.0 MW, 3.5 MW, and 3.25 MW)

Feeder total power

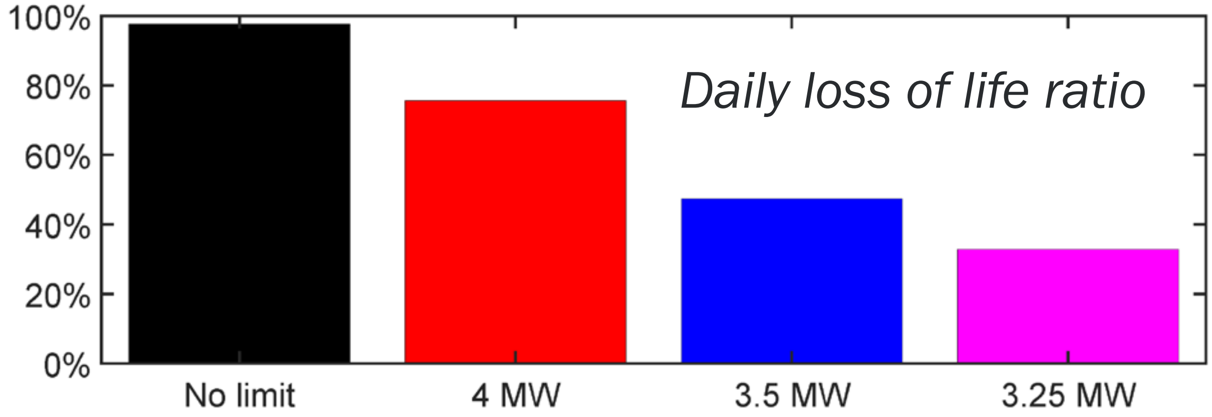


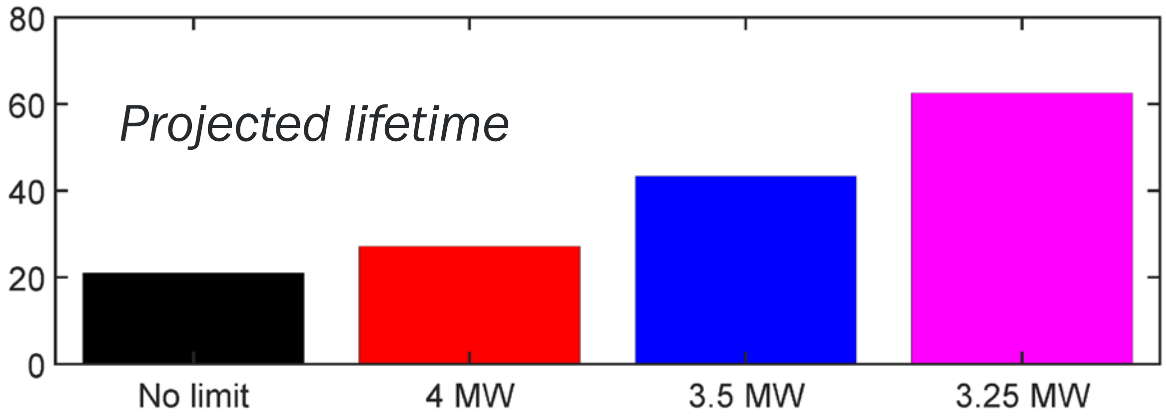
Hottest-spot temperature



Progress: Open-loop Assessment (cont.)

- Transformer lifetime baseline is around 21 years, which is obtained by assuming continuous operation at full load
- Transactive load control increases transformer lifetime by 6.15, 16.24 and 19.13 years, respectively, corresponding to three capacity limits





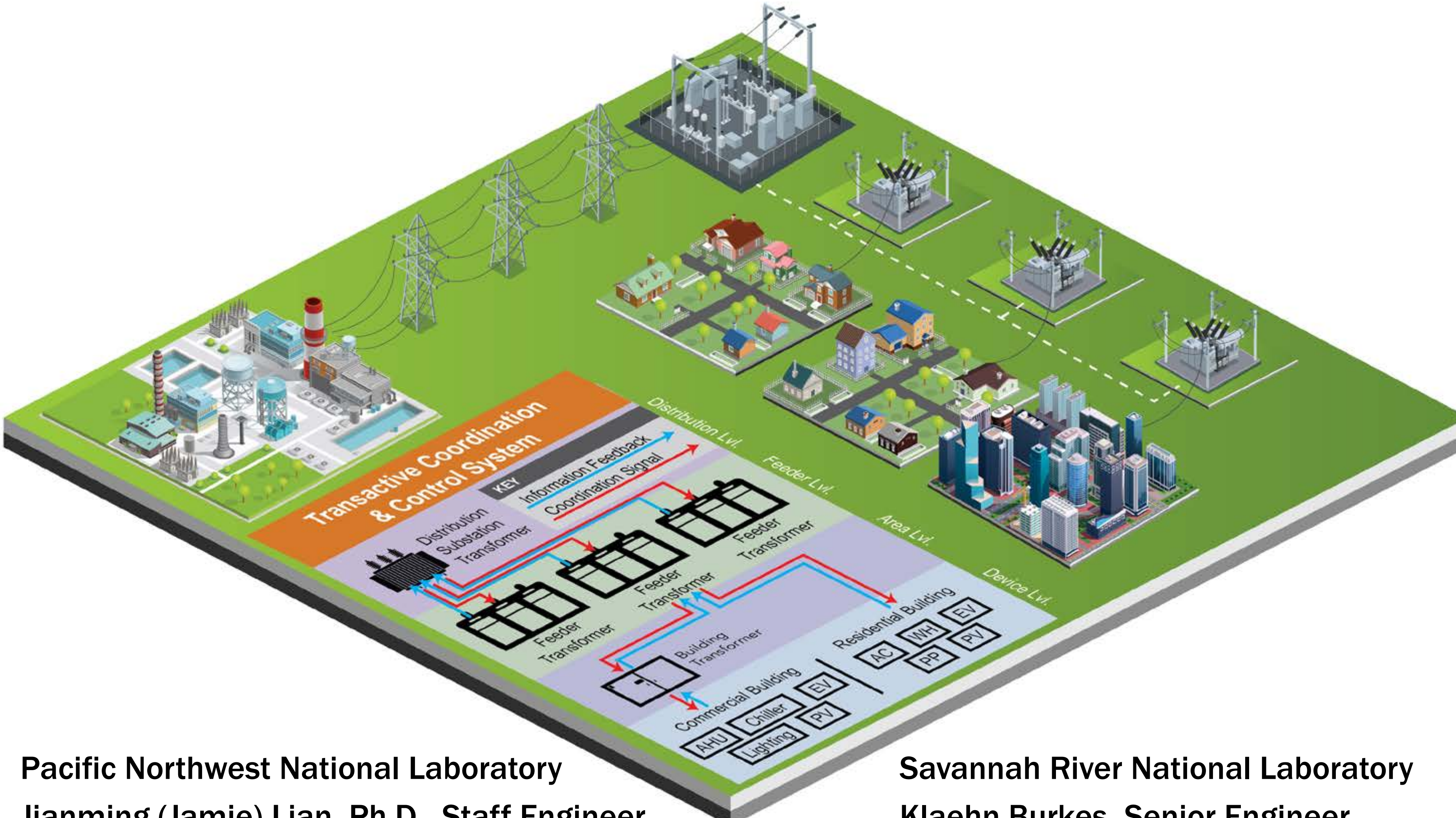
Stakeholder Engagement

- Santee Cooper: Public Power Utility, supplied 25 years of distribution transformer purchase data, supplied 4 distribution transformers at scrap costs, and engaged in the results of performance testing to dictate future purchases
- National Rural Electric Cooperative Association: introduced EMRCO's power electronic augmented transformer, represents 42 percent of America's distribution lines
- ERMCO: Transformer manufacturer, supplying power electronic augmented transformer, Totally Integrated Grid Energy Router, invested in the performance testing of comparison of three types of transformers

Remaining Project Work

- Finish performance testing of distribution transformers under harmonics, over and under voltage and frequency, and bidirectional operation
- Perform performance testing on Totally Integrated Grid Energy Router
- Perform economic analysis to determine the cost function quantifying loss of life of transformers
- Develop transactive control for transformers and associated loads together to systematically manage lifetime
- Calibrate transformer model in GridLAB-D™
- Design large-scale distribution system simulations to assess the cumulative impacts of control deployment
- Conduct hardware-in-the-loop experiments using VOLTTRON™ platform on full-scale building transformer

Thank You



Pacific Northwest National Laboratory
Jianming (Jamie) Lian, Ph.D., Staff Engineer
(509)372-4504
Jianming.Lian@pnnl.gov

Savannah River National Laboratory
Klaehn Burkes, Senior Engineer
(803)725-2459
Klaehn.Burkes@srnl.doe.gov

REFERENCE SLIDES

Project Budget

Project Budget: $1,200K
Variances: No variances
Cost to Date: Cost through March 2018, totals $568K
Additional Funding: None

Budget History					
8/2016– FY 2017 (past)		FY 2018 (current)		FY 2019 – 12/31/2018 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$351K	$0K	$699K	$0K	$150K	$0K

Project Plan and Schedule

- Project started in 3/2016 and is scheduled for completion with field testing and validation in 3/2019
- Schedule and Milestones (see table below)
- All milestones and deliverables are on track

Project Schedule

		Completed Work
Project Start: 8/2016		Active Task (in progress work)
Projected End: 12/2018		Milestone/Deliverable (Originally Planned) use for missed
		Milestone/Deliverable (Actual) use when met on time

	FY2016		FY2017				FY2018				FY2019
Task	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
Past Work											
Confirm utility participation in the project team											
Complete a report on transformer utilization and performance data											
Finalize test plan											
Eight distribution transformers purchased from Santee Cooper											
Distribution transformers installed at *e*GRID Center											
Complete report summartizing to DOE data collected and analysis of											
Current/Future Work											
Transformer testing and data summary complete											
Transformer control method design complete											
Transformer control method implemented & initial validation complete											
Transformer control method validation complete											