SSPS 1.0 Controller – Nodes and Hubs Coordinator

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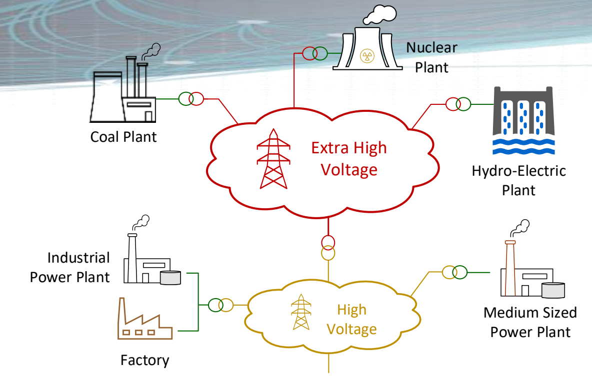
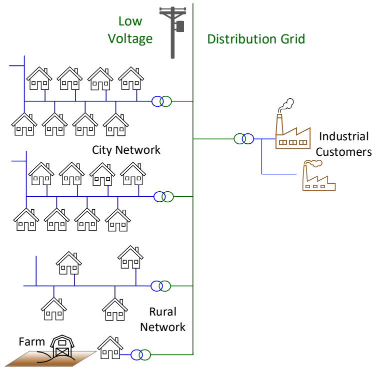
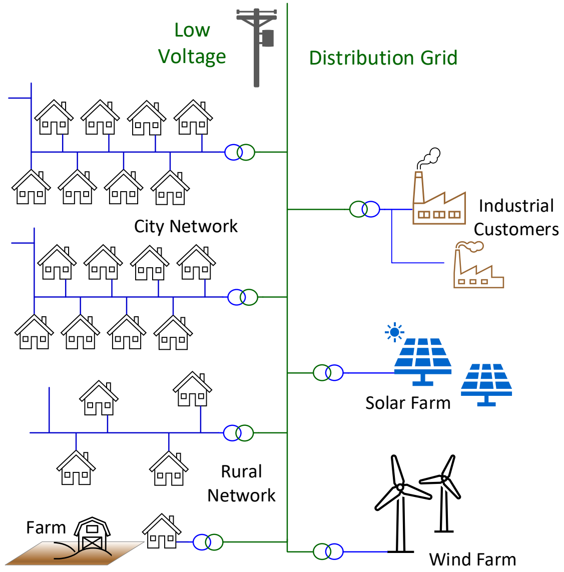
Context



Traditional Transmission Power System
- Low granularity
- Dispatchable resources



Traditional Distribution Power System
- Loads only
- High granularity
- Predominantly radial circuits
- Discrete and binary operation points (CB, OLTC, …)
- Small span of operating points ("easy" to compute)



"Future" Distribution Power System
- Loads, and flexible, but **non-dispatchable resources**
- High **granularity**
- Predominantly radial circuits
- **Continuous operation points** due to **PE devices**
- **Operation possibilities spans** to **infinite**
- The **solution surface** is **multi-modal**
- **Decision-making** is very **complex**

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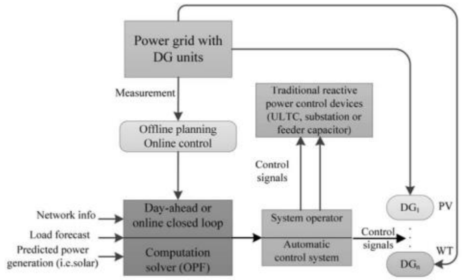
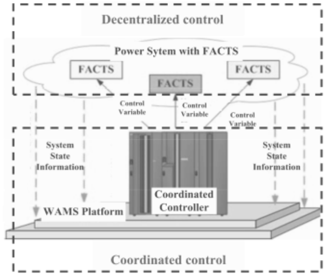
State of Art

Shortcomings in the existing approaches:

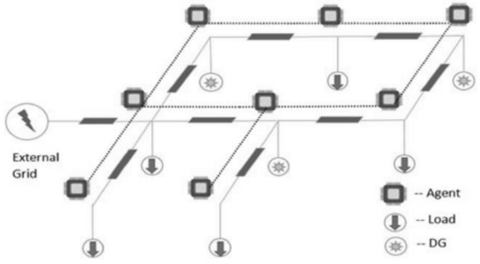
- Only one service is considered, in general, voltage control
- Difficulties to extend the approaches to other grid services
- Long computation time
- For distribution level, since PE devices are fairly new, this type of tool is still the subject of research
- Standard algorithms are likely to get stuck in local optima
- No evaluation in CHIL testbed



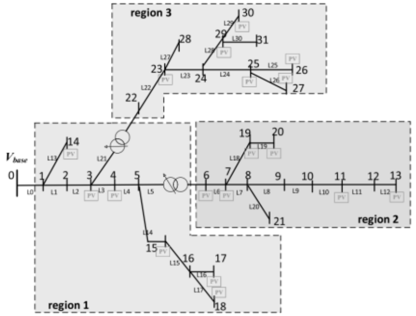
W. Sheng et al, **2016**



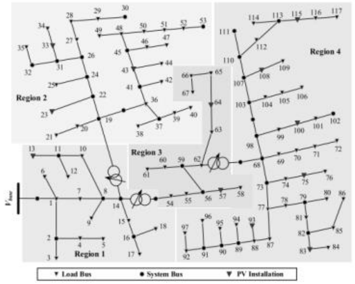
Shiyun Xu et al, **2017**



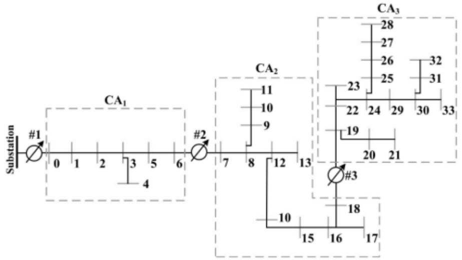
K. Utkarsh et al, **2017**



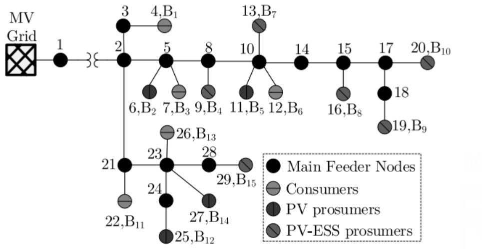
Y. Liu et al, **2019**



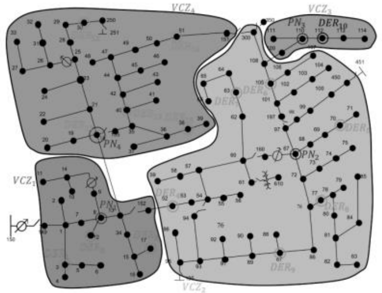
Y. Liu et al, **2019**



Z. Tang et al, **2021**



L. Tziovani et al, **2022**



A. R. D. Fazio et al, **2022**

Challenges & Goal

Challenges:

- **Interfacing** renewable energy and storage devices with the grid in a **reliable** and **efficient** way
- **Operating** and **controlling** the **grid** with the additional **uncertainty** from most of the primary energy resources
- **Operating** and **controlling** the **grid** with **non-centralized** and **non-coordinated control** of the renewable energy **generation**

Goal:

To develop **data-driven solutions** based on techniques such **artificial intelligence/machine learning**, aiming operation aiming increased:

- **Multiples** and/or **simultaneous grid services** to a single or multiple feeders
- **Resilience** through **reconfiguration** and **creation** of **temporary microgrids**

The Numbers

- DOE PROGRAM OFFICE:
  OE – Transformer Resilience and Advanced Components (TRAC)
- FUNDING OPPORTUNITY:
  AOP
- LOCATION:
  Knoxville, TN
- PROJECT TERM:
  09/01/2022 to 08/31/2024
- PROJECT STATUS:
  Ongoing
- AWARD AMOUNT (DOE CONTRIBUTION):
  $750,000/year
- AWARDEE CONTRIBUTION (COST SHARE):
  NA
- PARTNERS:
  NA

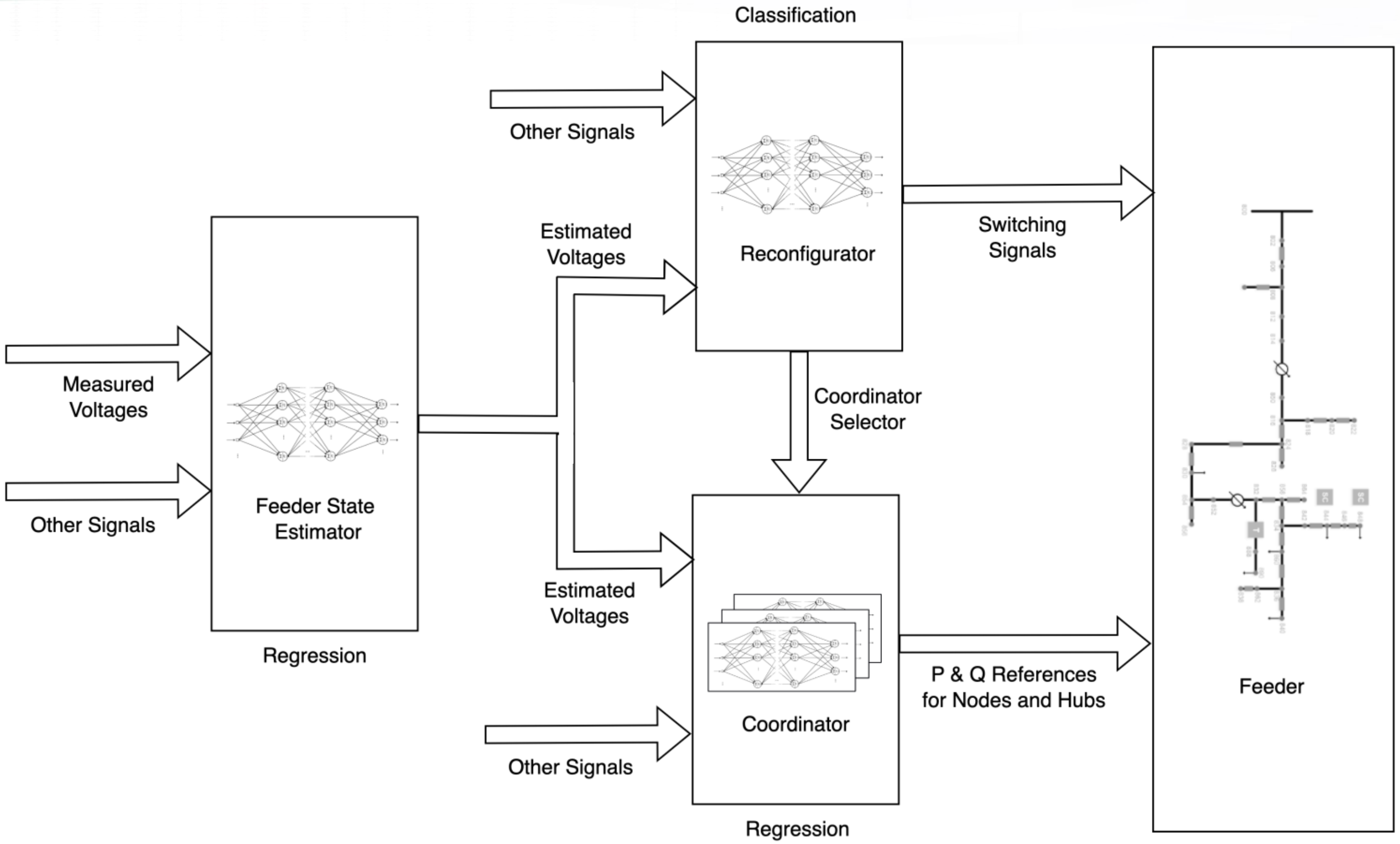
Technical Approach: SSPS 1.0 Controller Architecture

Assumptions:

- **Feeders** are the **best grid building blocks** to aggregate and coordinate
- The grid is a set of "**decoupled**" feeders

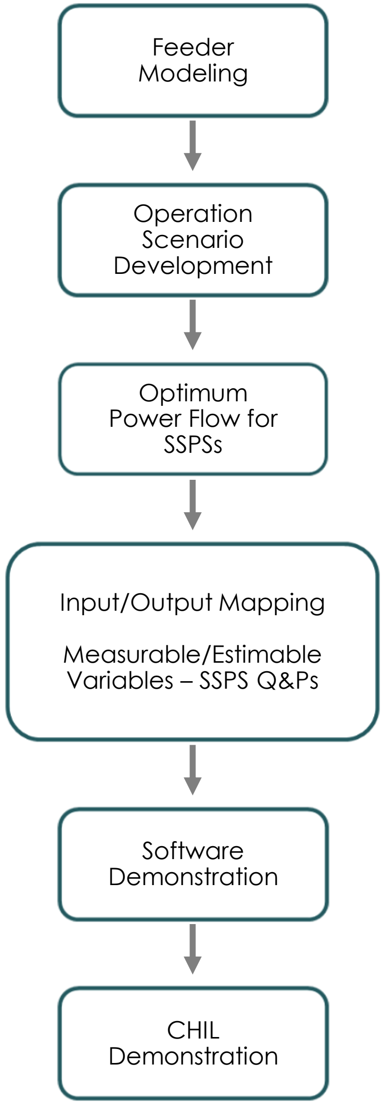
Composed by:

- Resources near **optimum coordinator:** coordinates nodes and nodes (other resources can also be coordinated). Multiples models are present for each possible feeder configuration.
- **State estimator:** estimates feeder variables from low number of measurements
- **Reconfigurator:** select the best feeder operation topology; send switching signals for feeders; select the coordination model for that topology



In this project the focus is the coordinator, but work is also being done on State Estimator and Reconfigurator

Technical Approach



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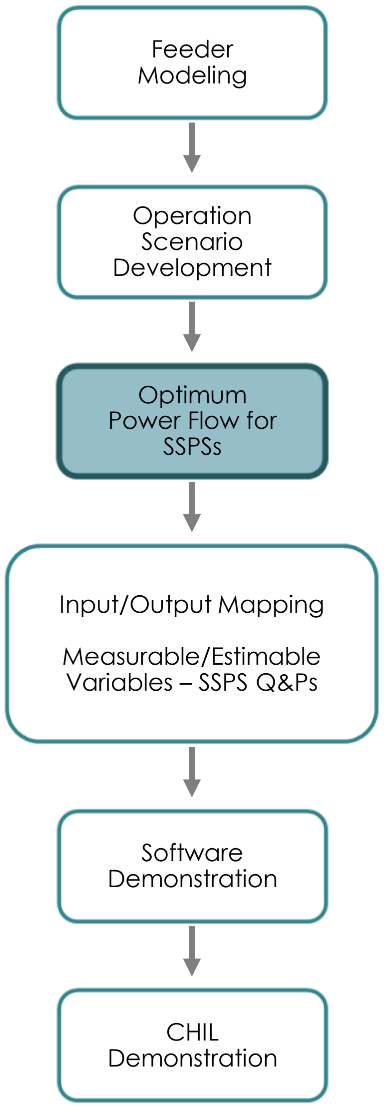
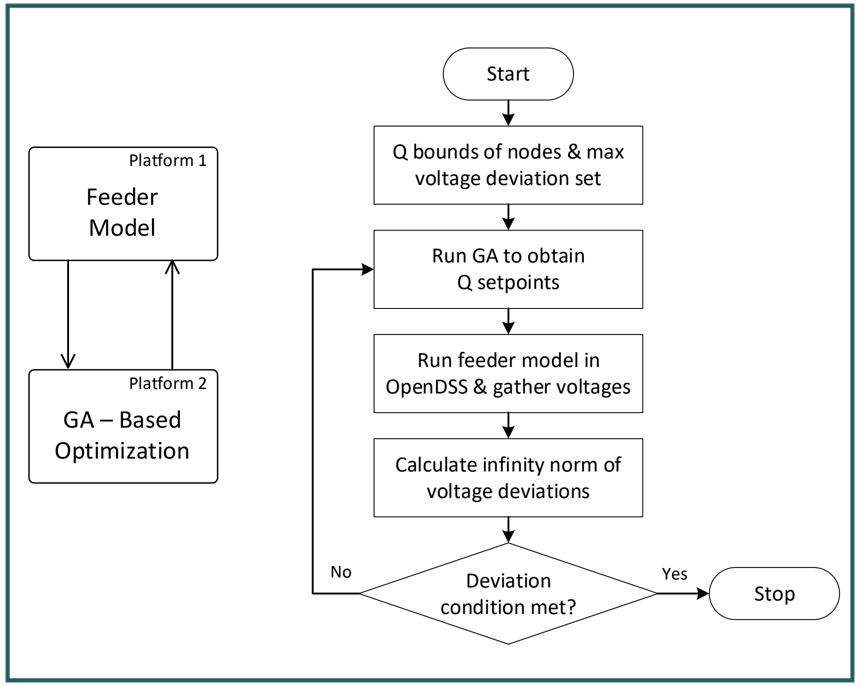
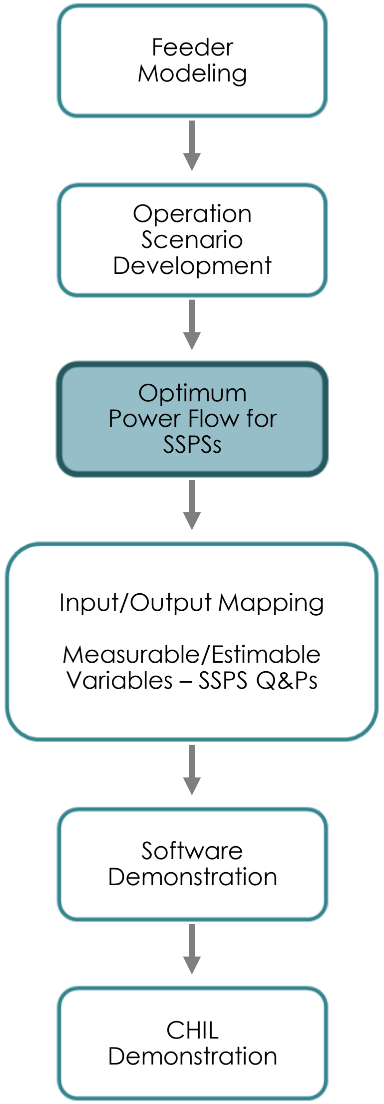
Technical Approach: Coordinator





Technical Approach: Coordinator



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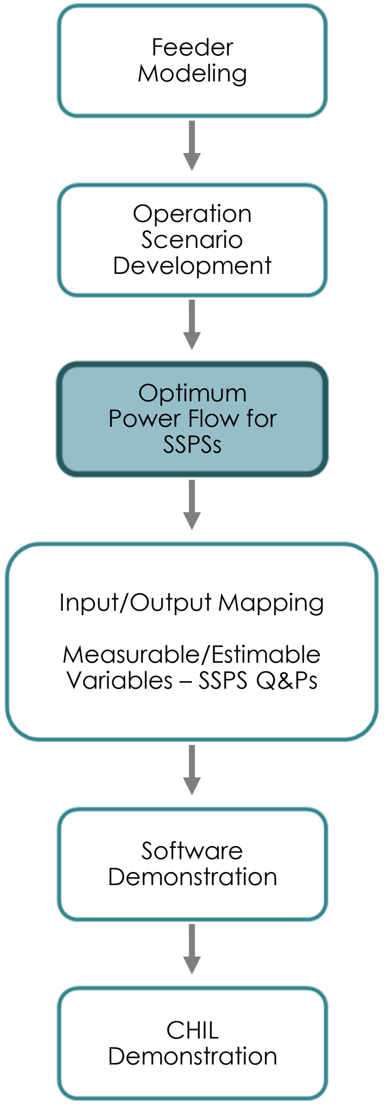
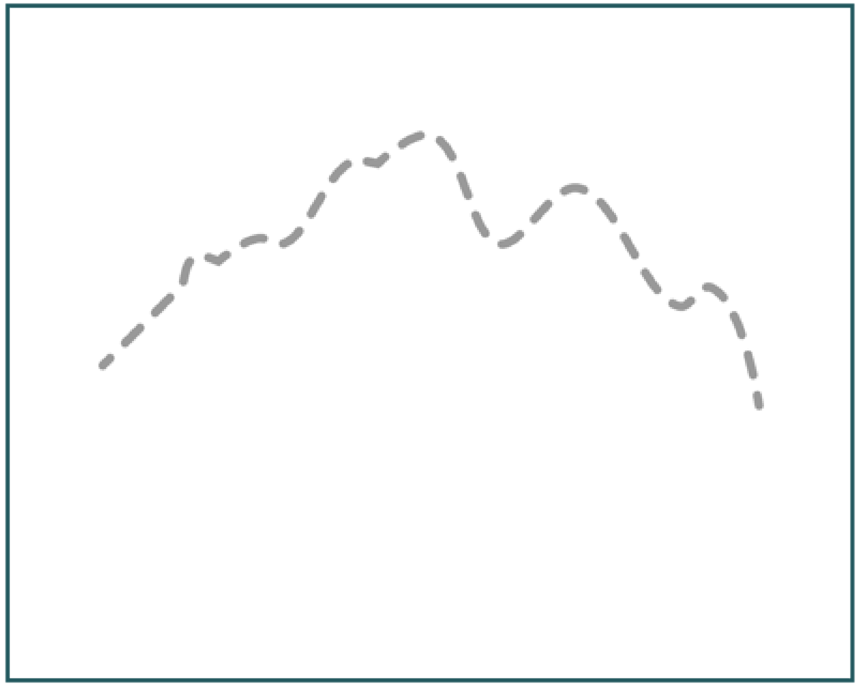
Technical Approach:Coordinator





Technical Approach: Coordinator

Feeder Modeling

↓

Operation Scenario Development

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Optimum Power Flow for SSPSs

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Input/Output Mapping

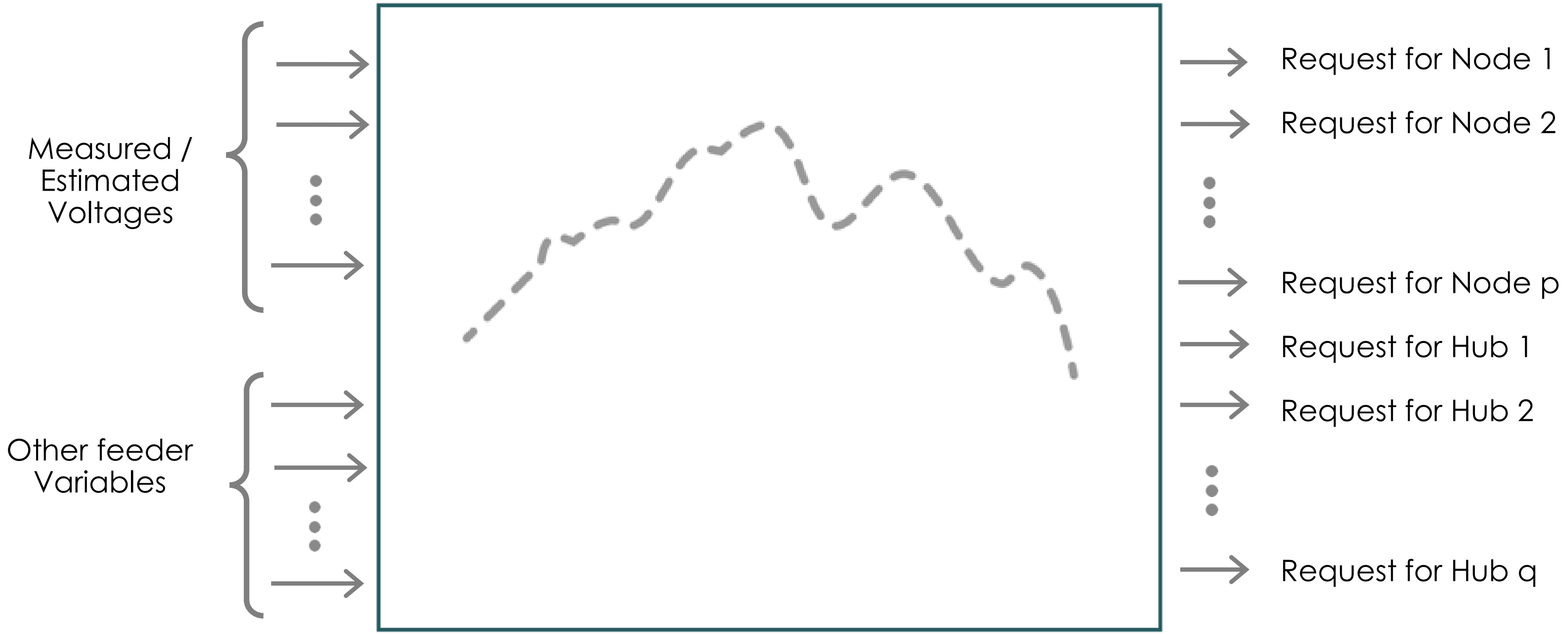
Measurable/Estimable Variables – SSPS Q&Ps

↓

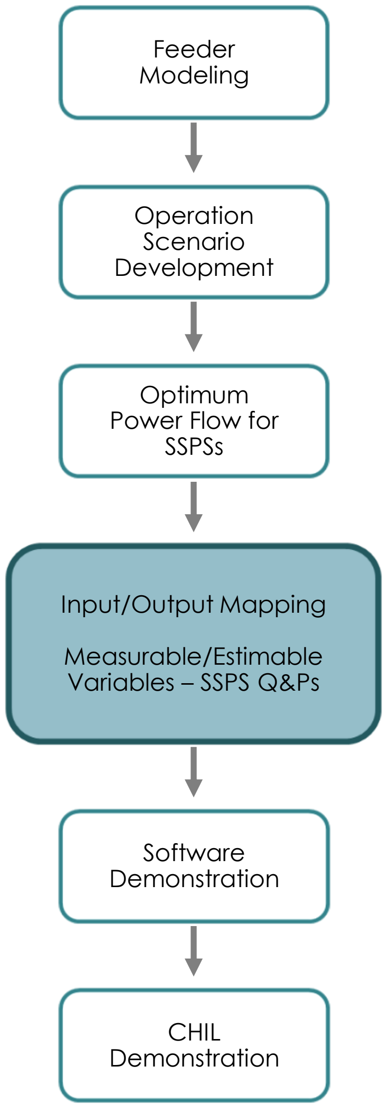
Software Demonstration

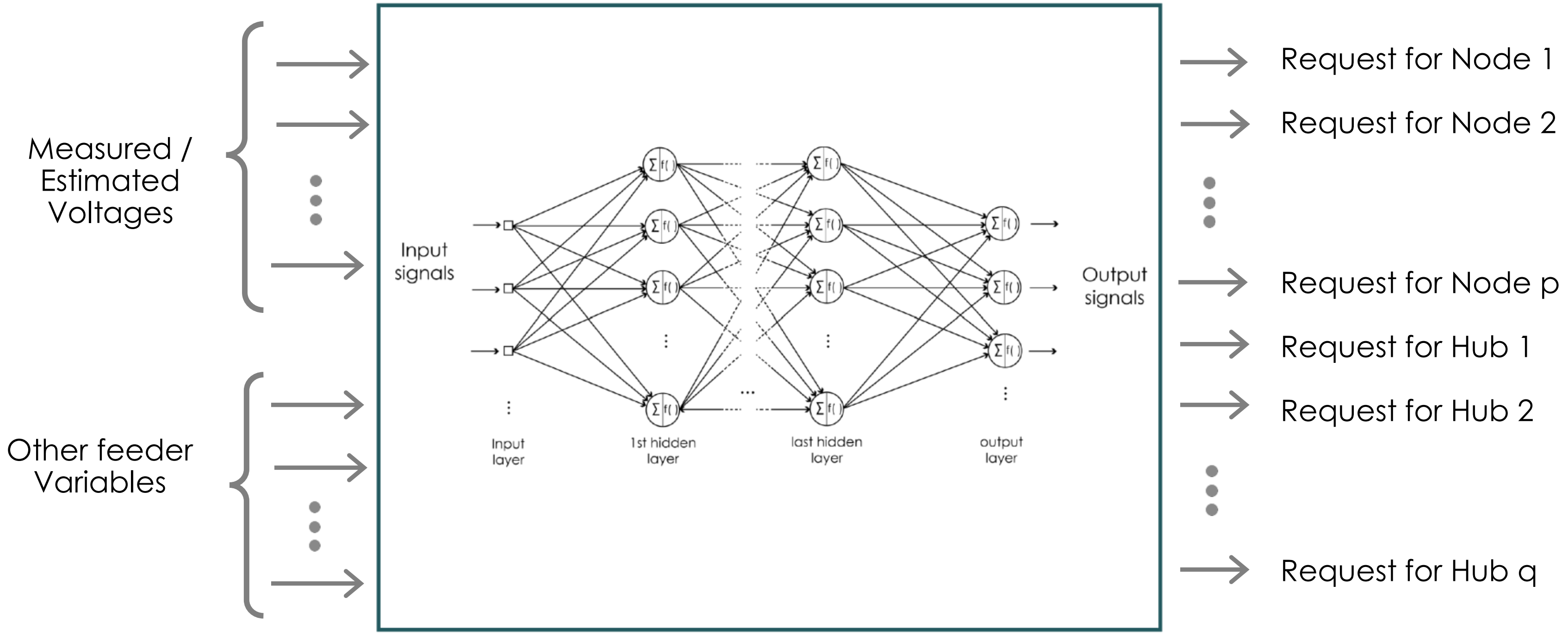
↓

CHIL Demonstration

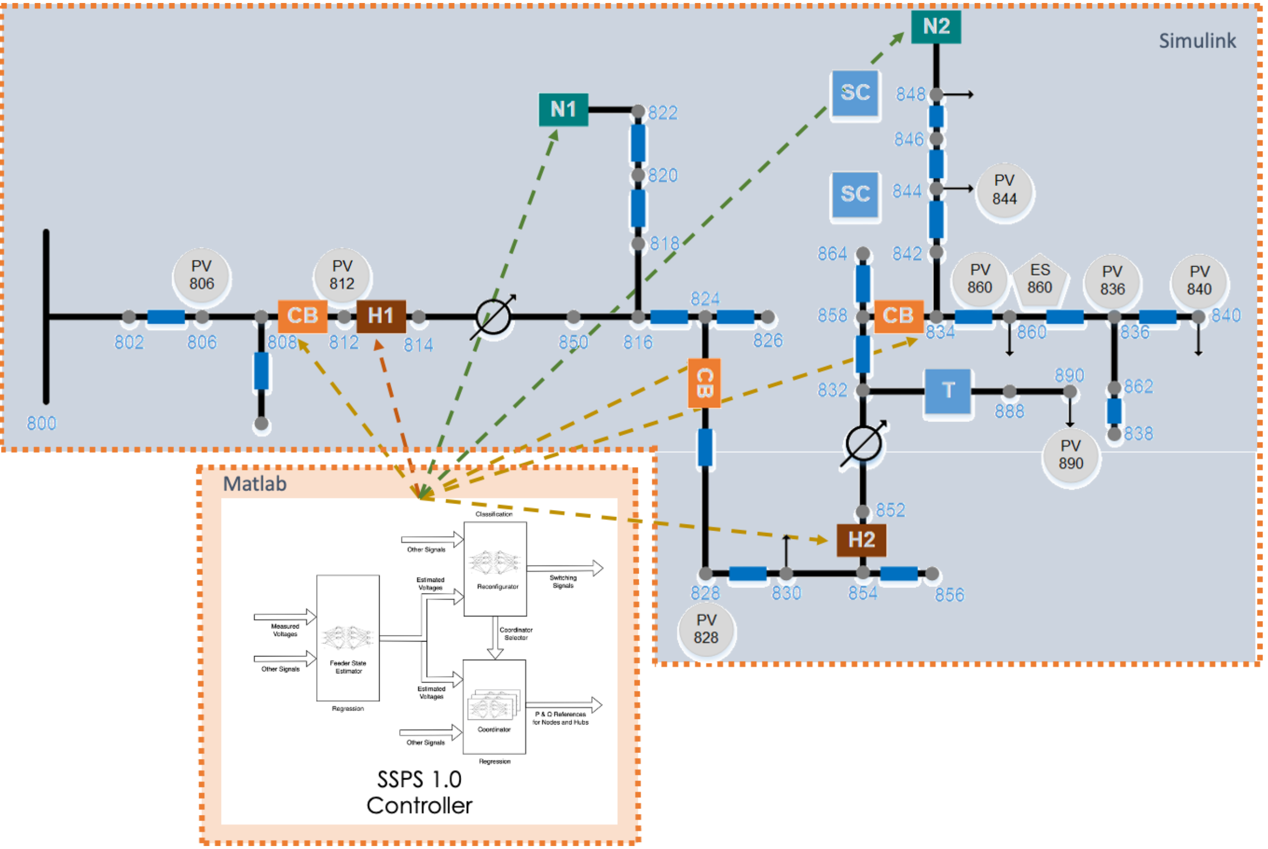


Technical Approach: Coordinator

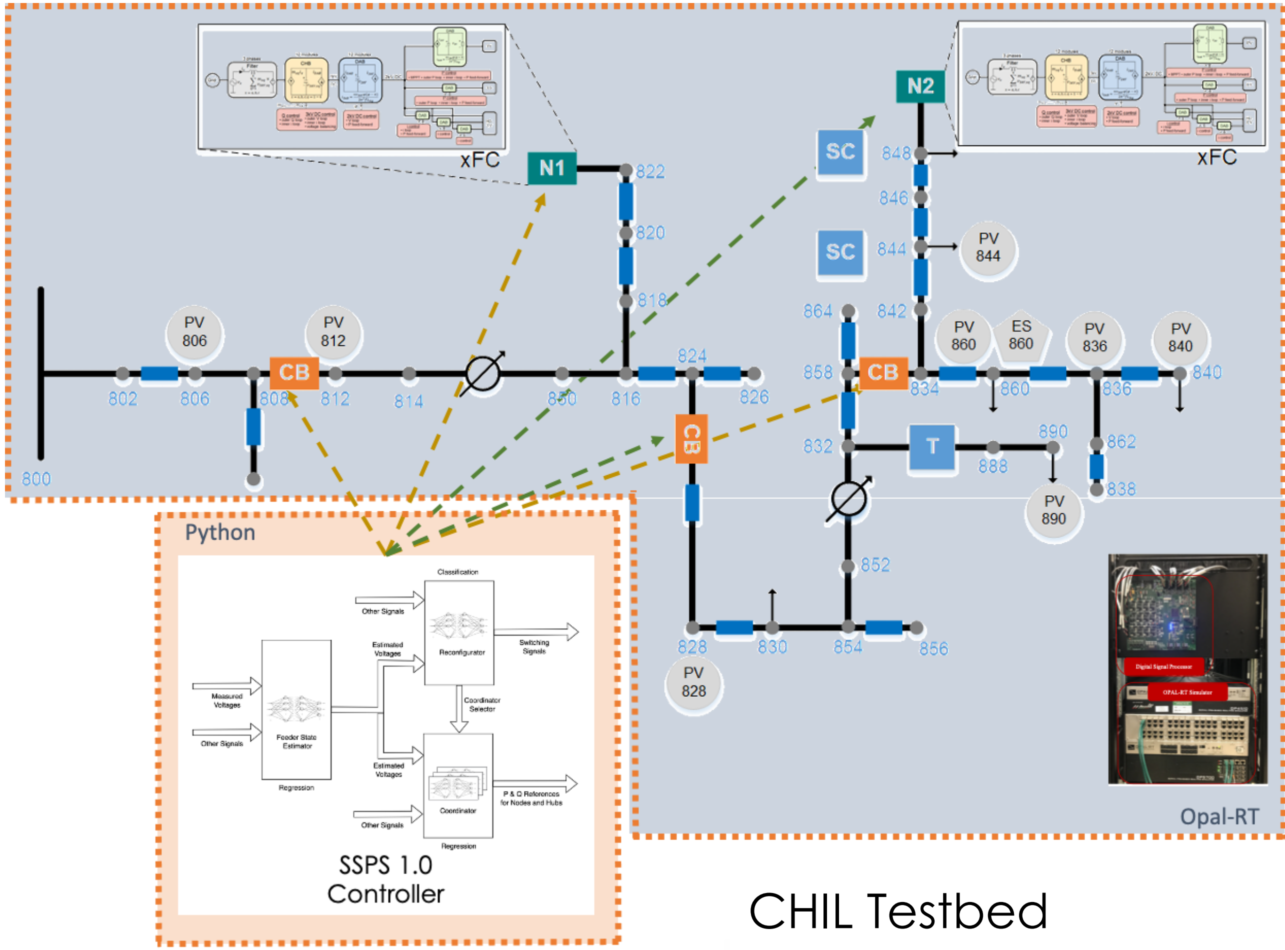




Technical Approach: Software and CHIL Demonstration



Software Testbed



CHIL Testbed

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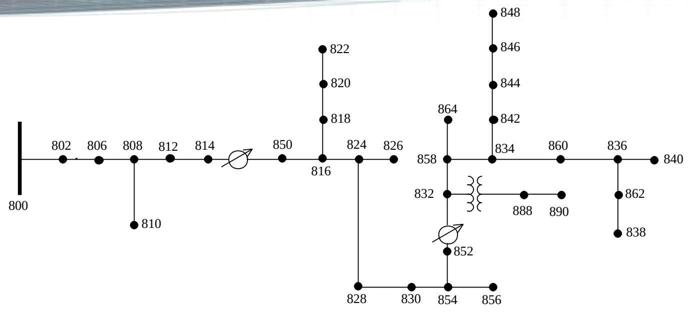
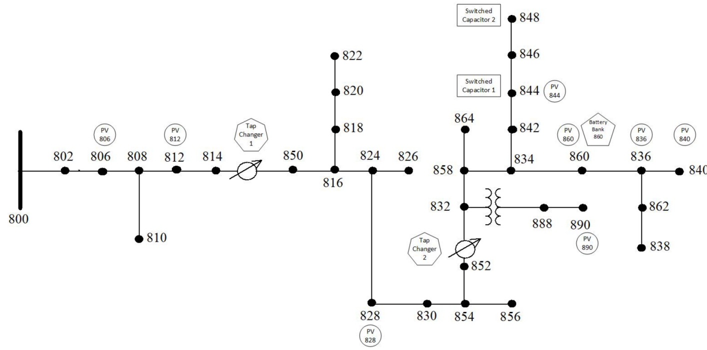
Technical Accomplishment 1: Feeder Selection, Modification and Modeling

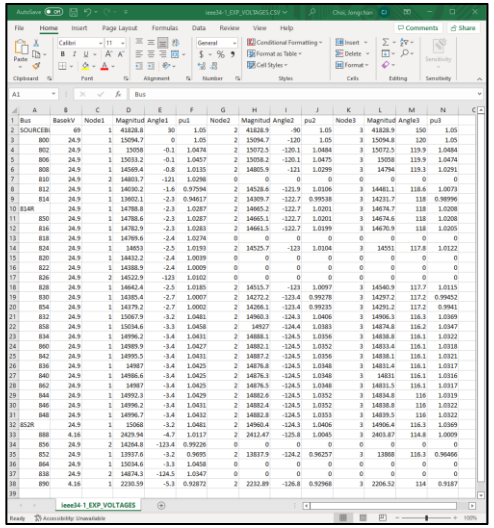


Selected Feeder*

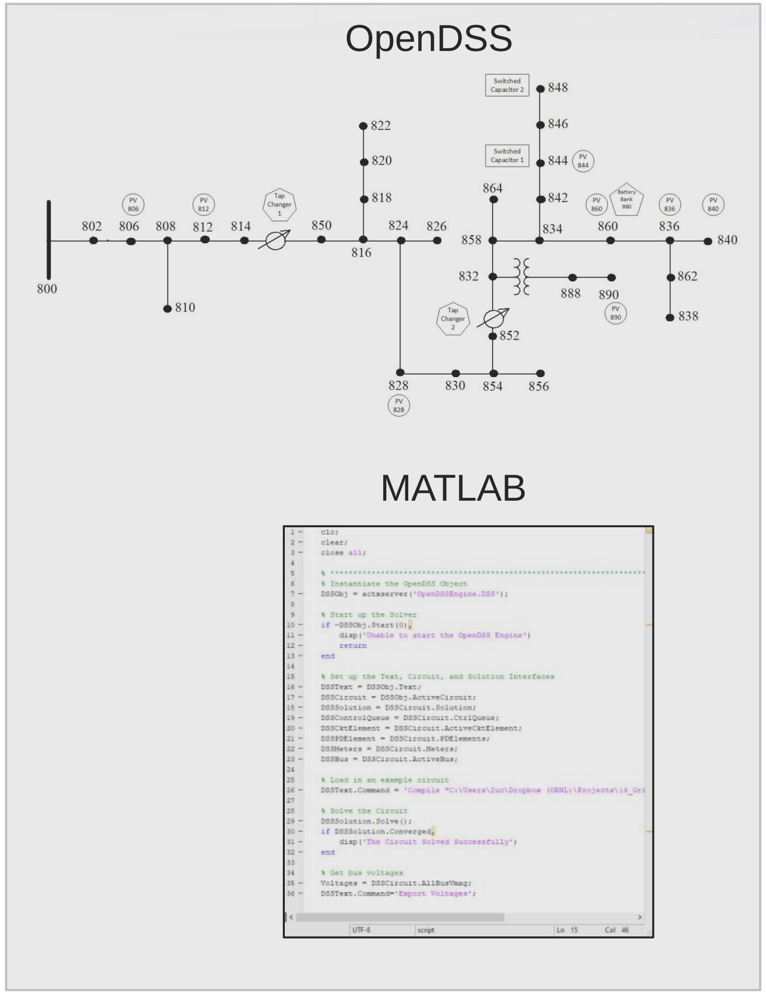


Modified Feeder

- Selected Feeder – IEEE-34 buses:
  - 2.5 MVA – 24.9kV/4.16 kV
  - Radial - Rural - Long (34 miles)
- Modification:
  - 3,950 kVA PVs
  - 250 kW/125 kWh Battery
- Multi-platform modeling and simulation:
  - OpenDSS – feeder model for data generation
  - Matlab – scenarios generation and optimization algorithm (Genetic Algorithm)



Results Sample

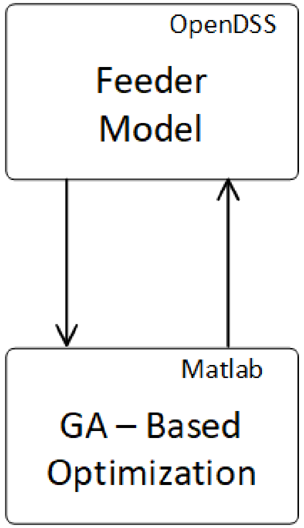


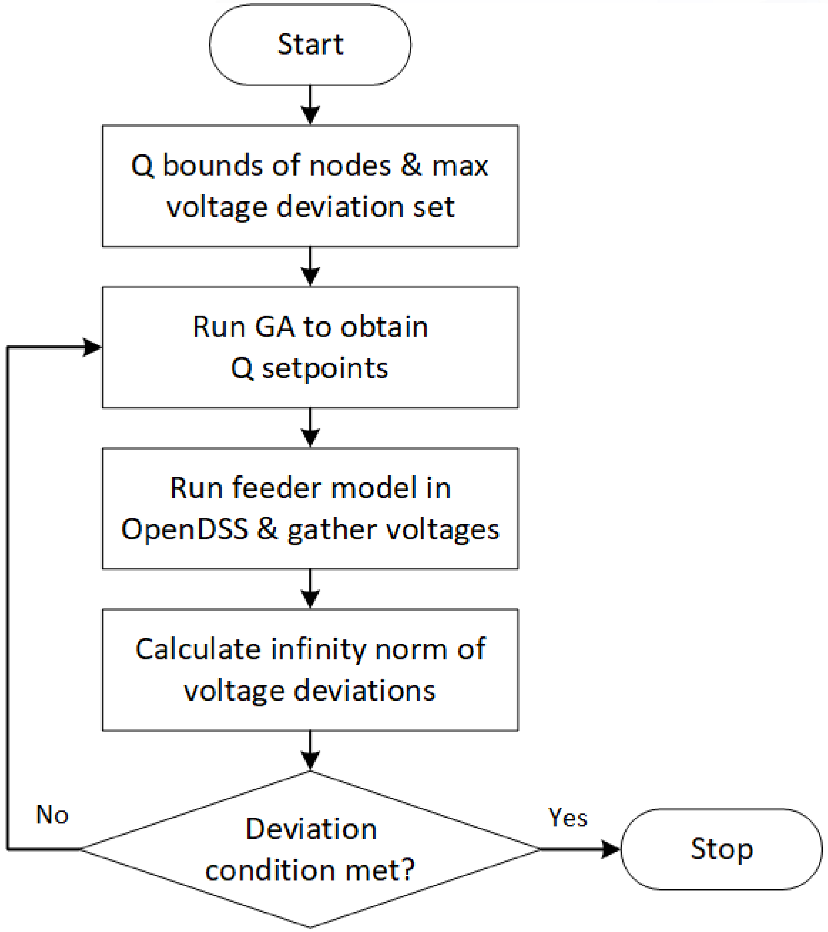
Co-simulation Model

* https://cmte.ieee.org/pes-testfeeders/resources/
** Dharmawardena, H. et all,, 2018

Technical Accomplishment 2: Training Data Generation

- Five sets of data gathered to train an artificial neural network (ANN) Monte Carlo Simulation method: loads and DER variation (0 – 200%)
- GA as the optimization technique to find the Nodes setpoints
- For each load and DER sample, the near optimum reactive power reference was generated aiming at voltage regulation (maximum 5% deviation) throughout the feeder
- Infinite norm (voltage deviation) was used as the fitness function



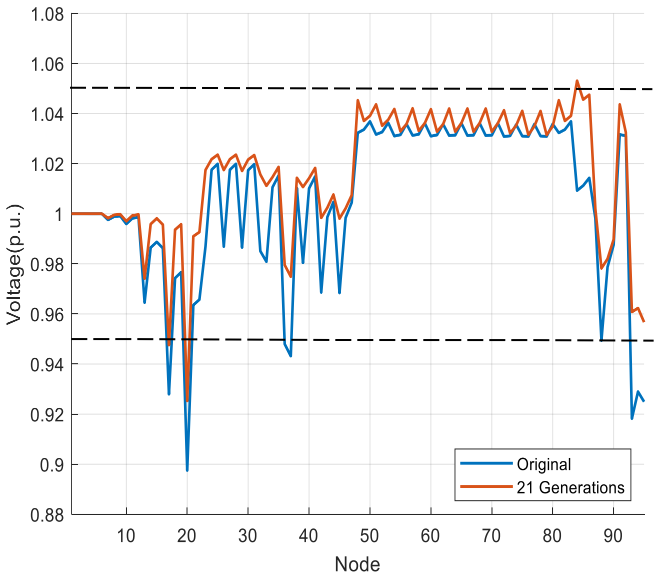


Technical Accomplishments 2 (cont.): Training Data Generation

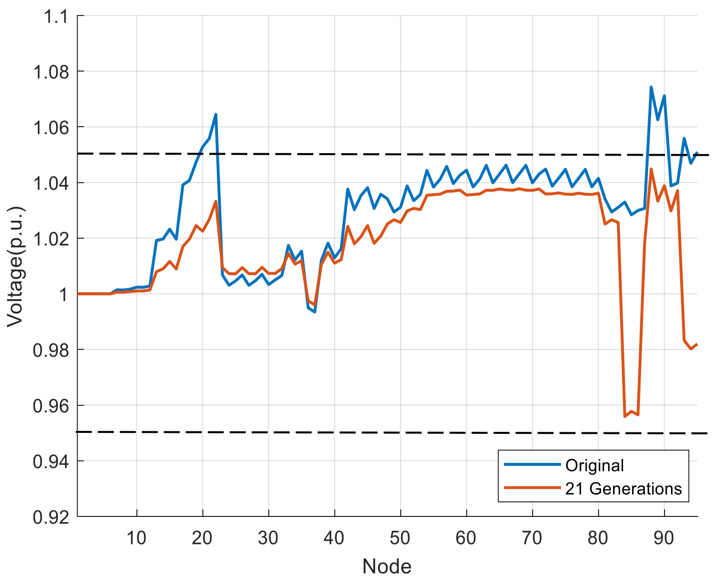
Comparison of compensated and uncompensated voltages

- The number of voltage violations are smaller with reactive power reference set by GA
- Number of violations comparison of compensate vs uncompensated:
  - Scenario 1: 2 vs 7
  - Scenario 2: 0 vs 8

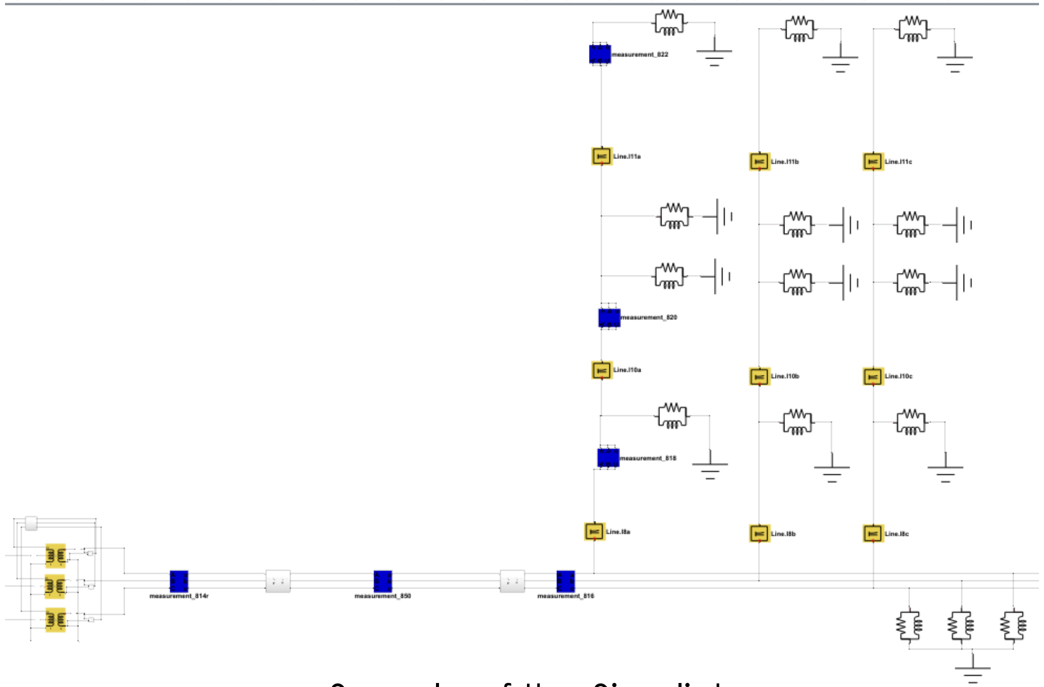
Scenario # 1
50% Overload + 50% PV



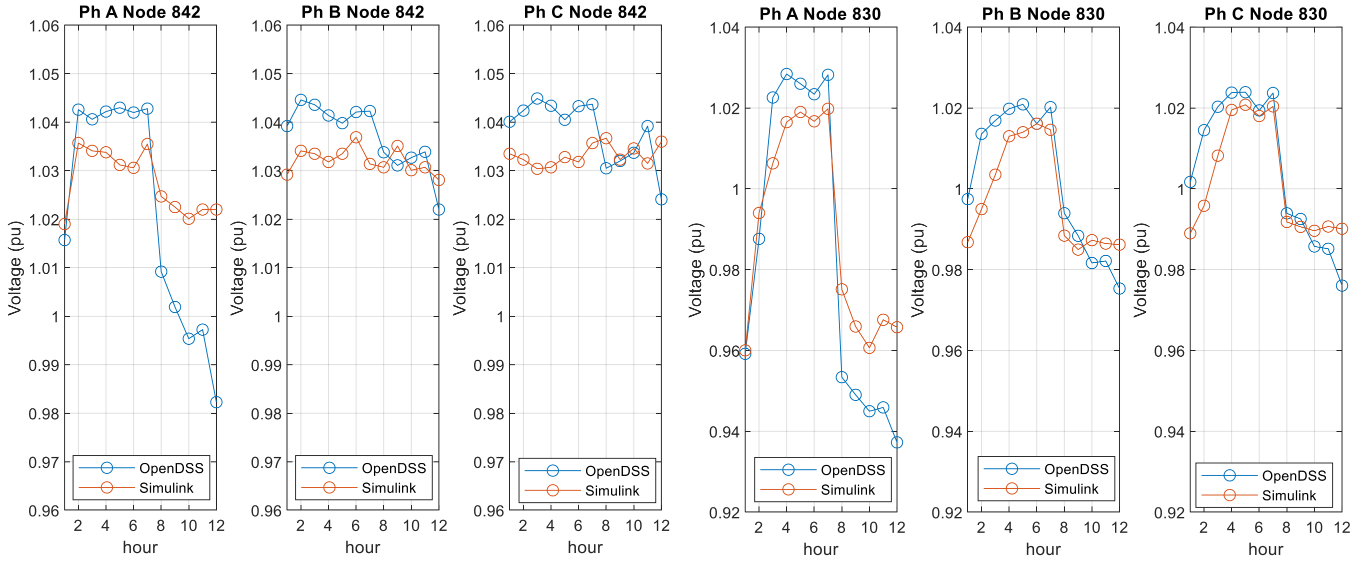
Scenario # 2
50% Load + 150% PV



Technical Accomplishments 3: Feeder Modeling in SIMULINK for Software Demonstration



Sample of the Simulink Model

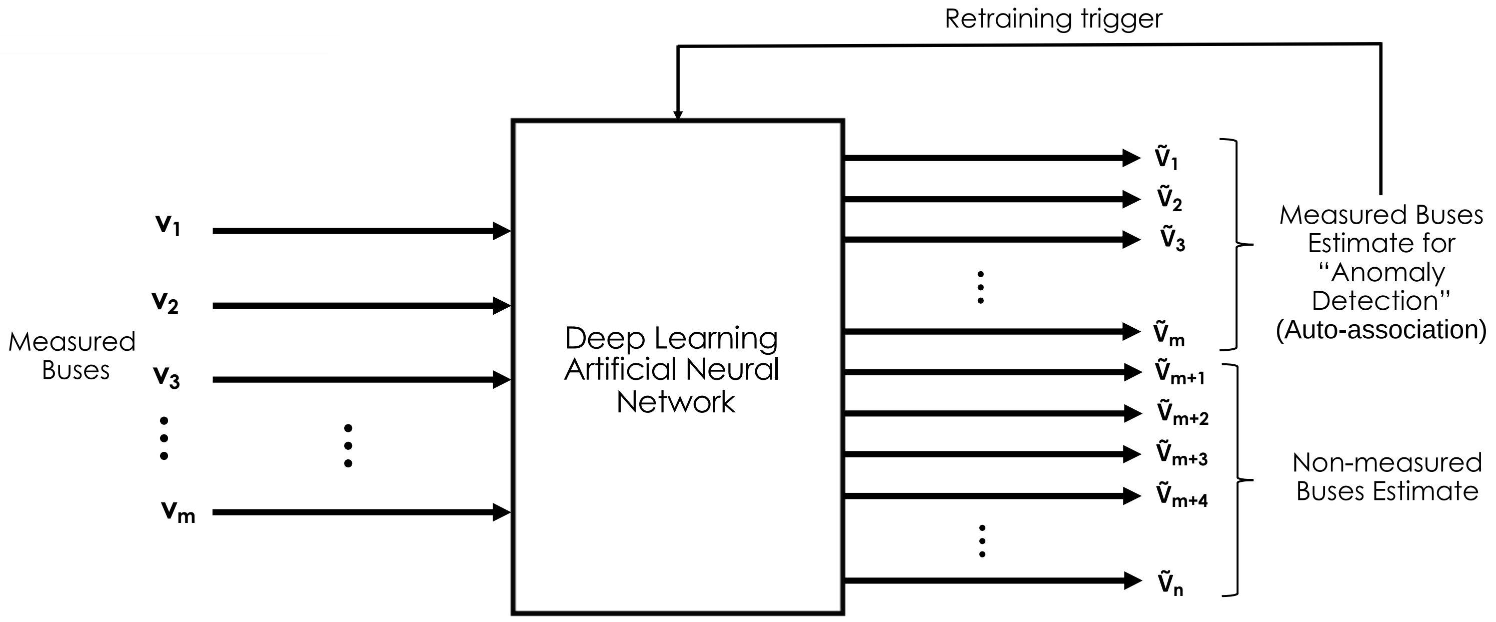


Simulink vs OpenDSS Results Comparison two random three-phase nodes

- The Simulink model is necessary for demonstration to evaluate the SSPS Controller dynamically
- The deviation between Simulink model results in comparison to OpenDSS model is because the models used for Simulink was more accurate
- The deviation from one to the Other was less than 4%.

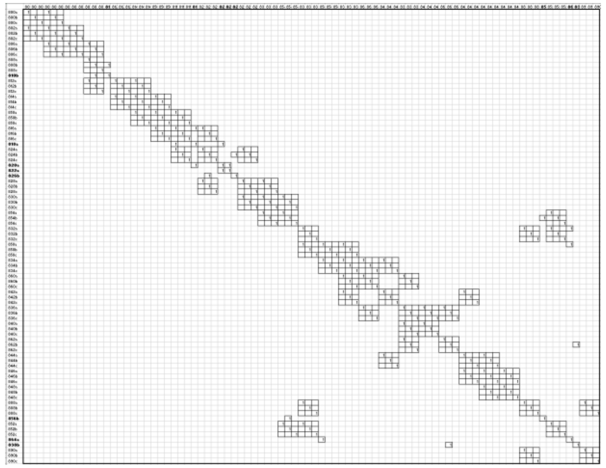
Technical Approach: Data-Driven State Estimator Architecture

- The neural network inputs are the measured variables, while the outputs are two sets: measured and non-measured variables
- The estimates of measured outputs re used to detect anomaly originally to identify feeder changes, and trigger the ANN retraining, but it may be used for other purposes, such as cybersecurity.
- The non-measured estimates are to access the voltages on buses without sensors

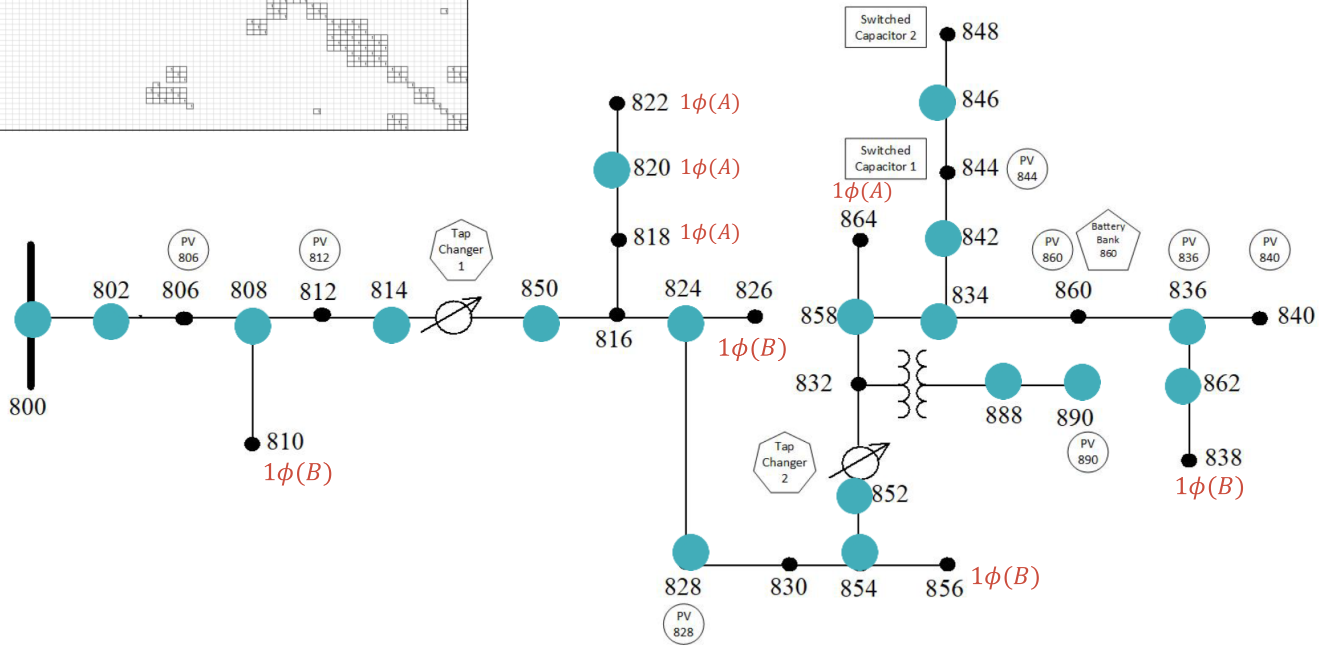


Technical Accomplishments – 5: Network Observability Analysis for Minimum Measurements

- Objective for minimum measurements
  - $\min \sum_{i=1}^{86} w_i * x_i$
  - $x_i = \begin{cases} 1, if\ a\ meter\ is\ installed\ at\ bus\ i \\ 0, otherwise \end{cases}$
  - s.t. $f(x_i) \geq 1$
  - e.g., $f_1 = x_1 + x_2 \geq 1$ for 800-802 phase A.
- Results
  - 30 nodes (highlighted in blue) out of 86 nodes are the nodes to have sensors



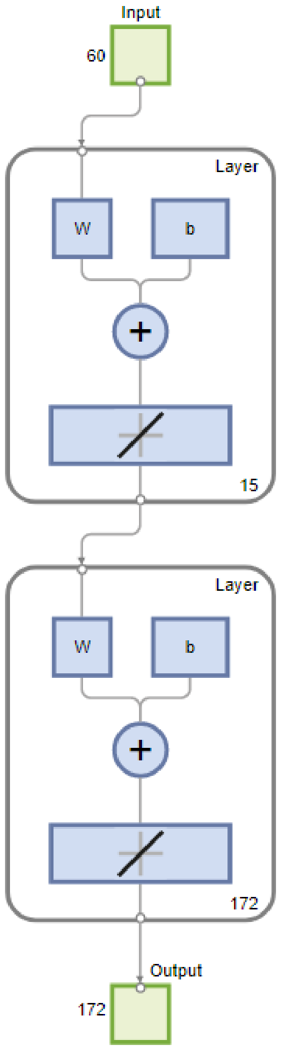
Observability matrix by the constraints*



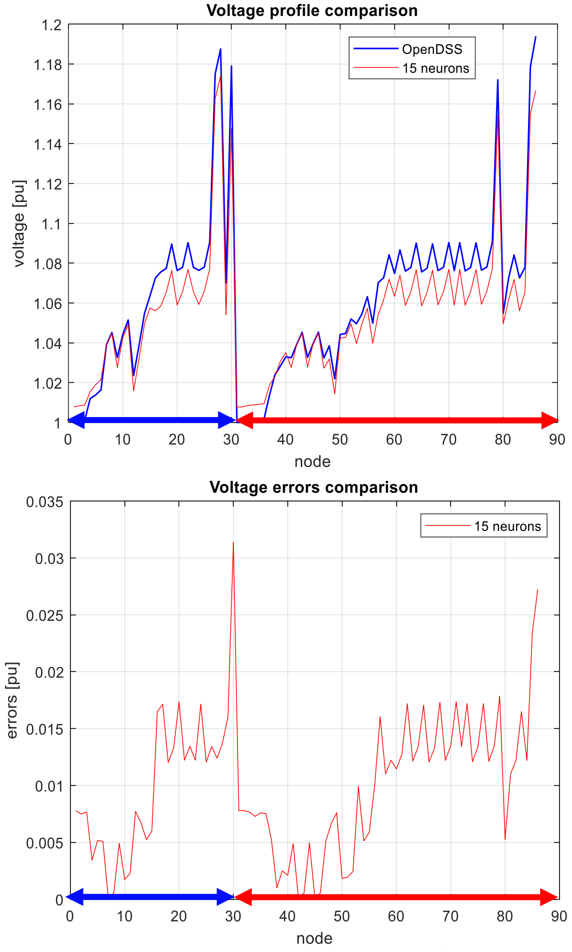
* Xu et all, "*Observability Analysis and Measurement Placement for Systems with PMUs*", 2004

Technical Accomplishments – 6: Data preprocessing (normalization), ANN Design and Training

- ANN architecture
  - Inputs layer – 60 neurons
    - V and Angles from 30 nodes
  - Outputs layer - 172 neurons
    - V and Angles for all 86 nodes.
    - Linear function
  - Hyden Layer – 15 neurons
    - sigmoid function
- Performance
  - The error between estimated and measured (simulated) was below 3%



ANN architecture



Measured bus estimates

Non-measured bus estimates

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Timeline

Milestone	Planned End Date	% of Execution
Modeling of the modified feeder, and Load, DER penetration, and fault scenarios development	3 months	100
Database generation through simulation of the feeder with the scenarios	6 months	100
DSS with advanced algorithms development for SSPS Controller coordination of the Hubs and Nodes	9 months	50
Development use cases for demonstration of the DSS in a software platform *	12 months	100
Real-time modeling of the modified feeder, including hubs and nodes, and their inner and outer loop controllers	15 months	30
CHIL Implementation of the hubs	18 months	0
Implementation of the decision support system in a central controller and establishing communication	21 months	0
CHIL demonstration of the decision support system via use cases	24 months	0

Risks:
- ANN trainability: ANN performance may not be satisfactory

Mitigation Strategy:
- Change the approach for on-line training (online GA)

Impact/Commercialization

Publication

- "GA-Based Voltage Optimization of Distribution Feeder with High-Penetration of DERs Using Megawatt-scale Units", Aswad Adib, João Onofre Pereira Pinto, Madhu Sudhan Chinthavali, Energies – accepted for publication

Future Work

- Train the ANN
- Develop and include state estimator
- Include reconfiguration features for resilience
- Demonstration of algorithm in a software platform
- Demonstration of algorithm in CHIL

THANK YOU!

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Backup Slides

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Acronyms

PE – Power Electronics

SSPS – Solid State Power Substation

ANN – Artificial Neural Network

GA – Genetic Algorithm

CB – Circuit Breaker

OLTC - On Load Tap Changers

P – Active Power

Q – Reactive Power

PV – Photovoltaic plant

ES – Energy Storage