CHANGING WHAT'S POSSIBLE

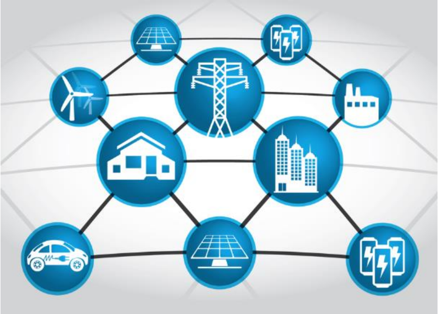
# A Novel Hierarchical Frequency-Based Load Control Architecture


Adilson E. Motter

*Northwestern University* (lead)


**Network Optimized Distributed Energy Systems (NODES)**
**Annual Review Meeting**

March 26-28, 2018



# Project Summary

- **Overall goal of the project**: To develop and validate a new, hierarchically coordinated, frequency-based load control architecture that provides a reliable complement to generator inertia and governor response so as to enable a high penetration of renewable generation.

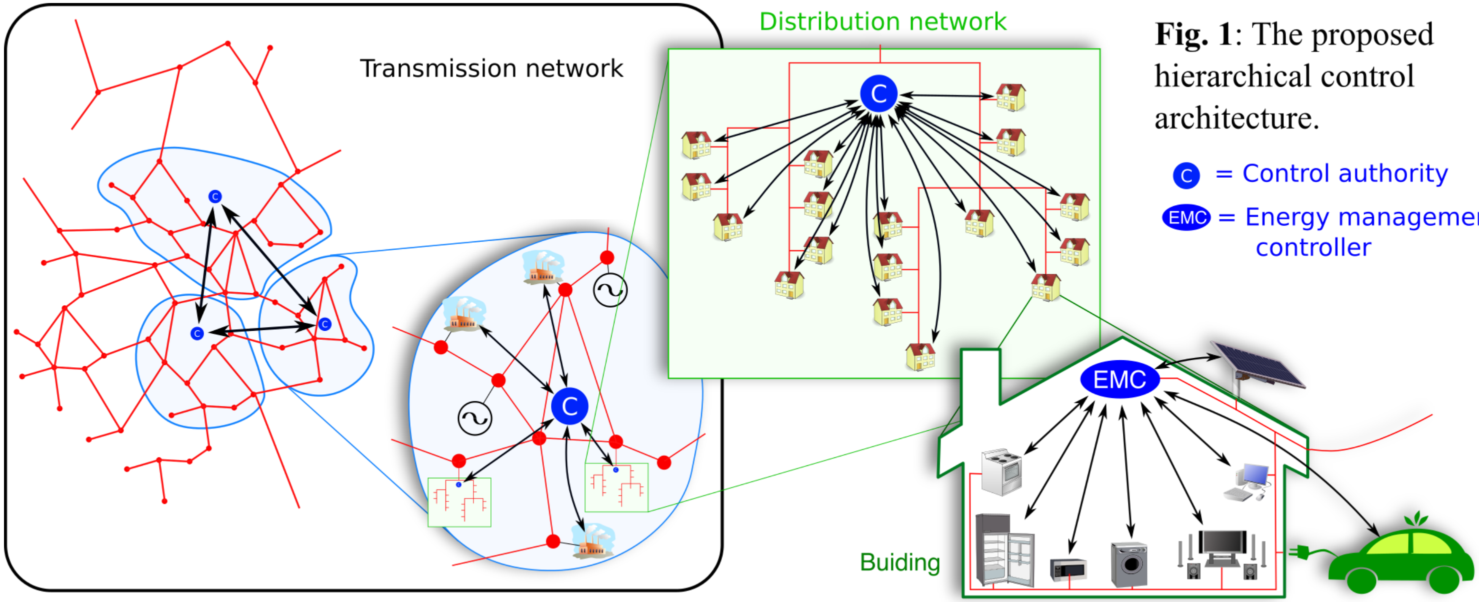



**Fig. 1**: The proposed hierarchical control architecture.

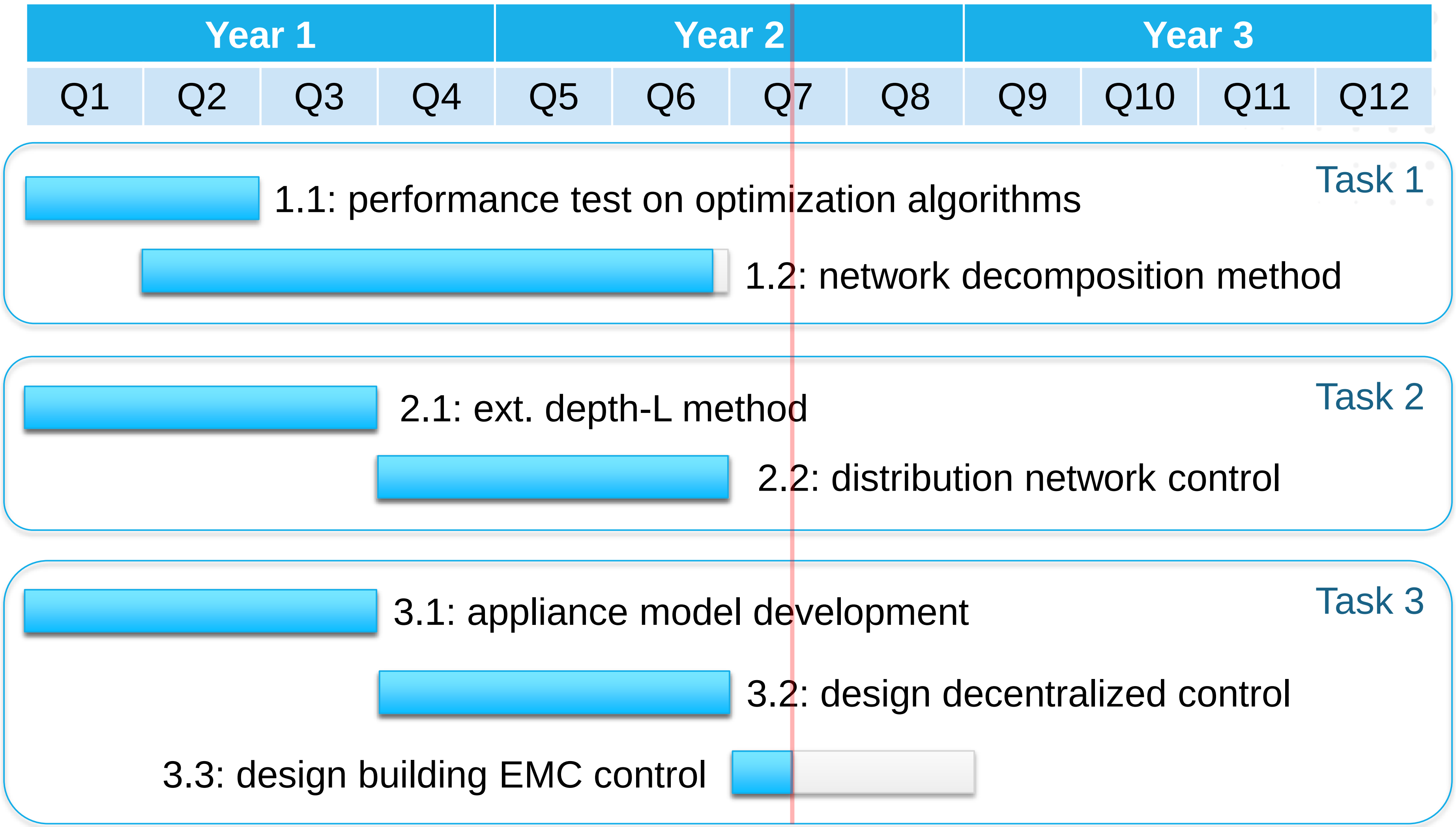
# Project Summary

- **Challenge**: To control a large amount of appliances distributed in the whole system in a coordinated manner while simultaneously achieving the objectives of guaranteeing system stability, ensuring fast frequency regulation, and maintaining customers' QoS.
- **Deliverables**:
  1. Scalable algorithms for frequency-load control.
  2. Validation of the algorithms using real power-grid network models and datasets via large-scale real-time simulations and HiL testing.
- **Expected outcome**: Demonstration that the developed control architecture can provide additional synthetic frequency response reserve to the existing grids, which would enable higher penetration of renewable generation.

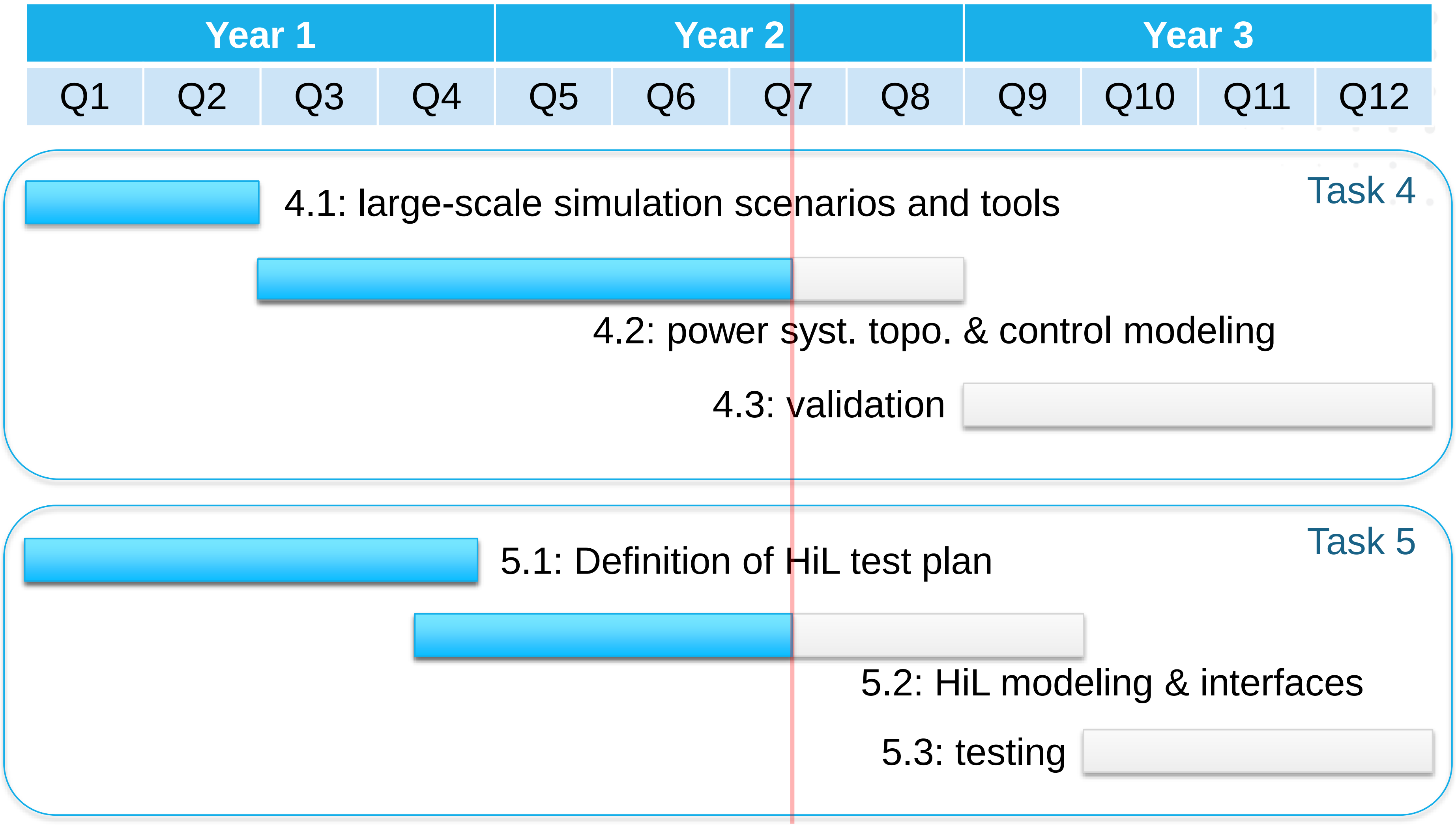
# Team

- **Partners**
  - **Northwestern University** (NU): Leader in research on complex network control and frequency-synchronization phenomena.
  - **Argonne National Laboratory** (ANL) has extensive expertise/experience in modeling, analysis, and control of power systems.
  - **OPAL-RT** is a leader in providing real-time simulation/HiL environment.
  - **Schneider Electric** (SE) has experience/expertise in hardware/software development, providing microgrid solutions, and commercialization.
  - **CPS Energy** is a utility serving San Antonio area.
- NU will design control algorithms with help from ANL on power system modeling.
- OPAL will help perform real-time simulations and HiL validation.
- CPS will provide distribution network data.
- SE will conduct a commercialization review.

# Project Progress

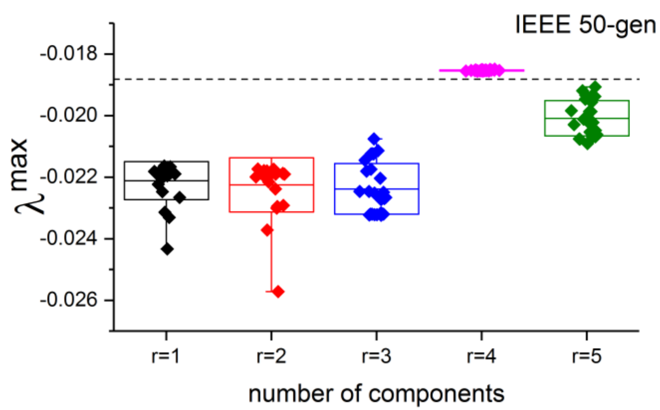


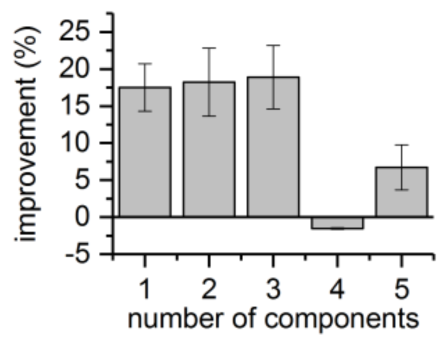
# Project Progress

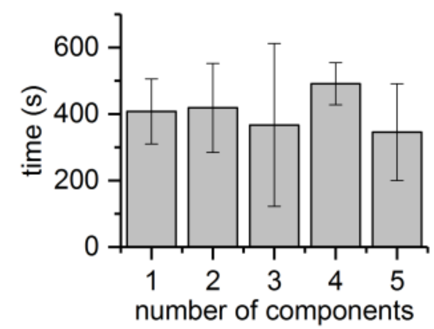


# Development of control methods

- **Task 1: Load assignment algorithms for transmission system stability using network decomposition**
  - Divide the network into components, compute optimal load assignment for each component, and combine.
  - Task 1.2: Development of network decomposition method
  - Milestone M1.2.1 (completed)**:** Deliver report on performance of the network decomposition method and the definition of Texas grid demo.




CHANGING WHAT'S POSSIBLE

# Development of control methods

- **Task 1: Load assignment algorithms for transmission system stability**

Image removed due to compliance with NDA

**Selected portion of ERCOT system for the demo**

Reformulation of $\lambda_{max}$ optimization into an easier-to-solve OPF problem

+

Highly optimized commercial optimization software (Knitro)

↓

Optimization of the ERCOT demo completes in 5–10 min and yields 10–15% improvement in $\lambda_{max}$.

# Development of control methods

- **Task 2 (completed): Depth-L observability control**
  - Distributed control of each node using signals from only the depth-L *state information neighborhood* (SIN).
  - SIN determined through the *participation matrix* corresponds to local neighborhoods of every node and produces accurate distributed control performance.

# Development of control methods

- **Task 2 (completed): Depth-L observability control**
  - SIN determined through the *participation matrix* corresponds to local neighborhoods of every node and produces accurate distributed control performance.

**Walzem distribution network used for testing**

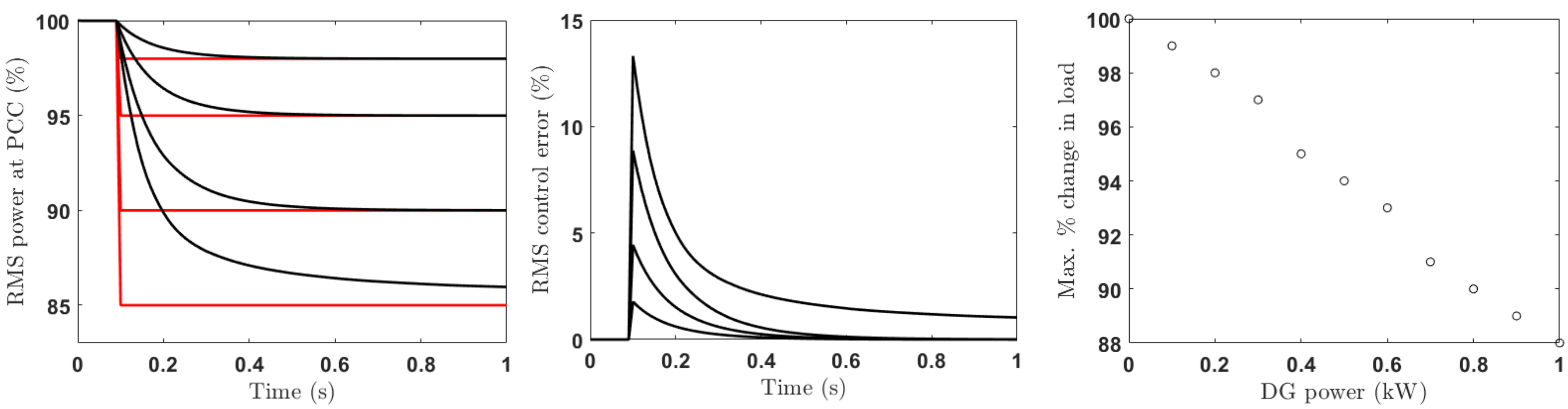
*Data provided by CPS Energy*

Image removed due to compliance with NDA

# Development of control methods

- **Task 2 (completed): Depth-L observability control**
  - Task 2.1: Extension of theory to general nonlinear systems.
  - Task 2.2: Design of frequency regulation scheme for distribution networks.
  - Milestone M2.2.3: Demonstrated capability of control algorithm for the Walzem distribution network model.

**Control performance for Walzem network**



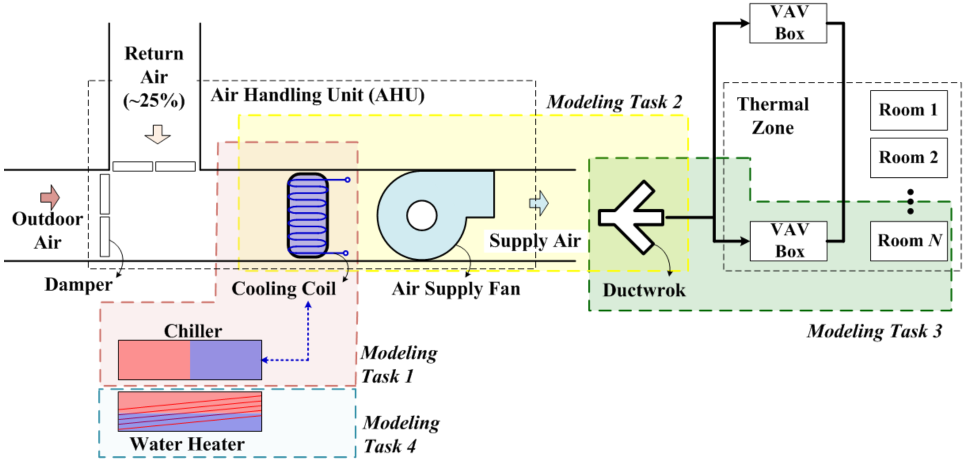

arpa·e
CHANGING WHAT'S POSSIBLE

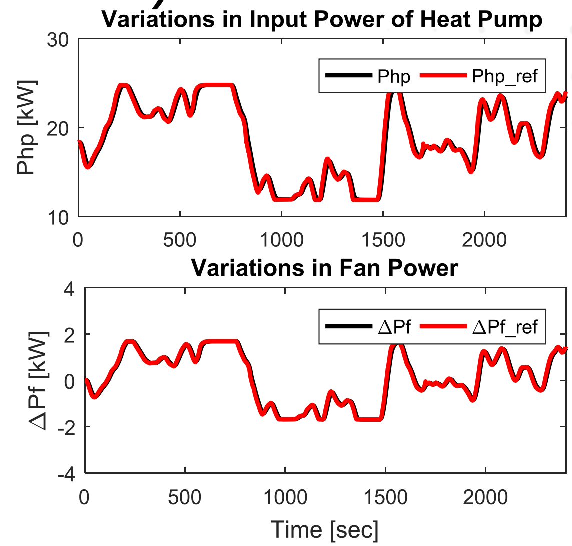
# Development of control methods

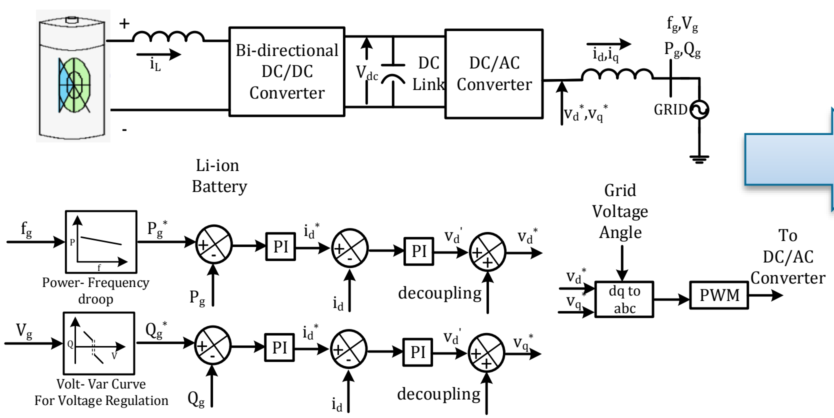
- **Task 3: Control algorithms for flexible appliances in buildings**
  - Control algorithms designed for flexible appliances to shape the aggregated building demand profile
  - Using both HVAC systems and battery-based loads as controllable loads in the building control framework
  - Implementing building-level energy management control (EMC) based on consensus algorithm

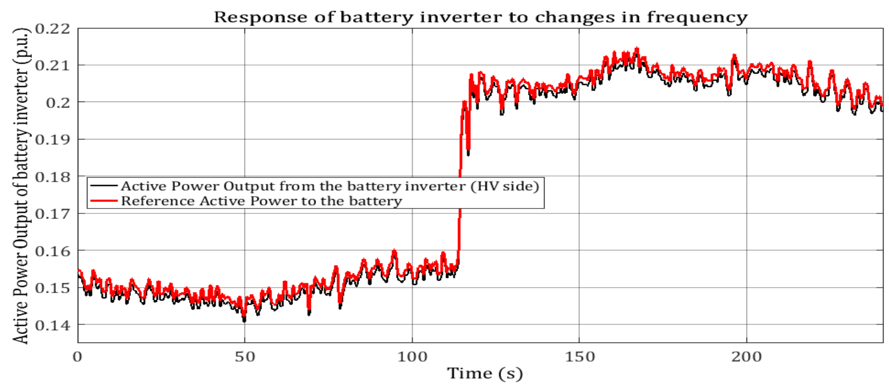
# Development of control methods

– <u>Task 3.1</u> (completed): Develop flexible appliance models (HVAC systems and battery-based loads)



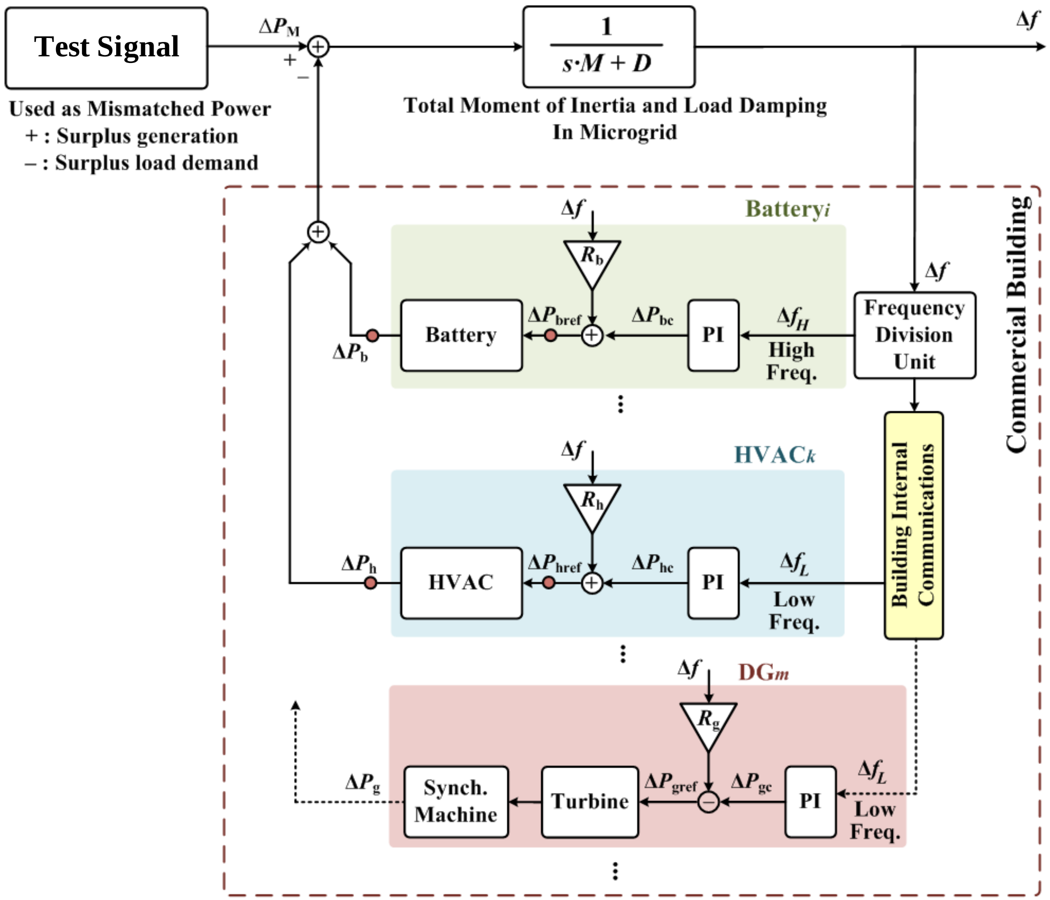



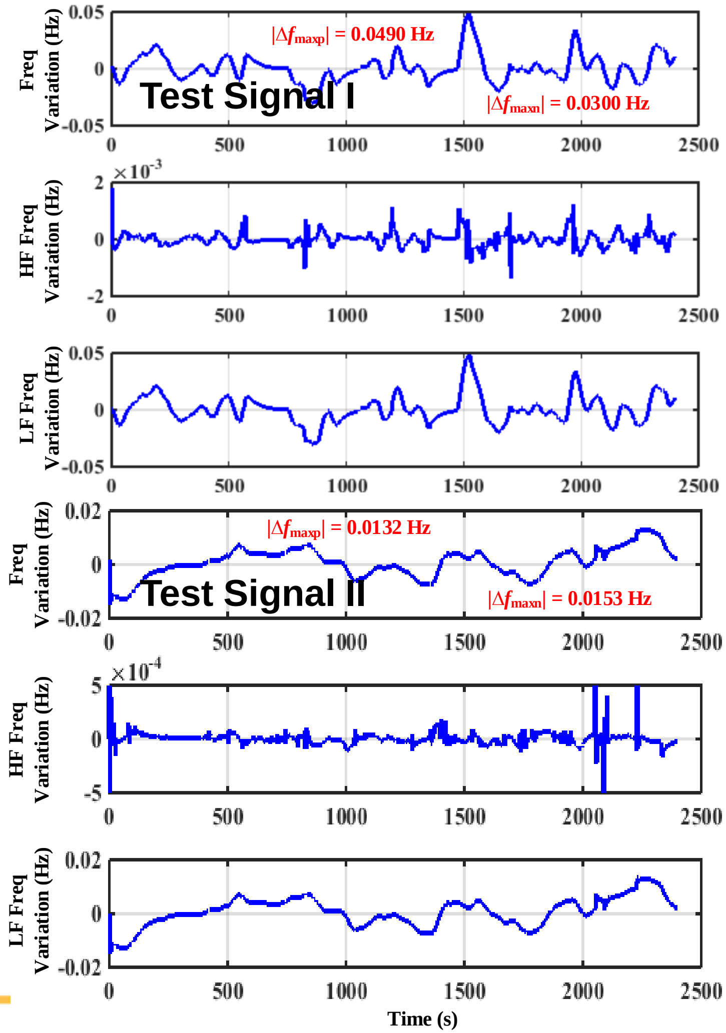



# Development of control methods

– Task 3.2 (completed): Develop the decentralized droop control for load scheduling

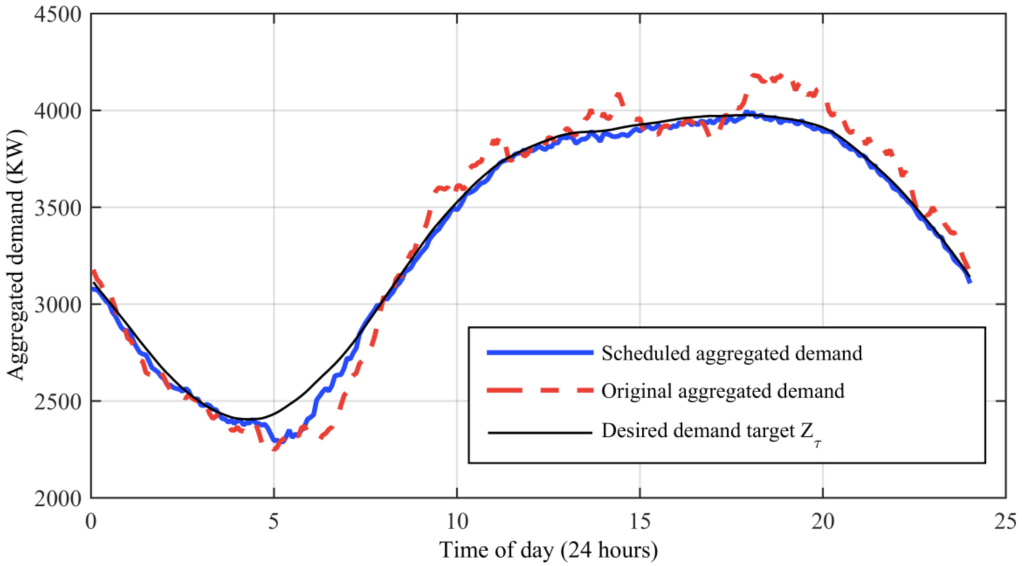


# Development of control methods

– <u>Task 3.3</u> (60% completed): Develop the building level EMC algorithm based on consensus algorithm

Use consensus algorithm to schedule both HVAC systems and battery loads to minimize the mismatch between actual and desired demand profiles




CHANGING WHAT'S POSSIBLE

# Validation Plan

- **<u>Task 4</u>: Large-scale simulations**
  - *Using OPAL-RT ePHASORsim platform*

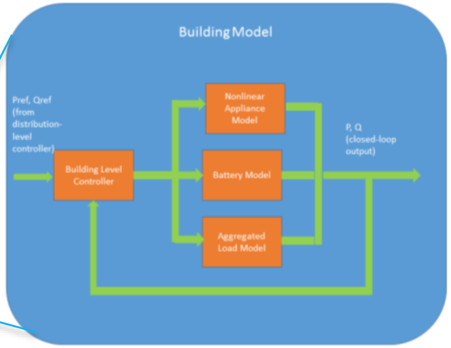

  - *Building level modeling*: Flexible appliance models developed in Task 3
  - *Distribution network modeling*: Based on data from CPS Energy
  - *Transmission network modeling*: Part of Texas ERCOT model (the portion used in the Task 1 demo)

# Validation Plan

– Task 4.1 (completed): Create a range of validation scenarios for each hierarchical level and for the integrated system, to configure simulation tools to run these scenarios.
– Task 4.2: Power systems topologies and control modeling
  - Milestone M4.2.2 (completed): Deliver validation data for transmission network simulation

Image removed due to compliance with NDA

Image removed due to compliance with NDA



# Validation Plan

- **<u>Task 5</u>: HiL testing**
  - Planned to be conducted at Energy Resource Station (ERS), Iowa Energy Center

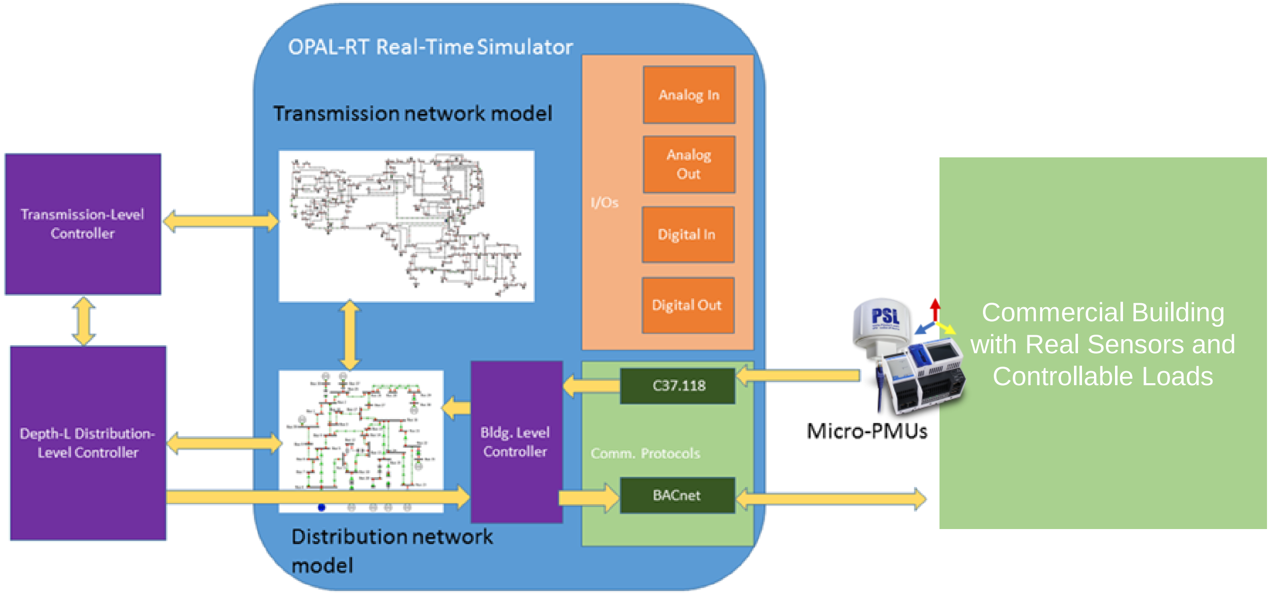
# Validation Plan

- **<u>Task 5</u>: HiL testing**
  - Planned to be conducted at Energy Resource Station (ERS), Iowa Energy Center

# Validation Plan

- **<u>Task 5</u>: HiL testing**

  Alternative sites:
  - Northwestern University campus
  - Stone Edge Farm
  - NREL
  - Navy Yard
  - Group NIRE



# Validation Plan

- **<u>Task 5</u>: HiL testing**

  Northwestern University campus: Control small smart appliances and (portable) batteries in our building using the developed EMC algorithm.


Smarter iKettle
Wifi controllable Electric Kettle


Goal Zero Yeti 150
Portable Power Generator
(Lead acid battery)
+
WiFi controllable switch

# Project Challenges

- **Challenges**
  - Proposed network decomposition method was not adequate when scaled up → reformulation of optimization problem + commercial optimization software
  - HiL validation plan needed to be re-formulated.

# Project Challenges

- **Publications so far:**
  - Y. Yang, T. Nishikawa, and A.E. Motter, *Vulnerability and Co-susceptibility Determine the Size of Network Cascades*, Phys. Rev. Lett. 118, 048301 (2017).
  - Software for simulation of physical cascade model and identification of cosusceptibile groups, https://github.com/yangyangangela/determine_cascade_sizes
  - Y. Yang, T. Nishikawa, and A.E. Motter, *Small vulnerable sets determine large network cascades in power grids,* Science 358, eaan3184 (2017).
  - Y. Yang and A.E. Motter, Cascading failures as continuous phase-space transitions, Phys. Rev. Lett. **119**, 248302 (2017).
  - A. Haber, F. Molnar, and A.E. Motter,
    State observation and sensor selection for nonlinear networks,
    IEEE Trans. Control Netw. Syst. (to appear). arXiv:1706.05462

# Tech to Market Path and IAB

- **Commercial objectives:** License/patent developed control algorithms
- **Target markets/segments:** Building managers, Microgrid operators, ISOs
- **Finalized IAB members:**
  - Sunny Elebua, *Vice President, Corporate Strategy*, Exelon Corporation
  - Troy Nergaard, *Director of Technical Product Management*, Doosan GridTech
  - Dave Kaplan, *Chief Technology Officer*, Doosan GridTech
  - Holly Benz, *Senior Vice President, Commercial & Industrial*, CLEAResult
  - Jean Bélanger, *Chief Executive Officer & Chief Technology Officer*, OPAL-RT Technologies
  - Mark Feasel, *Vice President, Electric Utility Segment & Smart Grid*, Schneider Electric
  - Shaneshia McNair, *Manager, Customer Engineering*, CPS Energy

# Tech to Market Path Update

- **Tasks completed:**
  - Defined process for selecting target market segment (“beachhead”), and value proposition.
  - Reviewed technology reports, and identified potential value propositions, target market segments, and channel access to target market segment.
  - Completed team discussions on value propositions for residential, and medium to large commercial building segments, and reviewed competing offers addressing similar value propositions to identify solution differentiations.
  - Concluded demand response type of solution best positioned to deliver a strongly differentiated solution to load aggregators and large commercial customers.
- **Next steps:**
  - Review findings with IAB
  - Review demand response programs to confirm value proposition and level of competitive differentiation.
  - Define whole product solution
  - Identify and interview commercial building customers participating in demand response programs to confirm value proposition.

# Future Plan

- **By the next annual meeting:**
  - Task 3: Building level EMC control testing completed
  - Task 4: Deliver large-scale simulation results after optimizing control algorithms
  - Task 5: Deliver HiL test report after optimizing control algorithms
- **T2M:** (previous slide)