Co-Simulation of Decentralized Grid Control Algorithms

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The future grid will consist of billion smart devices including distributed resources, and millions of decision-makers.

- Emerging dynamic behavior at new space and time scales.

Need much faster, better, tighter coordination across subsystems: ISO, utilities, microgrids, buildings, homes, etc.
The Challenge

‣ How can we coordinate the simultaneous operation of a very large number of devices and subsystems (actors) to achieve system-wide objectives such as ultra-reliability, economic optimization, and sustainability?

‣ Recognition that (for many reasons) it is impossible to have a single organization making all operational and control decisions.

‣ Decision making needs to be decentralized.
Decentralized

- Recognizes more than one decision-maker.

- Microgrids
- Demand Response
- Building Energy Management Systems
- Home Energy Management Systems
- Building, Home, Vehicle, X to Grid
- Transmission/distribution effects
- Consumer Empowerment
- Prosumers
- Imbalance Markets
- Distribution System Operators (DSO)
- ISO Seams Issues
- Wide-Area Control
- Etc. . . .
Interdisciplinary collaboration including power systems, networked control, cyber-physical systems, and decentralized optimization.

Project Contribution:
1. Decentralized Control Reference Architecture
2. Power/Cyber Co-Simulator
3. Decentralized Frequency Control Application
4. Decentralized Energy Scheduling Application
Concept 1: Prosumer Abstraction

- A generic model that captures basic functions (produce, consume, store) can be applied to power systems at any scale.

- The fundamental task is power balancing:
  \[ P_{INT} = P_G - P_D - P_{Loss} - P_{STO+} + P_{STO-} \]

- Energy services can be virtualized.

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Concept 2: Networked Grid

Interconnection

ISO

Utility

\( \mu \) Grid, Building, Home

- Interactions occur among entities of the same type (prosumers)
- Supports hierarchical or flat paradigms
Prosumer exposes standardized services
- Energy balancing
- Frequency regulation
- Reserve
- Sensing and Information
- Forecasting
- Security
- Self-identification
- Voltage control
- Black Start
- Etc.
The grid is naturally divided into subsystems.

All subsystems can produce, consume and store.

- They become prosumers.

Prosumers are equipped with distributed intelligence.

Prosumers interact through formal power protocols.

Layered cyber-physical network coordination stack.
Two distinct aspects need to be covered:

- **Power System Simulation**
  - Numerical solution of a system of differential equations
  - Traditional Tools: PowerWorld, OpenDSS, SimPowerSystem

- **Cyber Systems Simulation**
  - Discrete-event simulation
  - Traditional Tools: ns2, ns3, OMNET++
Grid Co-Simulation

- Literature presents two approaches:
  - **Integrated Approach**
    - A new simulation environment with integrated hybrid semantics for Power and Communication aspects
      (e.g. Nutaro et.al “Integrated Hybrid Simulation of Electric Power and Communication Systems”)
  - **Federated Approach**
    - Combine existing simulators from the domains of Power Systems and Computer Networks using co-simulation libraries, such as High Level Architecture co-simulation standard
      - Examples: EPOCHS (ns-2 + PSCAD); Godfrey et.al. (ns-2 + OpenDSS)
Control and Optimization Algorithms are usually prototyped in domain-specific environments such as MATLAB.

Decentralized control requires a *Platform-Aware Integrated Simulation Environment*

- Demonstrate the integrated operation of individual algorithms.
- Investigate the effect of computing platform performance on algorithms.
- Demonstrate the self monitoring (and mode switching) capabilities of algorithms.
Grid Co-Simulation for Decentralized Algorithms

- Uses ns-3 as the basis of ‘computing platform’ simulation
  - Simulate “appropriate” software layers as ns-3 extensions

- Consistent with ns-3 philosophy
  - Ns-3 has an inherently extensible design in order to simulate the software stack involved in networking

Ns-3 Software Organization
Grid Co-Simulation for Decentralized Algorithms

- ns-3 + Existing Power System Tools (e.g. PowerWorld)
- ns-3 nodes extended with system-level software modules
Grid Co-Simulation for Decentralized Algorithms

Front End
- MATLAB-based Rendering of Output Data in CSV Files
- XML-based Smart Grid Scenario Description

Back End
- Power System Simulator
  - PowerWorld
  - Configurations
  - Co-Simulation Data Exchange
- Co-Sim Library
  - Sensor
  - Actuator
- Cyber System Simulator
  - Service-based Apps
    - DFC
    - DED
  - Service-Oriented ProsumerAF
  - Core NS3
Decentralized Frequency Control

- Bring steady-state frequencies to desired value while:
  - Returning output power to the scheduled interchange
  - Minimizing system-wide control effort
  - Avoiding oscillations
  - Performing only local computations (distributed!)
Decentralized Energy Scheduling

- Application able to schedule energy in the day-ahead timeframe in a decentralized manner.
- Large-Scale ISO with realistic Unit-Commitment Data
- Solution orders of magnitude faster.
Final Co-Simulator State

- Large Scale ISO (PJM) System
  - Divided into 100 prosumers
  - Described as XML document
  - Outputs the rolling horizon generator set points as .csv files
  - Mfile reads the csv file and plots the behavior of a generator under the “integrated influence “ of various algorithms
Large-Scale ISO Subsystems

- PJM Case
  - Divided into 100 prosumers
  - Described as XML document
  - Outputs the rolling horizon generator set points as .csv files
  - Mfile reads the csv file and plots the behavior of a generator under the "integrated influence" of various algorithms
Integrated Demo

![Graphs showing power output over time for Prosumer 98, Gen1.](image)
Effect of Link Delay

- Prosumer 98, Gen1 (Link Delay = 5ms, Task Period = 2ms)
- Prosumer 98, Gen1 (Link Delay = 8ms, Task Period = 2ms)
- Prosumer 98, Gen1 (Link Delay = 12ms, Task Period = 2ms)
Effect of Task Execution Time

![Graph showing the effect of task execution time on power consumption. The graph compares two scenarios: Prosumer 98, Gen 1 (LinkDelay = 8ms, TaskPeriods = 2ms) and Prosumer 98, Gen 1 (LinkDelay = 8ms, TaskPeriods = 4ms). The y-axis represents power in kW, ranging from 46.25 to 46.75, and the x-axis represents time in seconds, ranging from 80 to 180.]
Mode Switching

![Graph showing mode switching with 45-second intervals and mode change highlighted.](image-url)
Summary

‣ Proposed decentralized control and management of the future grid using an energy prosumer paradigm.

‣ Simulation of decentralized coordination algorithms is key for a large number of future grid use cases.

‣ Project has developed an infrastructure for simulation environment for decentralized control algorithms.
  – Based on extension of ns-3
  – Achieves combined cyber-physical simulation
  – Provides flexible integration with existing simulation tools
  – Supports testing of decentralized algorithms in large-scale systems using realistic data.
Thanks

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