GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

GMLC Project Communications Summary

Date: 02/28/2020
Project Title: Advanced Sensor Development
Project Number: 1.4.4
Principal Investigator: Yilu Liu, ORNL, Olga Lavrova, SNL, Co-PI
Person Completing this Document: Anthony R. Florita (NREL), Pooran Joshi (ORNL), Lingwei Zhan (ORNL)

*There are three projects (i.e. End-Use, T&D, and Asset Health) under 1.4.4. This document is only for the End-use project, and the other two projects are being extended.

1. What problem is the project solving or what opportunity is it addressing?

   Model predictive control (MPC) based residential load shaping and modulation can raise the effectiveness of the generation-to-load system by decreasing operating costs and CO_2 emissions and allowing for greater penetration of renewable energy resources. This project focused on the Texas ERCOT and can readily be extended to national geographies. Load shaping is critical for meeting the goal of achieving carbon-free generation and viewed as next-generation demand response. The model/software could be further tuned and verified with hardware-in-the-loop testing.

   Fundamentally revolutionary technologies that are inherently low-cost are required to increase visibility in End-Use systems, such as Buildings. Sensing, measurement, and data processing are needed to make utilities aware of consumption needs and enable them to effectively manage demand while operating within safety and occupant constraints. Heating, ventilation, and air-conditioning (HVAC) systems account for approximately 50% of the building load and have untapped dispatch potential. The proposed approach on Advanced Sensor Development for End-Use applications has two key objectives: (1)

develop low-cost sensors, exploiting additive manufacturing techniques, to monitor the building environment and electrical characteristics of HVAC equipment, and (2) develop algorithms to use building-level data to provide utility-scale visibility of grid reliability and localized weather monitoring.

Using Internet connected devices to track power outages project demonstrated how communications networks can provide grid status information to electric utilities.

2. Who collaborated on this project? (e.g. labs, universities, utilities, vendors, others)
   University of Colorado Boulder, CableLabs, Oak Ridge National Laboratory, National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory. Comcast, ecobee, CableLabs, Electric Power Research Institute of Japan.

3. What is the solution or outcome that the project delivered?

   Building as sensor: Software, and a model architecture, for next-generation load shaping and modulation. The work models from a device level (e.g., hot water tank, home batteries, HVAC, etc.), to the feeder level to jointly optimize the generation-to-load bulk power system.

   Low-cost sensor:
   a) Developed a prototype flexible current sensor hardware using a combination of direct-write printing, 3D additive manufacturing, and laser processing techniques that shows a linear current response at least up to a measured value of 300A.
   b) In the present configuration, the flexible current sensor unit, employing printed Ag metal wire and strain annealed flexible magnetic foil, can be powered

through USB or 4 AAA batteries to allow data collection and sensor calibration in the field.

c) Initial frequency sensitivity measurements seem to indicate good response out to at least 1 MHz, well past the 1000th harmonic, with a potentially better sensitivity than the commercial CT used for ground truth measurements.
d) Field evaluation of prototype flexible current sensor conducted in light commercial building flexible research platforms (FRPs) at ORNL to demonstrate a path towards system integration.

Using Internet connected devices to track power outages project demonstrated two methods for identifying power outages and commercialized one of them. It also demonstrated how Internet-connected thermostats can be used to provide detailed load-shapes for AC and heating.

4. How does the solution/outcome break new ground or how is it differentiated from other R&D projects?

Building as sensor: Right now, due to the project's original scope, all developments were for modeling / simulation of an optimal load shape that informs demand-side devices of the cleanest and lowest cost supply-side generation. The work would have to be extended into emulation / hardware-in-the-loop to make it viable for demonstration purposes.

Low-cost sensor:

a) Flexible low-cost current sensor directly addresses the cost, performance and deploy ability requirements to connect with the opportunity to use building-level data to provide utility-scale visibility of grid reliability.

b) The flexible current sensor capability can be extended to 1000A or beyond using advances in nanomaterials, direct-write printing techniques, and additive manufacturing.

c) The integrated flexible current sensor system opens up the opportunity to incorporate harmonic detection capability, and enable simultaneous detection of ac and dc signals via cointegrated transducers.

The using Internet connected devices to track power outages project is the first time where the communications networks have been applied to inform grid problems on a national basis. It also demonstrated that hyper-local real-time voltage information can be obtained. Finally, it showed how Internet-connected thermostats can be used to provide detailed load-shapes for AC and heating.

5. How is the deliverable or outcome of the project being used?

   A start-up called "GRIDIoT®" has been formed by the graduate student involved in this work, Robert Cruickshank, at the University of Colorado Boulder. The name GRIDIoT stands for optimizing the grid using the Internet of Things. Extension work is being proposed to increase the TRL of the R&D. The optimal load shape could be extended to cover different sized geographic areas to provide a non-wires alternative to transmission and distribution constraints.

   The low-cost sensor work is being shared with utility companies (Southern Company, Exacter, Utility Technology Solutions, etc.).
   News Release: Grid—Wrap-around sensors: Story tips from the Department of Energy's Oak Ridge National Laboratory, April 2019, Weblink: https://www.eurekalert.org/pub_releases/2019-04/drnl-stf040119.php

   Comcast created an outage tracking solution for sale to utilities. CableLabs is developing a real-time voltage tracking service for utilities.

6. Impact metrics – has project impacted grid modernization in any quantifiable way? (E.g. reliability, resiliency, efficiency, DER integration, event response, etc.)

This Building as sensor project was focused on the valuation of advanced demand response in a series of modeling and simulation studies. As such, the scope did not allow demonstrations to assess the impact on grid reliability, resilience, etc. However, metrics were developed to quantify the extent of load shaping and modulation – which is directly related to these concerns. Moving up the TRL level, future projects will assess impact metrics in the field.

For low-cost sensor, the flexible and printed sensor approach has the promise to reduce the sensor system cost by an order of magnitude to realize widespread deployment while enabling sensor placement at locations of interest not accessible with presently available solutions. At the same time, the sensor, wireless communication, signal processing, and energy harvesting and storage components can be integrated on the same platform.

7. What IP and/or industry recognition or adoption has the project resulted in?

Patents:

1. HETEROGENEOUS NETWORK TOPOLOGY MANAGEMENT AND CONTROL United States Patent Application 20190140756.
2. “FLEXIBLE SENSOR TECHNOLOGY,” USPTO Appl. No.: 16/514868, Filed: July 17, 2019.

Open Source Adoption: In progress on multiple DOE projects.

Publications

1. Y. Yu, A. K. Mikkilineni, S. M. Killough, T. Kuruganti, P. C. Joshi and A. Hu, "Direct-Write Printed Current Sensor for Load Monitoring Applications," 2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 2019, pp. 1-6.
2. Cruickshank, R. F., Henze, G. P., Balaji, R., Hodge, B-M. S., & Florita, A. R. (2017, March). Empirical Investigations of the Opportunity Limits of Automatic

Residential Electric Load Shaping. In 2017 Ninth Annual IEEE Green Technologies Conference (GreenTech) (pp. 75-82). IEEE.
3. Cruickshank, R.F., Florita, A.R., Henze, Gregor P., & Corbin, C.D., Characterizing Electric Grid System Benefits of MPC-Based Residential Load Shaping. In 2018 ASHRAE Building Performance Analysis Conference and SimBuild, 26-28 September 2018, Chicago, Illinois
4. Cruickshank, R. F., Asperas, L. F., Grid over the Internet of Things: Jointly Optimizing Electric Power Generation and Use. In Society of Cable Telecomunications Engineers, Journal of Energy Management, Vol 4, No 1, Jan 2019
5. Cruickshank, R. F., Henze, G. P., Rajagopalan, B., Hodge, B. M. S., & Florita, A. R. (2019). Quantifying the Opportunity Limits of Automatic Residential Electric Load Shaping. (Submitted to Energies)
6. Cruickshank, R.F., Florita, A.R., Henze, Gregor P., & Corbin, C.D., Estimating the Value of Jointly Optimized Electric Power Generation and Residential Electrical Use. (To be (re)submitted May 2020)
7. Meier, Alan, Tsuyoshi Ueno, and Marco Pritoni. 2019. “Using Data from Connected Thermostats to Track Large Power Outages in the United States.” Applied Energy (Submitted).
8. Meier, Alan, Tsuyoshi Ueno, Leo Rainer, Marco Pritoni, Abigail Daken, and Dan Baldewicz. 2019. “What Can Connected Thermostats Tell Us about American Heating and Cooling Habits?” In ECEEE 2019 Summer Study. Hyères, France: European Council for an Energy Efficient Economy.
9. Ueno, Tsuyoshi, Marco Pritoni, and Alan Meier. 2018a. “Residential HVAC Usage in the United States Based on Data Collected by Connected Thermostats.” In Proceeding of annual meeting of the Society of Heating, Air Conditioning and Sanitary Engineers of Japan. Sapporo, Japan.
10. Ueno, Tsuyoshi, Marco Pritoni, and Alan Meier. 2019. “Survey of Actual Conditions of Residential HVAC Usage and Proposal of a Generation Method for Parameters of Simulation Input Based on Data Collected by Connected Thermostats in the United States.” SHASE Transactions 265.

11. Ueno, Tsuyoshi, Marco Pritoni, and Alan Meier. 2018. “Residential HVAC Usage in the United States Based on Data Collected by Connected Thermostats.” In Proceeding of annual meeting of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan. Sapporo, Japan.

8. If you look ahead 5-10 years, how do you see the work of this project impacting grid planning and operations in the U.S.?

   The idea we’ve proposed is not 100% novel, in that it’s never been done before, but more along the lines of a “valuation of technology.” We envision that multiple uses are possible for optimal load shaping (OLS). OLS reverses the 132-year-old electricity supply-follows-demand relationship to enable a new demand-follows-supply model. OLS technology slashes billions of dollars in the annual operations and maintenance costs of generating electricity. OLS is an easy to implement technology platform that uses the Internet of Things to orchestrate distributed storage to accommodate the variable and uncertain production of wind and solar power while maximizing the efficiency of traditional fossil-fueled power plants. OLS is a broadcast signal, is the simplest method for optimizing the end-to-end generation-to-load system and can be readily introduced as a world standard.

   Low-cost, flexible sensors are required to realize large scale deployment at locations of interest to connect with the cost and energy saving opportunities that exist in the buildings and grid sectors. Advances in nanomaterials, direct-write printing techniques, and additive manufacturing have the potential to realize low-cost, multifunctional sensor systems for a broad range of energy and technology sectors. As pursued in this project, the confluence of emerging flexible hybrid electronics and IoT solutions directly addresses the cost, performance, integration, and deployment requirements to overcome the limitations of current technology and to ensure technology adoption.

The power outage tracking techniques developed could rapidly provide a cyber-secure means of providing grid status information at a hyper-local level but only if utilities overcome their institutional resistance to collaborating with communications companies.