



Resilient Architectures and Algorithms for Generation Control of Inertialess AC Microgrids

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Microgrid Notion

A group of loads and distributed energy resources (DERs) interconnected via an electrical network with a small physical footprint with the possibility of operating:

M1. as part of a large power system [Grid-connected mode]

M2. as an autonomous power system [Islanded mode]

Examples of Distributed Energy Resources (DERs)



PV systems



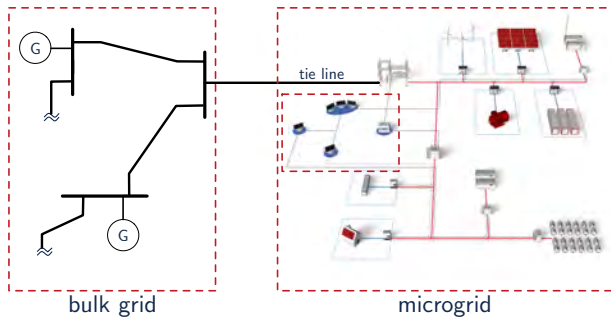
Electric Vehicles



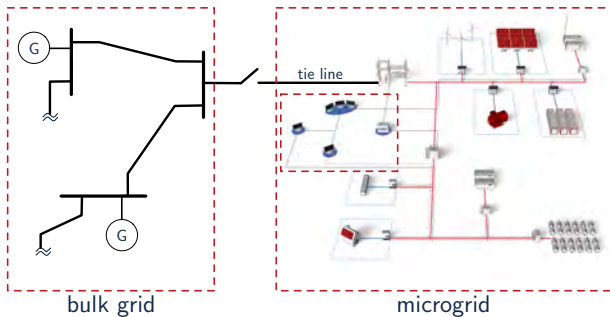
Fuel Cells



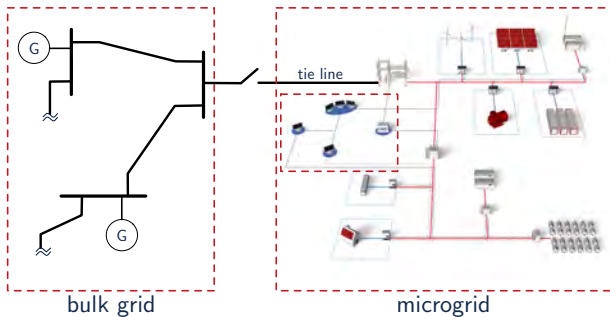
Residential Storage



- **Grid-Connected:** May be viewed as a single entity with the idea of controlling the DERs within its boundaries to provide services to the bulk grid



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- **Islanded:** Enables consumers to maintain electricity supply by appropriately controlling the DERs within its boundaries



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- **Islanded:** Enables consumers to maintain electricity supply by appropriately controlling the DERs within its boundaries
- Different control objectives for each operational mode and each type of DER

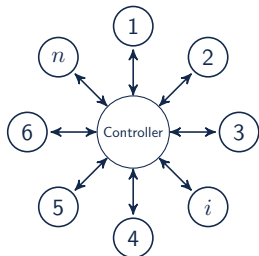
Architectural Solutions

- **Centralized:**

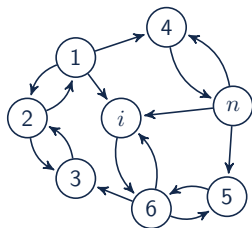
- ▶ Requires communication between a central processor and the various generation resources (and possibly loads)
- ▶ Requires up-to-date knowledge of generation resource availability
- ▶ Subject to failures at the decision maker (single-point-of-failure)

- **Distributed:**

- ▶ Inherent ability to handle incomplete global knowledge
- ▶ Potential resiliency to faults and/or unpredictable behavior



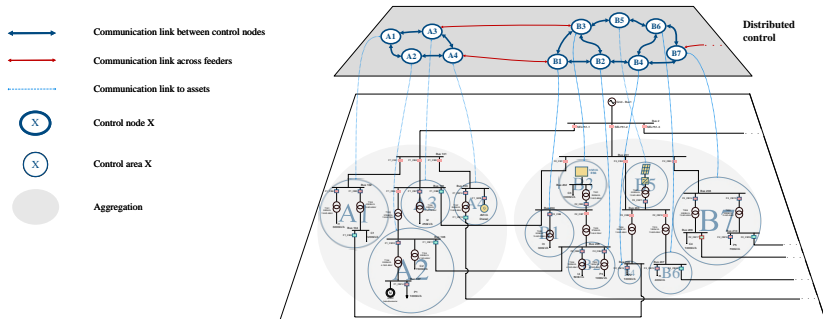
Centralized



Distributed

Our Distributed Control Platform

- Each control node acquires information locally (e.g., from measurements) and via exchanges with nearby control nodes
- The information is used as inputs to a suite of distributed algorithms implementing requisite control functions

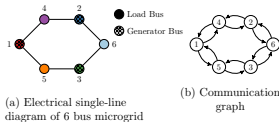


Our Work in the Last Decade

- We have developed, mathematically analyzed, and tested numerous distributed algorithms for performing several control functions, including:
 - ▶ frequency control, voltage control, optimal dispatch, provision of ancillary services, optimal power flow, synchronization
- Our laboratory-grade control node prototypes are currently equipped with distributed algorithms for *frequency control* [TCST 2017]

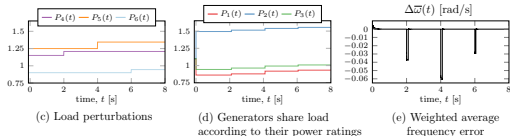


Laboratory-grade control node prototype



(a) Electrical single-line diagram of 6 bus microgrid

(b) Communication graph



(c) Load perturbations

(d) Generators share load according to their power ratings

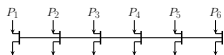
(e) Weighted average frequency error

Our Work in the Last Decade

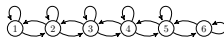
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- Our laboratory-grade control node prototypes are currently equipped with distributed algorithms for *optimal asset scheduling* [CDC 2012]



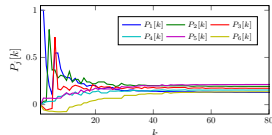
Laboratory-grade control node prototype



(a) Electrical single-line diagram of 6 bus microgrid



(b) Communication graph



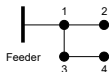
(c) Estimation of the optimal power outputs of the generation units, $P_j[k]$, $j = 1, 2, 3, 4, 5, 6$

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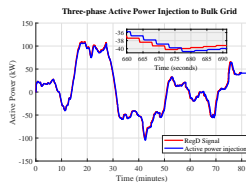
Laboratory-grade control node prototype



(a) Electrical single-line diagram of 4 bus microgrid



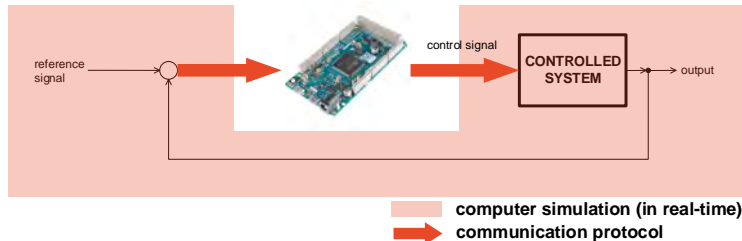
(b) Communication graph



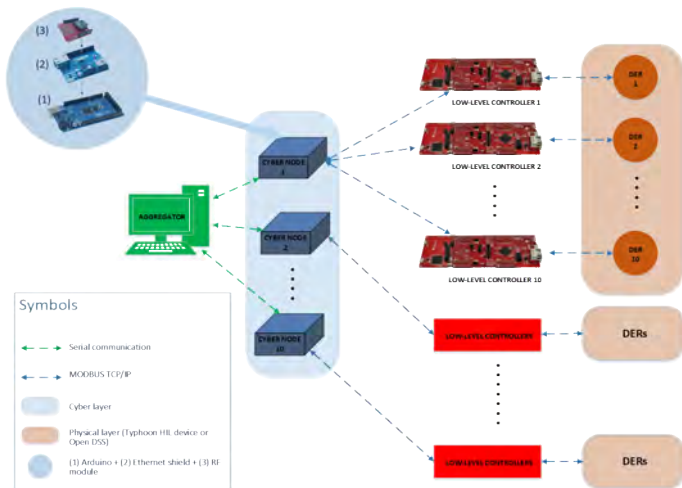
(c) Aggregate response of DERs to PJM RegD signal

Controller Hardware-in-the-loop (C-HIL) Testing

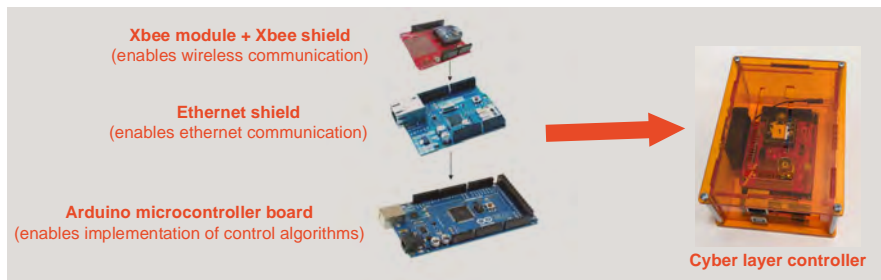
- All our distributed algorithms have been tested in a C-HIL environment
- C-HIL testing is a safe, low cost, repeatable, flexible and efficient approach for testing control hardware



Illinois C-HIL Testbed Architecture



Cyber Layer



- The cyber layer is equipped with **cyber layer controllers**, each outfitted with wireless and ethernet transceivers
- Cyber layer controllers execute the distributed algorithms necessary to implement each particular control function

Physical Layer

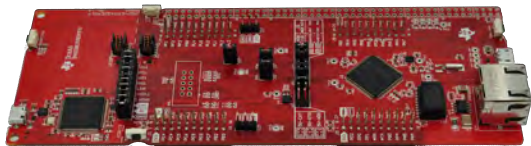


- The **Typhoon HIL402** and **Typhoon HIL603** are utilized for real-time emulation of the physical layer
- The emulators are equipped with detailed and reduced models of:
 - ▶ Rooftop photovoltaic (PV) panels
 - ▶ Battery storage systems
 - ▶ Wind turbine generators
 - ▶ Microturbines
 - ▶ Fuel cells
 - ▶ Loads
- Simulation time steps are as low as 500ns

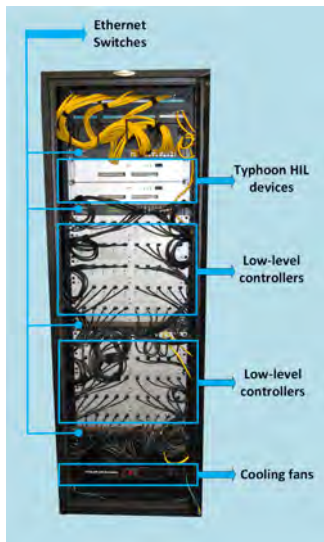
Low-level controllers



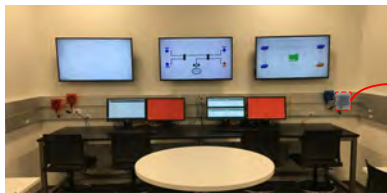
Low-level controllers cabinet



TI MSP-EXP432e401y Ethernet board



Equipment cabinet



A laboratory prototype of the control node

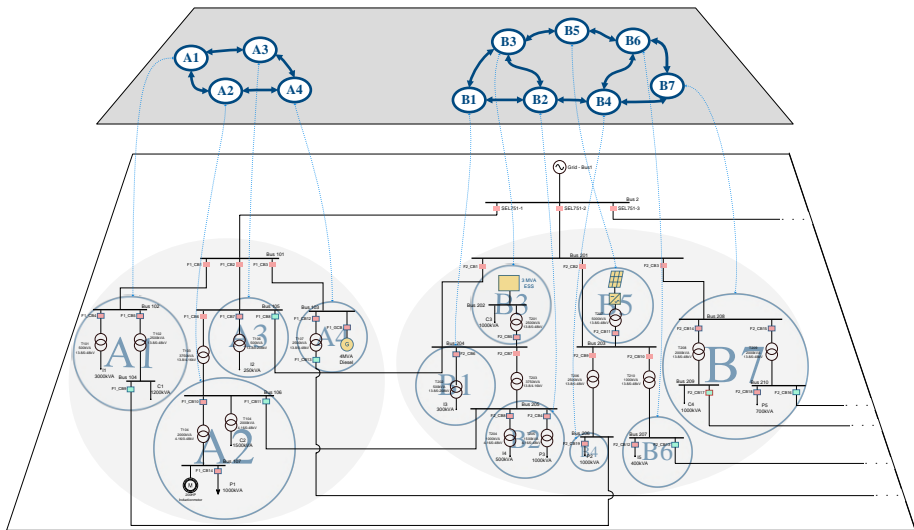
View of the testbed control console showing several laboratory-grade control node prototypes

Moving Forward

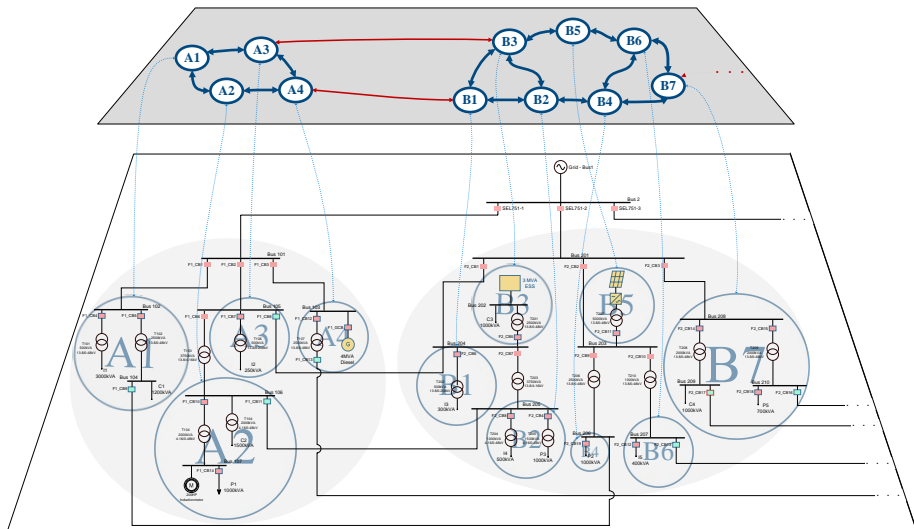
Demonstrate the ability of our distributed architecture to handle challenging scenarios, including:

- Networking multiple already-existing microgrids
- Plug-and-play integration of additional assets
- Communication failures and control node reboot/shutdown

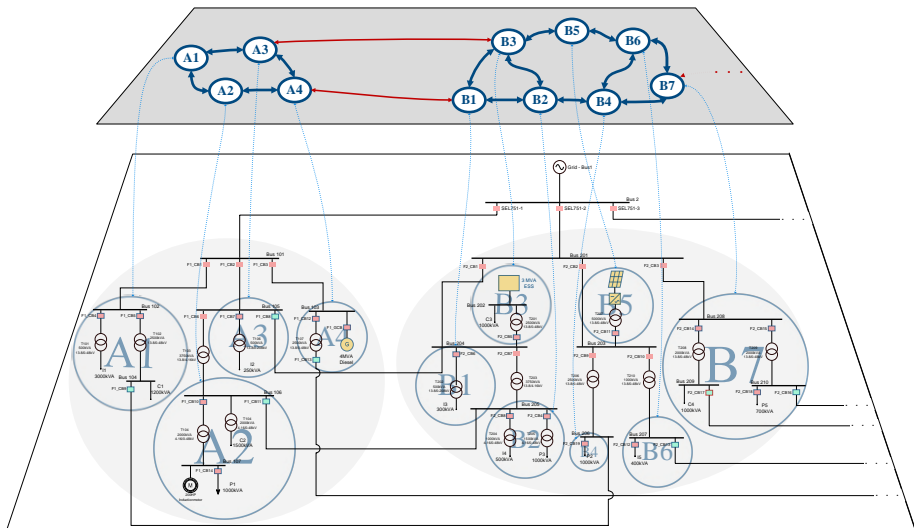
Networking of Multiple Microgrids



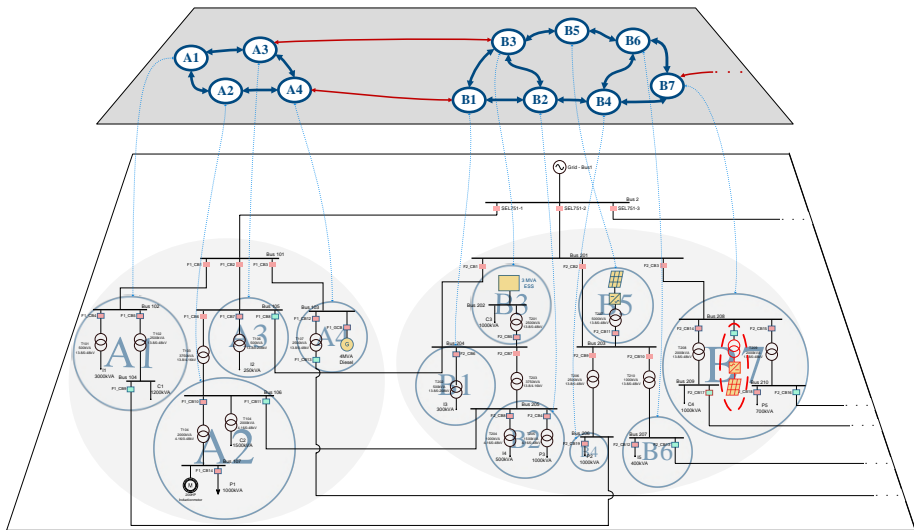
Networking of Multiple Microgrids



Integration of an Additional Asset



Integration of an Additional Asset



Failure of multiple control nodes

