SSPS Hardware in the Loop (HIL) Validation

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Context of the Problem Being Addressed

Challenges:

New grid architectures required with grid modernization efforts

- ✓ Traditional architectures with centralized control do not support complex control of DER

Computationally complex optimization with increased penetration of DERs

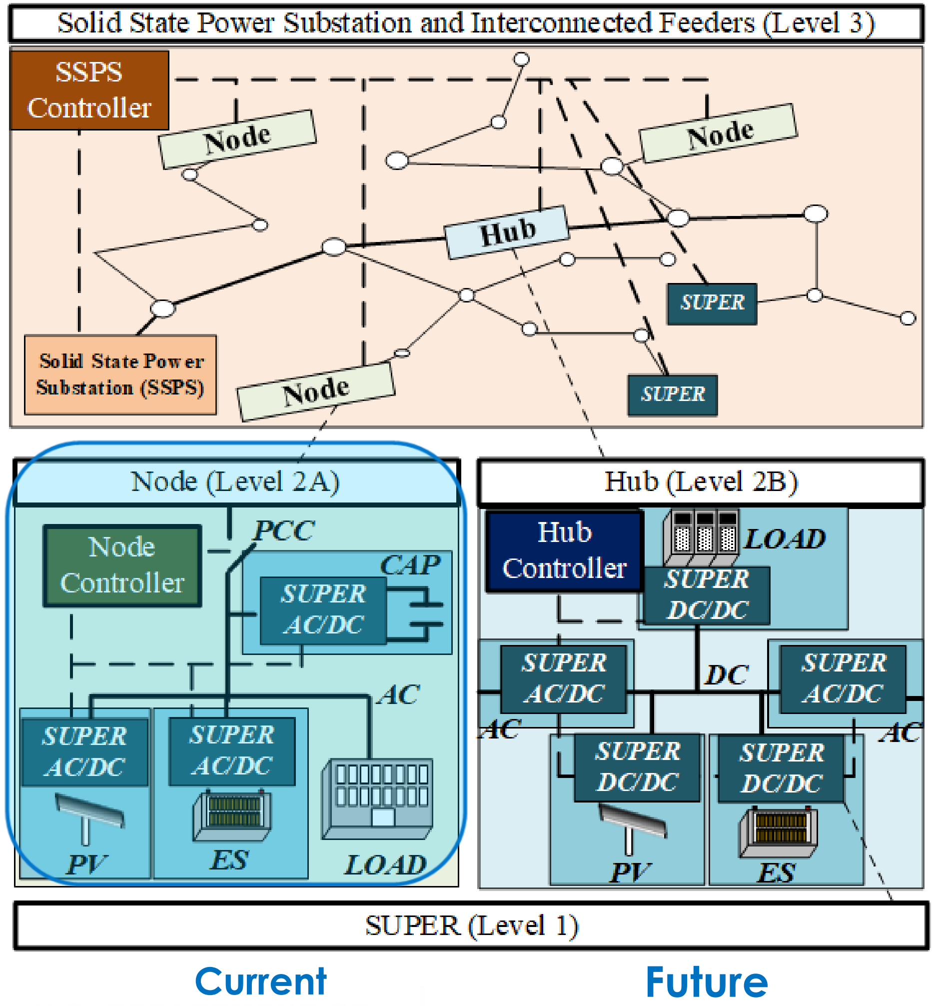
- ✓ Today's distribution management system responsible for coordination of devices cannot solve the complex optimization problem.

Solid state devices needed in lieu of legacy devices to enhance grid services

Critical Needs:

Hierarchal solutions of systems to sub-divide the optimization problem into different layers

Integration and validation of hierarchical layers in real-time environment to validate the system level benefits of new grid architectures.



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Problem Being Addressed - Real-Time Systems Integration

Overall Objectives

Goal – 1

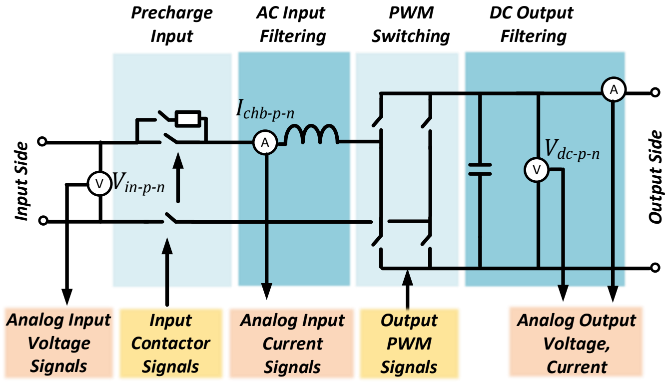
Framework for Coordination in SSPS

The Numbers

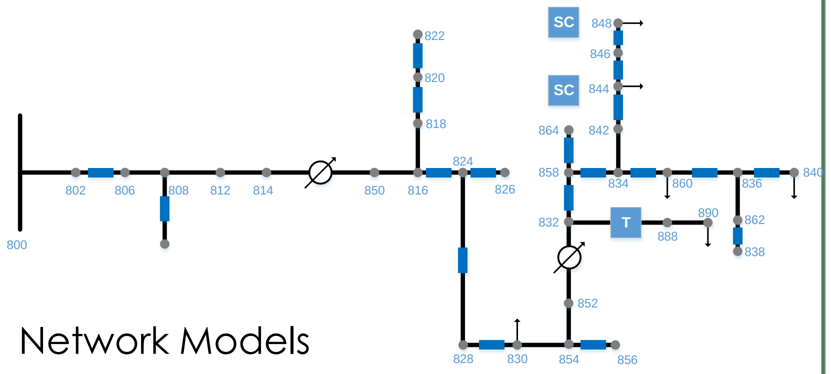
- DOE PROGRAM OFFICE:
  OE – Transformer Resilience and Advanced Components (TRAC)
- FUNDING OPPORTUNITY:
  Annual Operating Plan (AOP)
- LOCATION:
  Knoxville, TN
- PROJECT TERM:
  09/01/2021 to 08/30/2023
- PROJECT STATUS:
  Ongoing
- AWARD AMOUNT (DOE CONTRIBUTION):
  $500,000
- AWARDEE CONTRIBUTION (COST SHARE):
  $0
- PARTNERS:
  None

Technical Approach

Base Use Case: Operation of feeder with legacy voltage regulation systems without any coordination

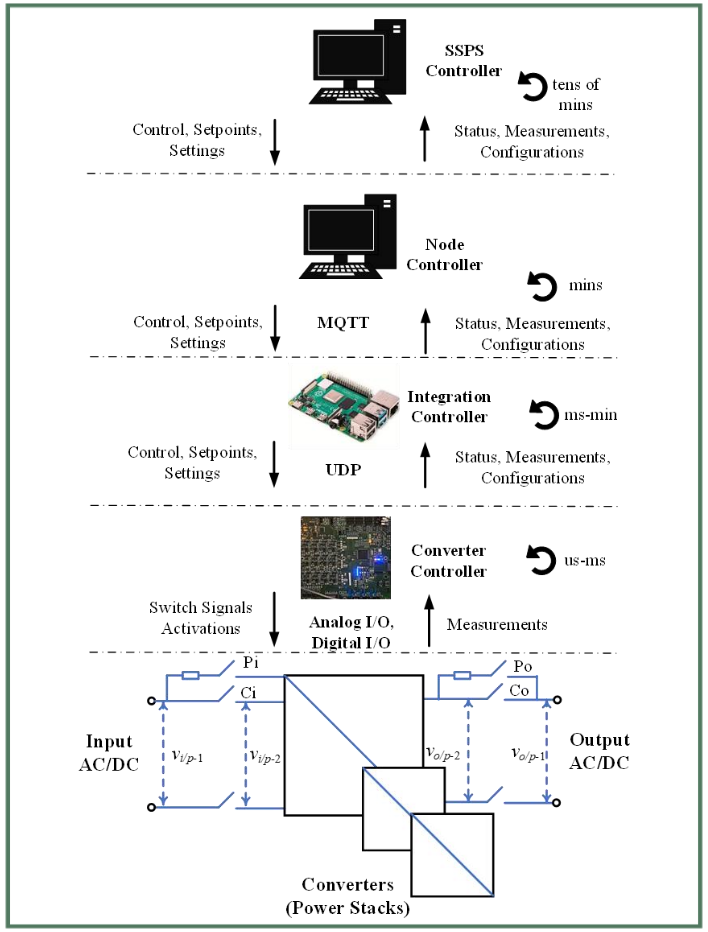


PE Models



Network Models

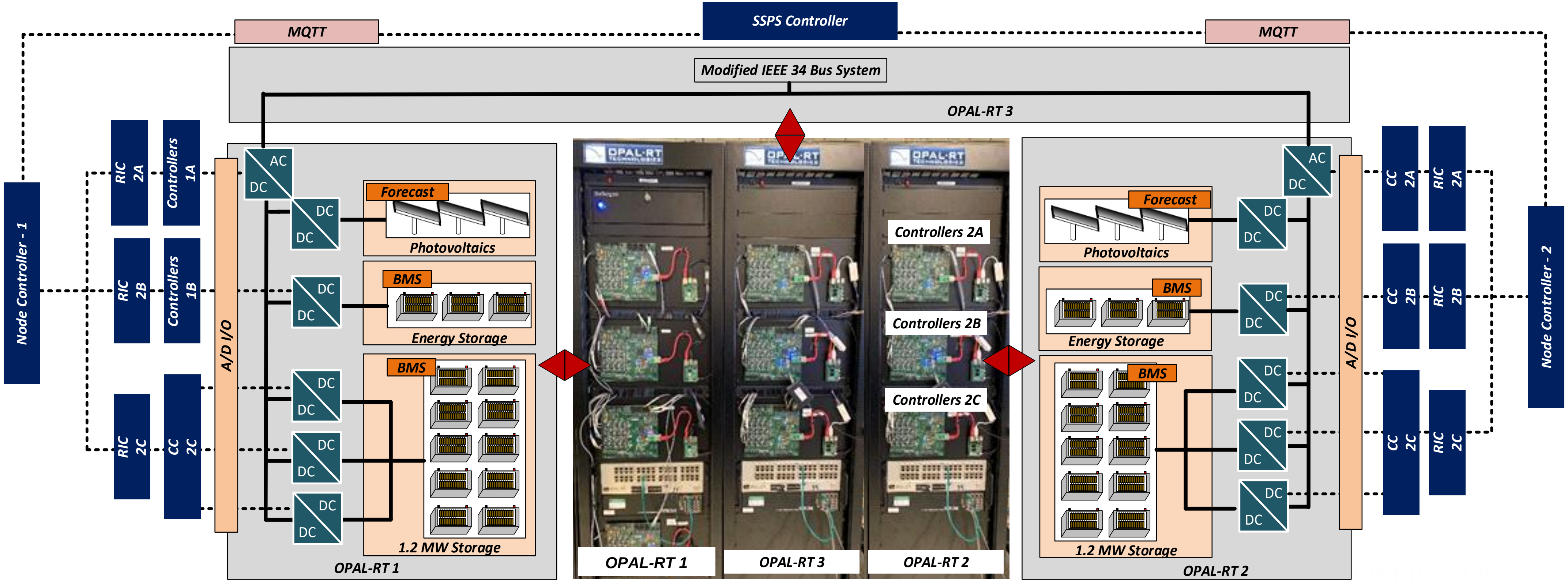
Real-time modeling



Hierarchical Layers Integration in **real-time platforms**

Major Accomplishment – Testbed for DER Integration Studies in Distribution Grid

- Model of balanced IEEE 34 bus system, 100+ converter models (2 MV grid interfaces), 6 DSPs for converter controls, 6 Raspberry Pi's for resource integration controls, 2 DELL OptiPlex as node controller, 1 DELL OptiPlex as SSPS controller & 3 OPAL-RT simulators for distribution system modelling with SSPS nodes running with advanced solvers.



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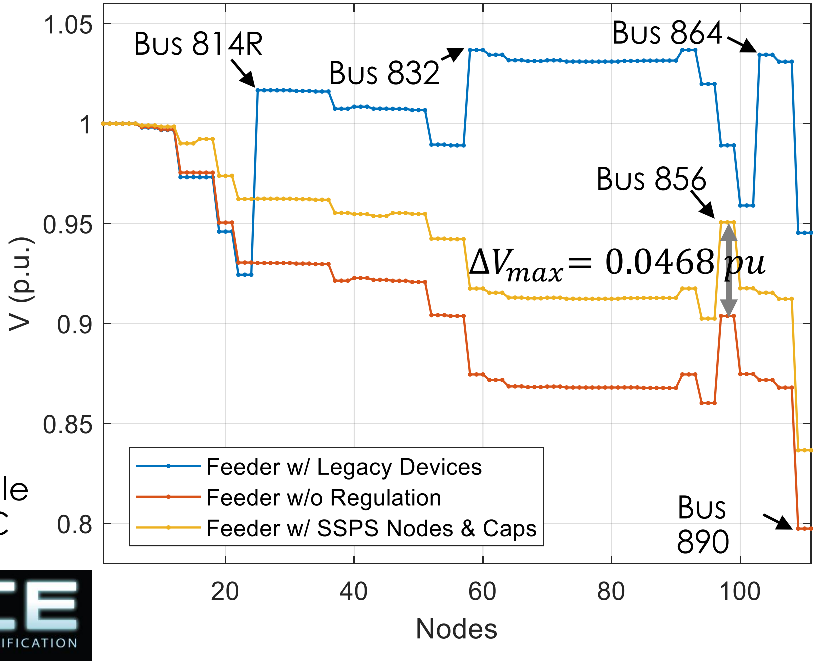
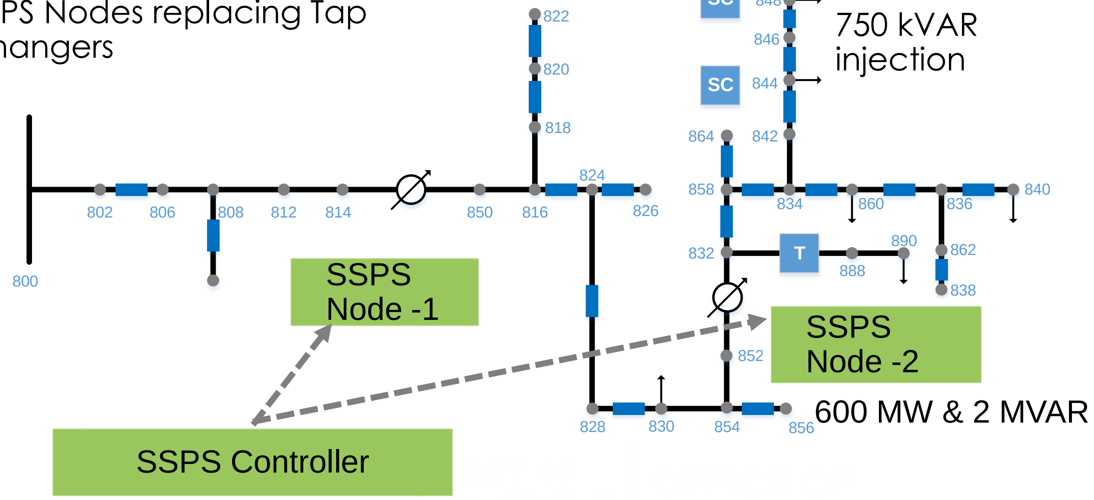
#1 – Identification/Validation of an Example Distribution Network in Open DSS & Node Placements

Objective: Standardized & simplified network model for initial validations

- **Feeder selection criteria:** small to medium sized feeder (complexity) with capability to emulate the need for grid functions (voltage regulation, phase balancing, power factor correction and harmonic filtering).
- An unbalanced feeder was converted to a balanced system to setup a simplified base case to understand coordination
- The feeder was balanced by balancing the distributed loads, modifying the line impedances to be balanced and transforming the 1-ph laterals to 3-ph
- For initial validation, the SSPS nodes, were placed in the buses instead of tap changers to improve the voltage profile along the feeder



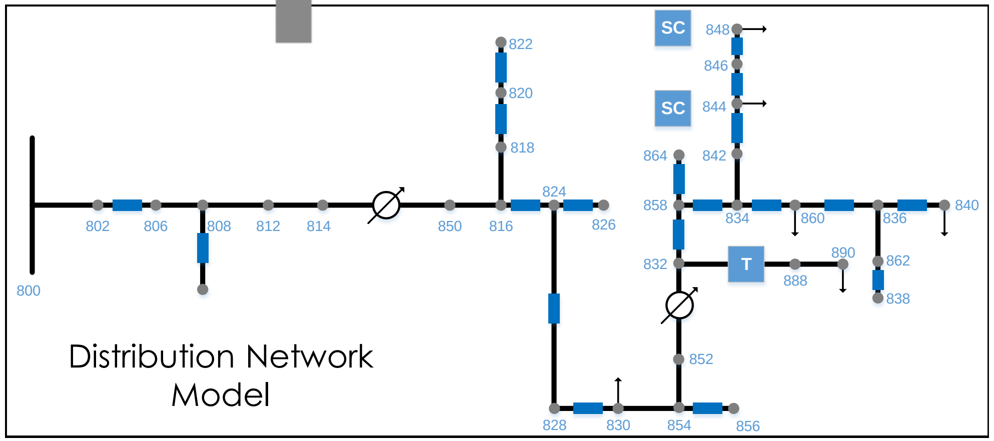
37 buses * 3-ph nodes = 111 single phase POC/PCC

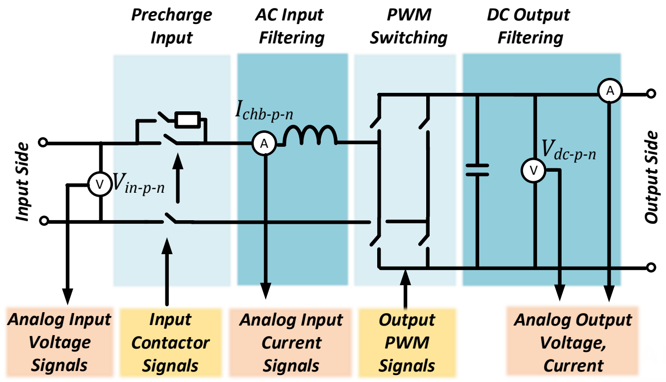


#2 – Framework for SSPS 1.0 Modeling in Real-Time

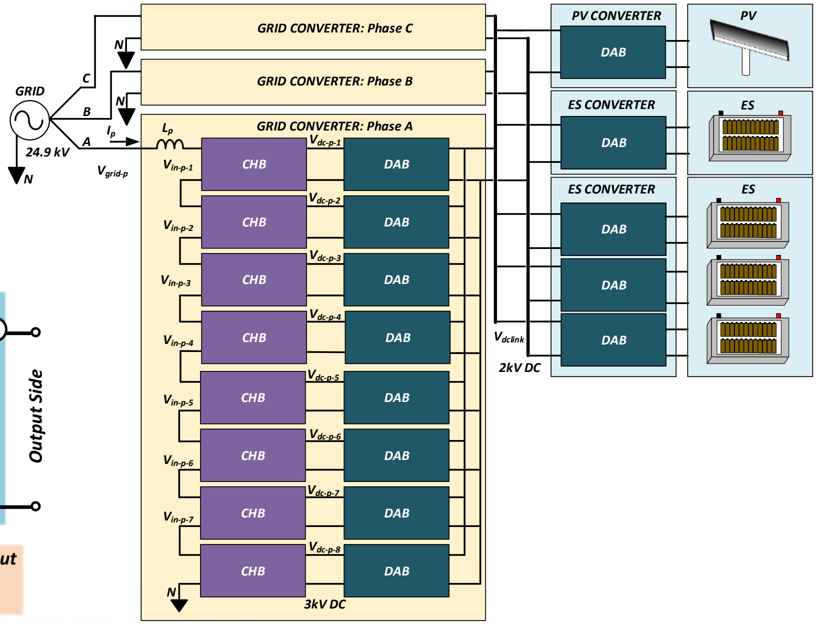
Barrier – 1a & 4: Integration of multiple real-time computational platforms & Scaling

- Owing to analog/digital connection constraints, each MV node was established in a simulator.
- To simulate a distribution network with multiple nodes, multiple simulators were connected through high speed PCIe links and synchronized with an internal clock.





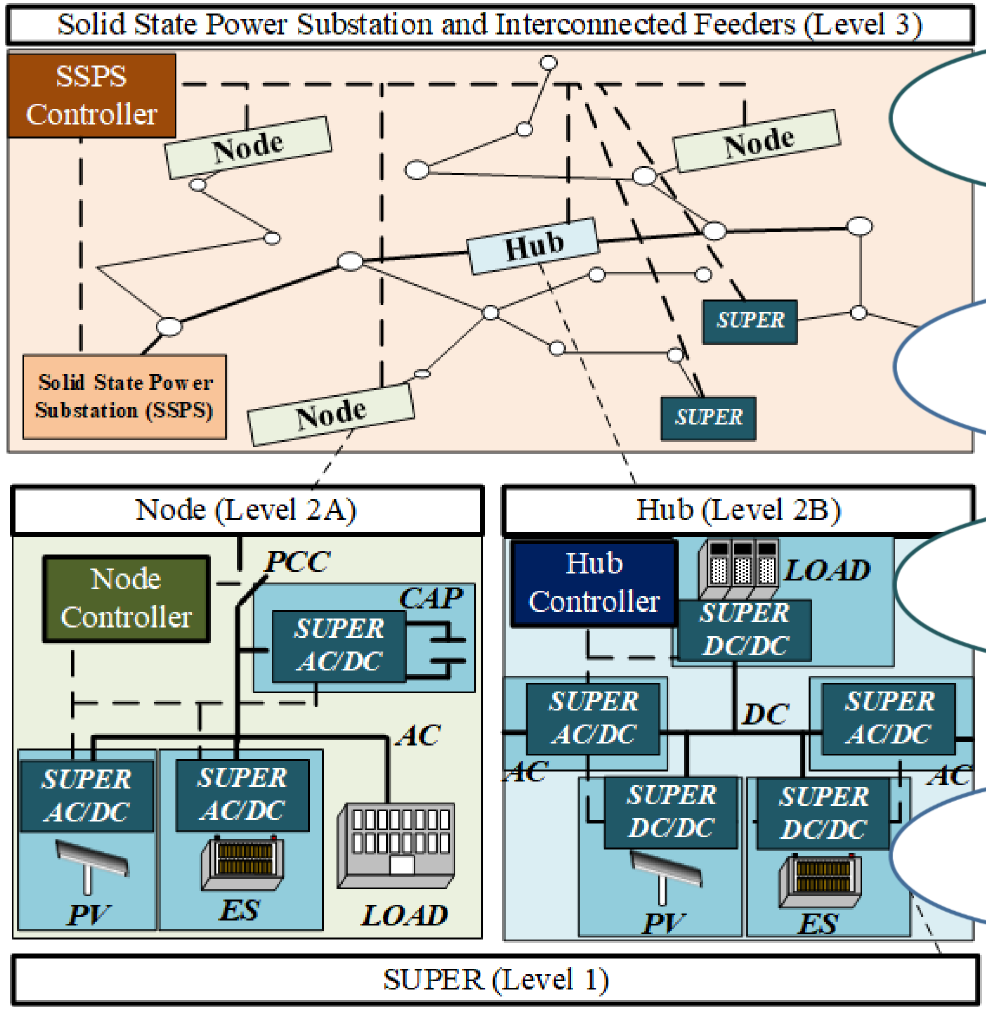
MV SSPS 1.0 Nodes



#3 – Integration of Distribution Network & PE Models

Barrier – 3: Identification of solvers/simulation tools required

- Verified that the Advanced Real-Time Electromagnetic Simulation (ARTEMiS) solver can be used for modeling the distribution network with the power electronic interfaces
- Used the State Space Nodal (SSN) approach to solve distribution networks while meeting real-time constraints with smaller time steps
- Identified the compatibility issues with SSN solver & PE interfaces.
- The PE interfaces were modeled using average representations whilst including circuitry for emulating precharge methodologies.



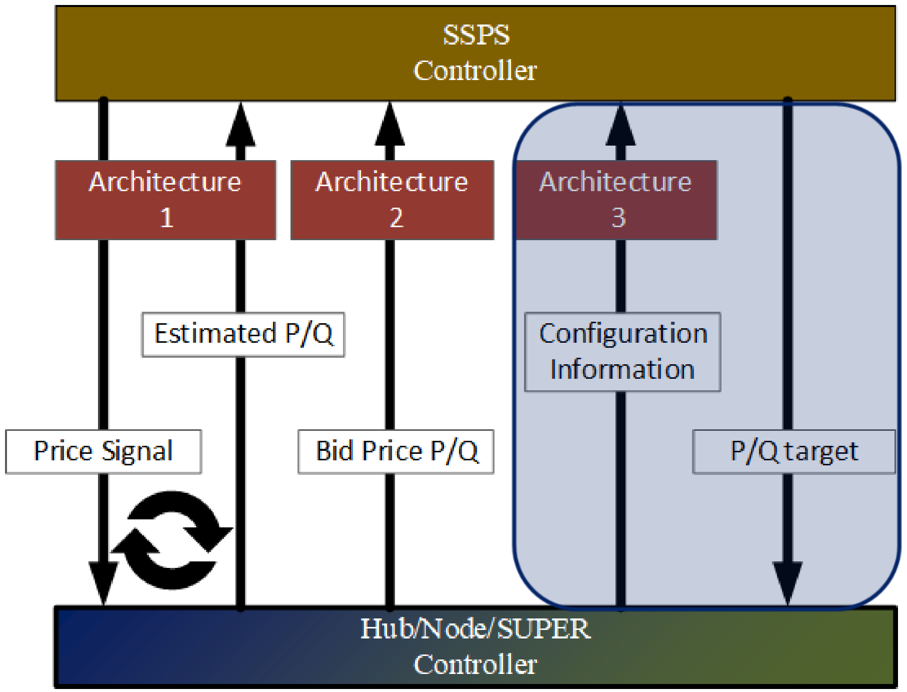
Solver: ARTEMiS with SSN

Model: π line models

Solver: ARTEMiS without SSN

Model: Average models

#4 - SSPS Framework & Implementation Strategy



Architecture for Communication & Integration

Approach– 1: Mixed Integer Linear Programing (MILP) ☑

- Optimization formulation considering economics i.e., cost of P & Q
- Full visibility
- Considers reserves, downstream nodes/hubs architecture, available control modes etc.
- Model requirements: Balanced IEEE 34 bus system + 3-ph LV nodes
- Software requirements: Balanced 3-ph optimization in SSPS controller
- Resource integration not considered

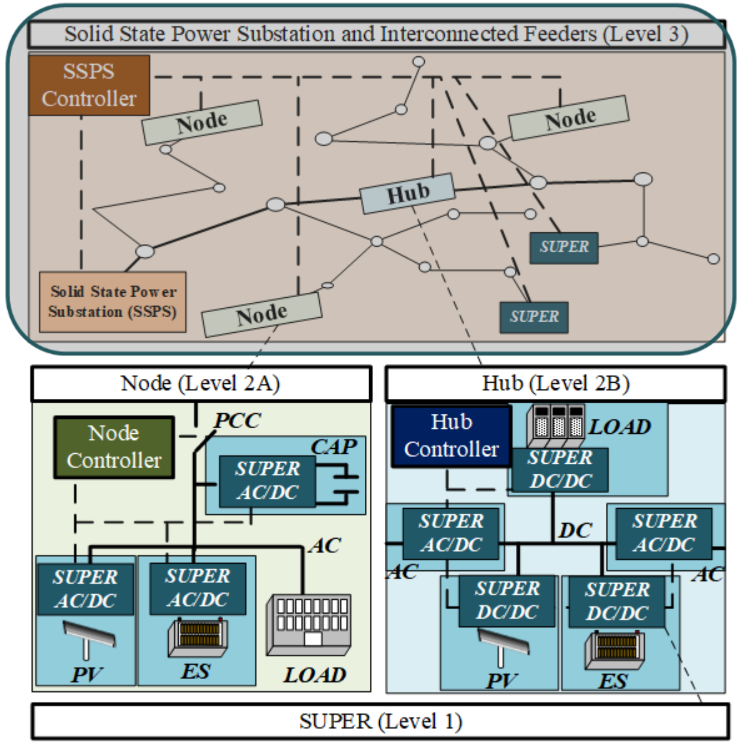
Approach – 2: Advanced Algorithm – Based Techniques

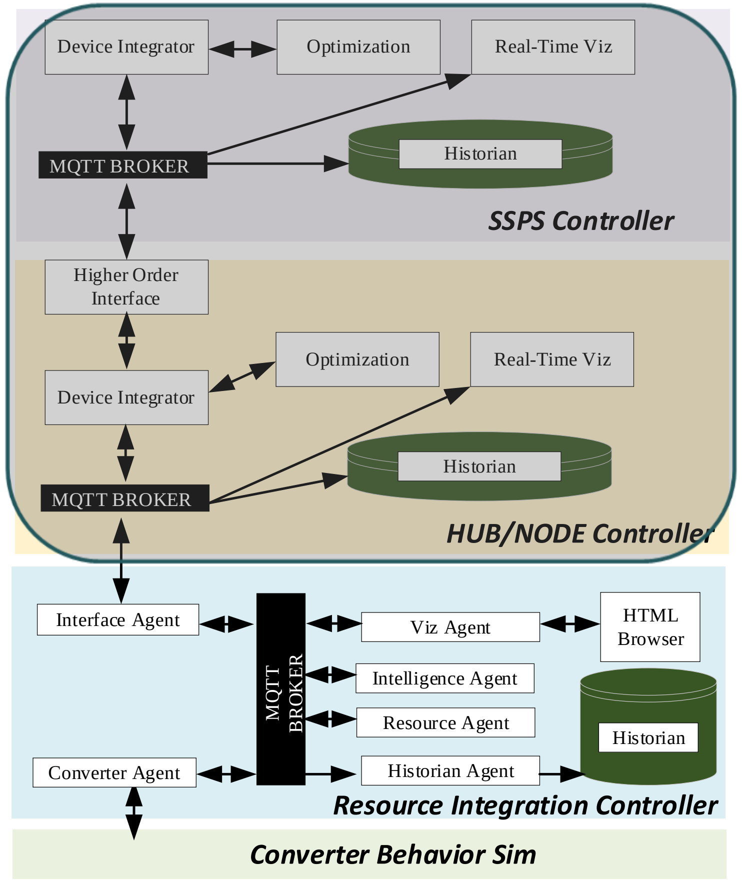
- Hybrid Technique: AI / machine learning
- Full visibility
- Problem formulation based on feeder losses, placement of nodes/hubs
- Model requirements: Unbalanced IEEE 34 bus system + 3-ph LV nodes (balanced & unbalanced)
- Software requirements: Unbalanced 3-ph optimization algorithm in SSPS controller
- Resource integration to be included
- Unbalanced control framework to be incorporated in the agent

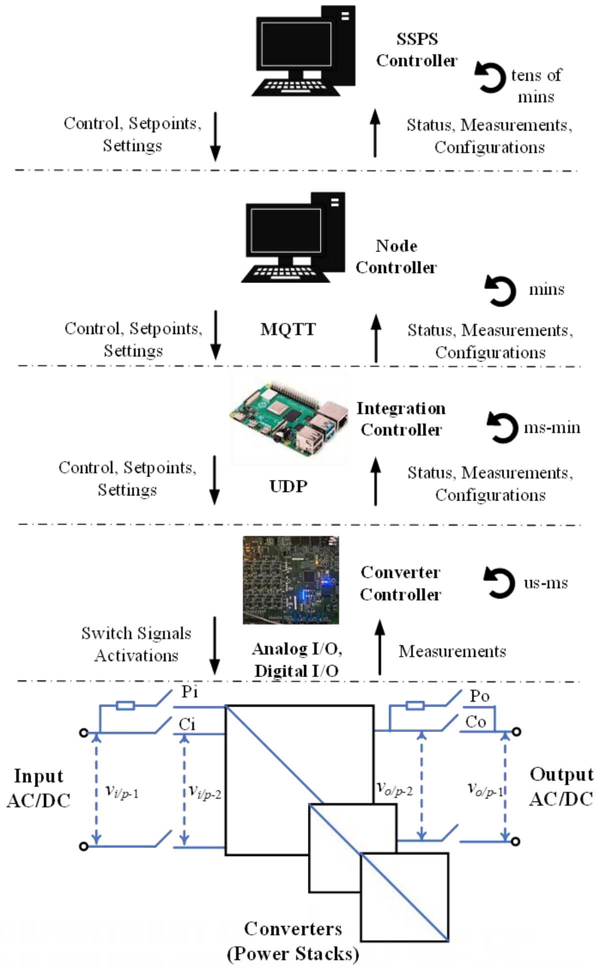
#5 – Software Architecture for SSPS 1.0 - CODAS

Barrier – 1b: Integration of multiple different computational platforms with real-time simulators

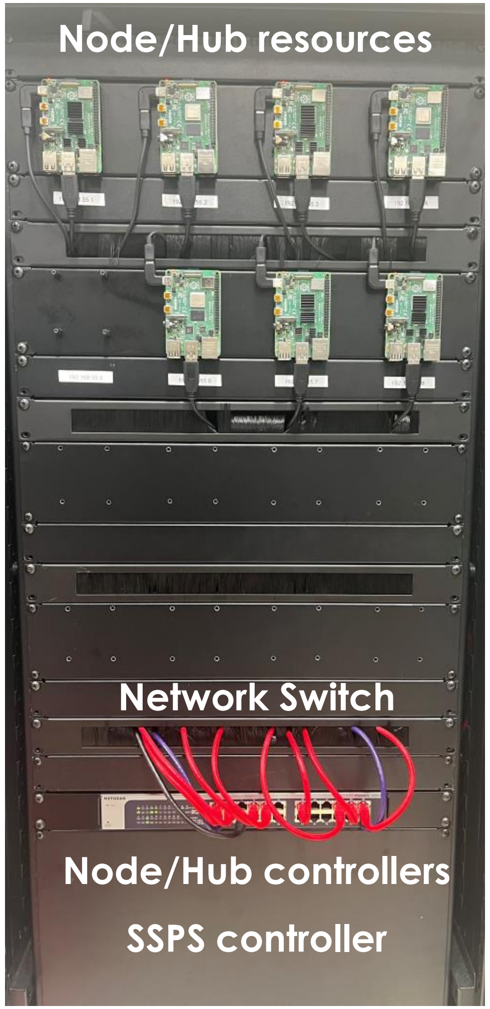
- Multiple computational/embedded are vital to integrate the various PE interfaces, assets, aggregators etc.
- Framework like CODAS are crucial to ease integration.



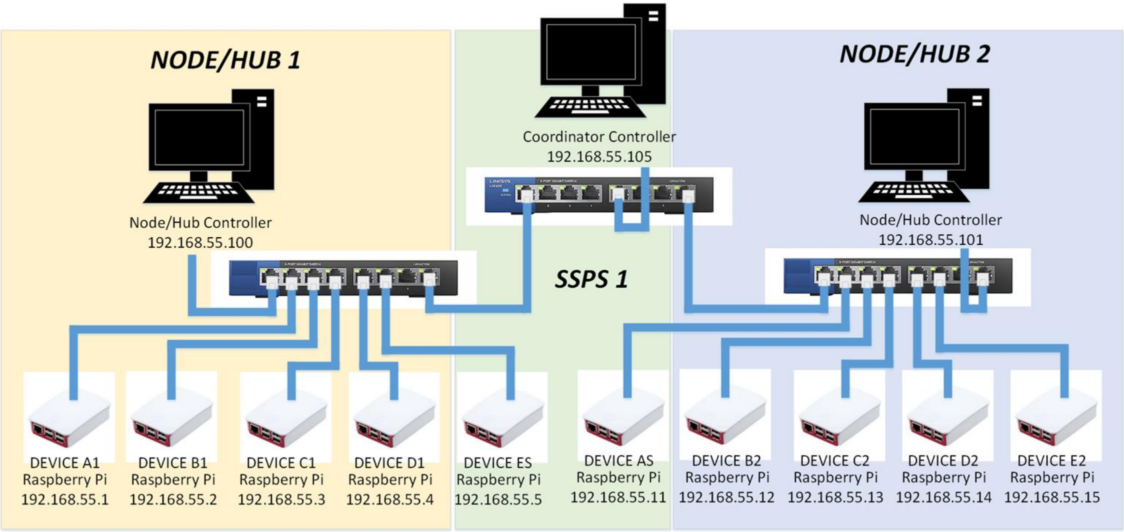


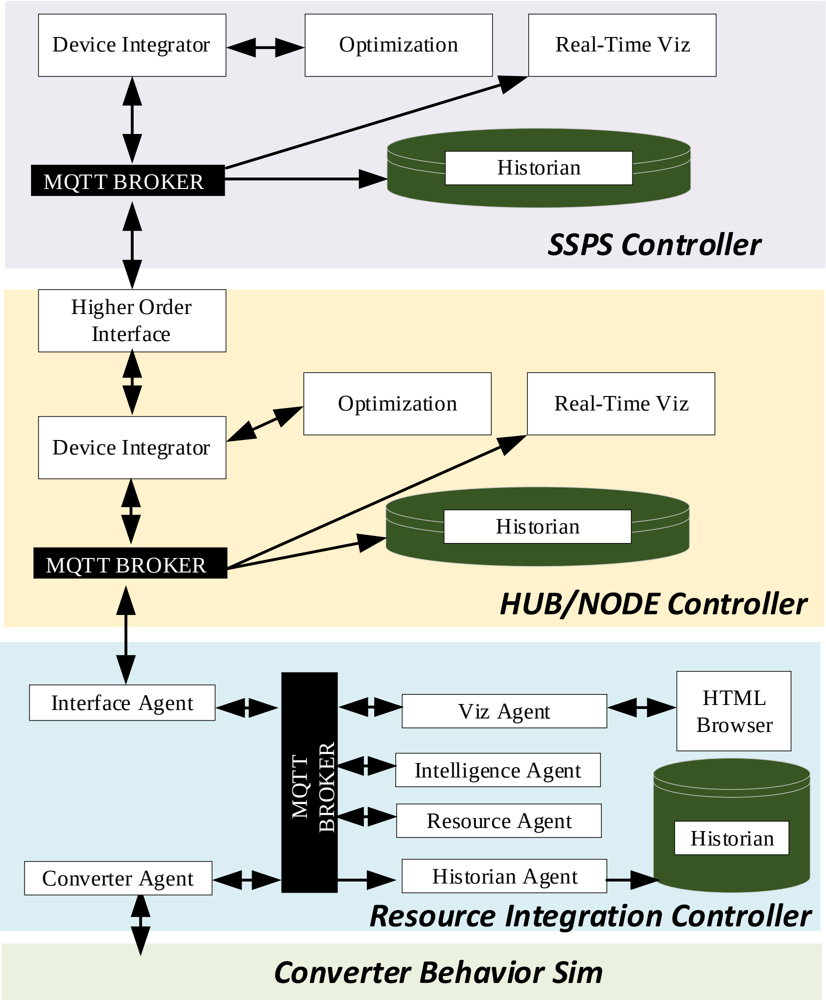


#6 – Communication Validation for SSPS



- Communication testbed developed for early-stage development and testing of higher order frameworks (SSPS <-> Node/Hub <-> Resource Integration)
- Focus on integration of new SSPS controller and plug-and-play adaptability

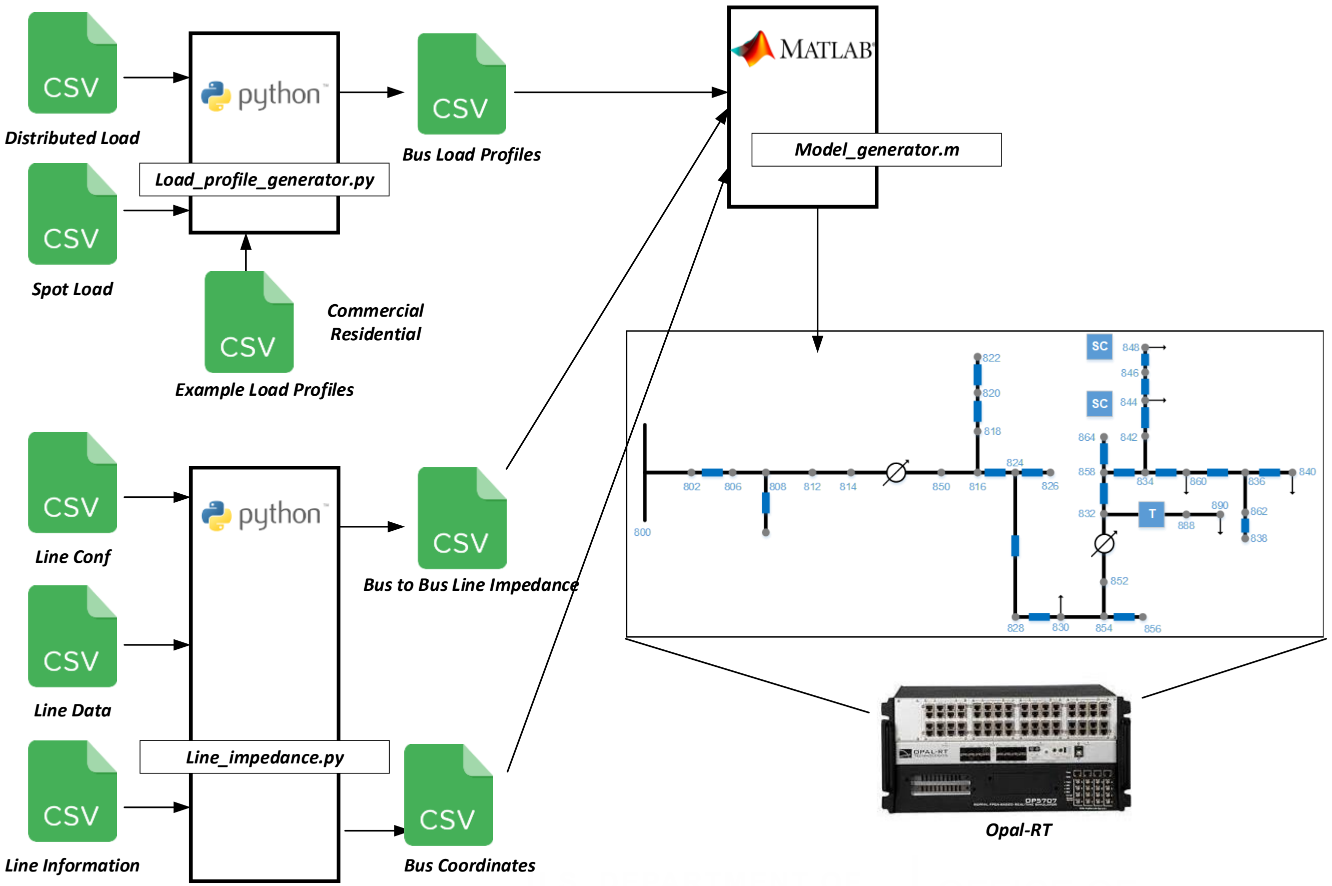




#7 – Framework for automation of feeder modeling & load/generation profile

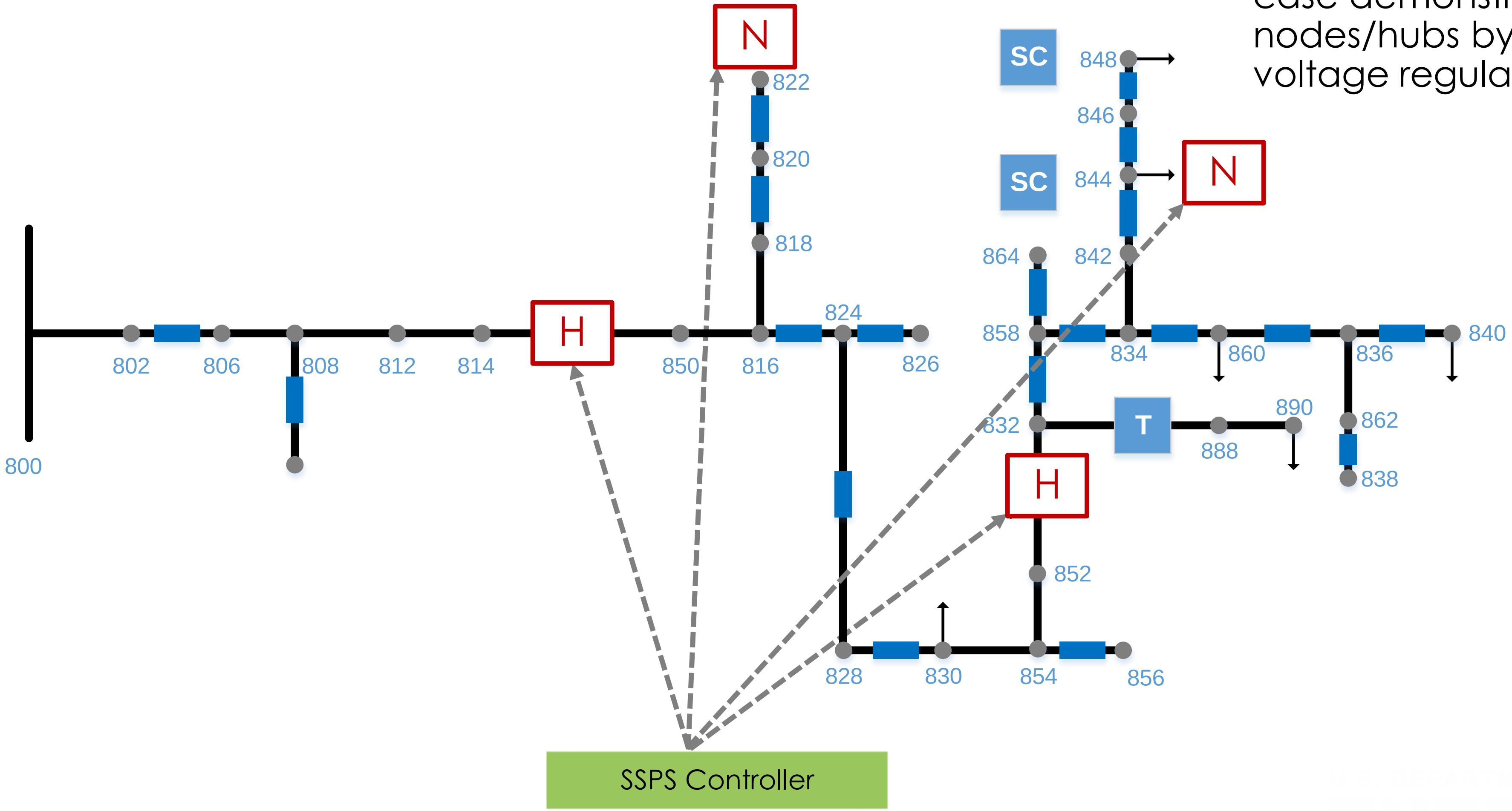
Barrier – 4: Automation & Scenario Management for long duration runs

- Long duration runs are crucial to validate the effective coordination of nodes in a distribution network
- Integration for load and generation profiles of the assets in the distribution network is key for utility-based use cases like voltage regulation
- **Scenario Management:** Framework for incorporating time varying load and source profiles which can be altered during the simulation was formulated.
- **Automation:** The distribution network model was automated – to easily incorporate any network model in the proposed RT framework.



Final Outcome – Futuristic Grid Architecture for Distribution Networks

Deliverable: CHIL framework for SSPS & Use case demonstrating the coordination of nodes/hubs by the SSPS controller for feeder voltage regulation



Timeline: Milestone Update

Milestone Description (or Go/No-Go Decision Criteria)	Due	Status	Accomplishments/Notes
1.1. Identification of the reference feeder model to validate the framework & architecture	Nov 2021	Completed	❑ IEEE 34 bus test system has been chosen for the study
1.2. Development of optimization formulation for the feeder	Feb 2022	Completed	❑ 3-ph optimization development for SSPS controller is in progress
1.3. Development and validation of hub and node models in RT	May 2022	Completed	❑ Node models have been validated in real-time
1.4. Development of futuristic grid architecture	Aug 2022	Completed	❑ Futuristic grid architecture with SSPS nodes, hubs etc. has been mapped out
2.1. Development and validation of node & hub controllers	Nov 2022	Completed	❑ Node models have been validated in controller hardware in loop (CHIL) platform
2.2. Development and validation of the SSPS controller	Feb 2023	Completed	❑ Development of SSPS controller (Balanced Optimization with load flow) ❑ Communication between nodes and SSPS established.
2.3. Integration of SSPS controller with the nodes & hubs in RT platform	May 2023	Completed	❑ Baseline testbed for validation has been established
2.4. Demonstrate use case scenarios to validate the futuristic grid architecture	Aug 2023	Not Started	

Timeline: Risks & Mitigation Strategy

Risks:

- Delays in integration of load profiles is anticipated owing to the developmental efforts required

Impact/Commercialization

US Patent:

- M. Chinthavali, M. Strake and R. S. K. Moorthy, “SSPS Controller Architecture: Coordinated Optimization and Control of Multiple Solid-state Power Substations in Electrical Distribution Network”.

Awards & Publications:

- M. Chinthavali, R. S. K. Moorthy, M. Starke and B. Dean, “Solid State Power Substations (SSPS): A Multi-Hierarchical Architecture from Substation to Grid Edge,” PEDG 2022, Kiel, Germany. (Best paper award)

Future Work

- Milestone 2.3: Feeder automation in real-time environment
- Milestone 2.3: Integration of load profiles with the feeder model
- Milestone 2.4: SSPS controller level optimization testing & validation
- Milestone 2.4: Use case validation and testing

ORNL - TEAM

Radha Sree Krishna Moorthy
Real-Time Systems Integration

Aswad Adib
Nodes/Hubs Modeling

Michael Starke
Optimization

Benjamin Dean
Communications & Software Development

Joao Pinto
Feeder Selection

THANK YOU

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