SSPS 1.0 Node Validation with Smart Universal Power Electronics Regulators

Principal Investigator: Radha Sree Krishna Moorthy

Affiliation: Oak Ridge National Laboratory (ORNL)

Team Members: Michael Starke, Benjamin Dean & Steven Campbell

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Context of the Problem Being Addressed

Challenges:

Architectures focused on grid/ancillary services for increased reliability & resiliency

- ✓ Traditional node architectures have laid emphasize mainly on power and energy management
- ✓ Multimode/mode transition operation is crucial for responding to internal & external abnormalities

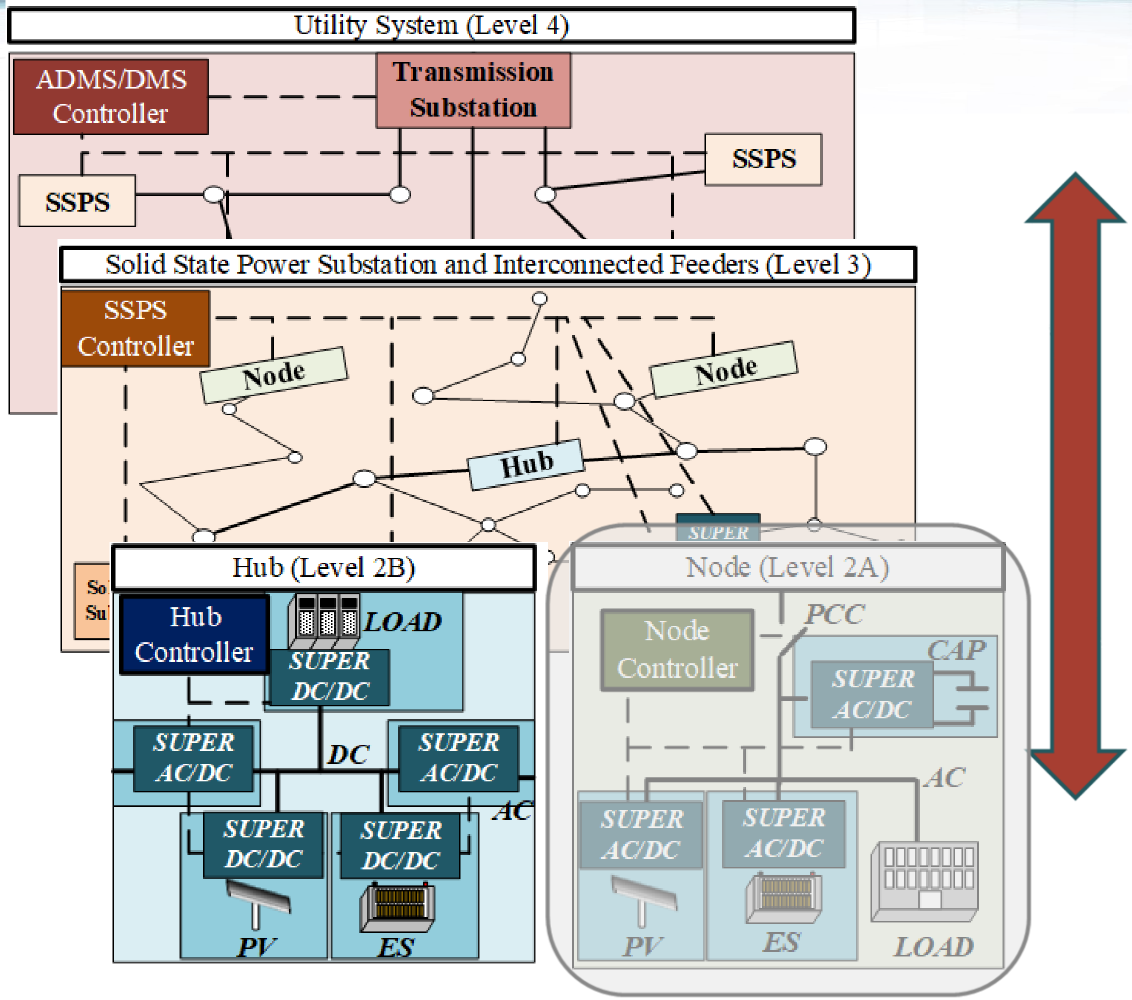
Need for health monitoring & data pipelining framework to reduce Operation & Maintenance (O&M) costs

- ✓ System level framework for health monitoring and resilient operation needs to be emphasized.

Critical Needs:

Architectures & frameworks that support various grid service control modes for grid reliability & resiliency enhancement

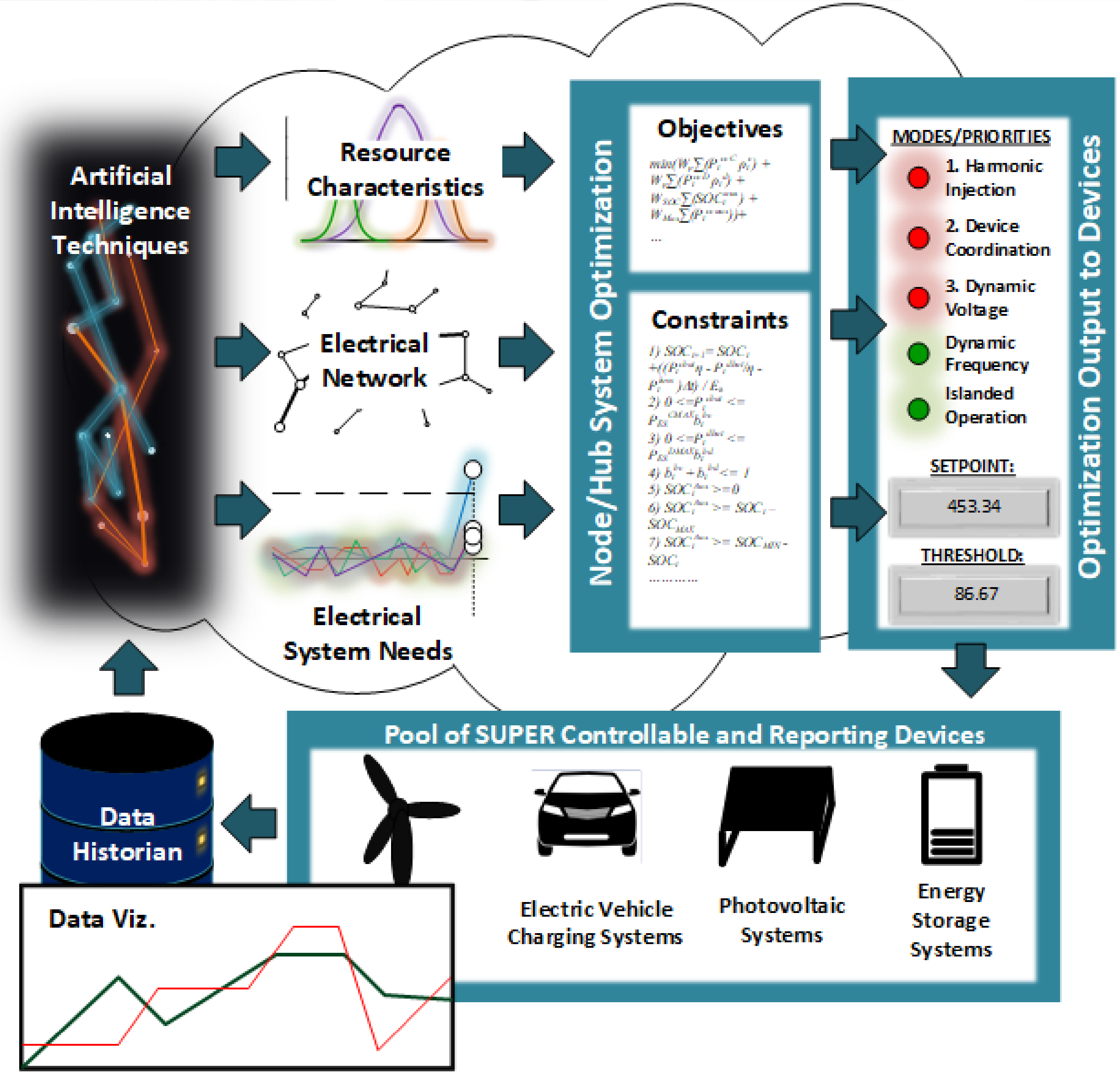
Framework for system level integration of health data & associated metrics.



Invention: M. Chinthavali, M. Starke and R. S. K. Moorthy, "Solid State Power Substation (SSPS) Distribution and Consumer End Grid Infrastructure".

Proposed Solution & Objectives

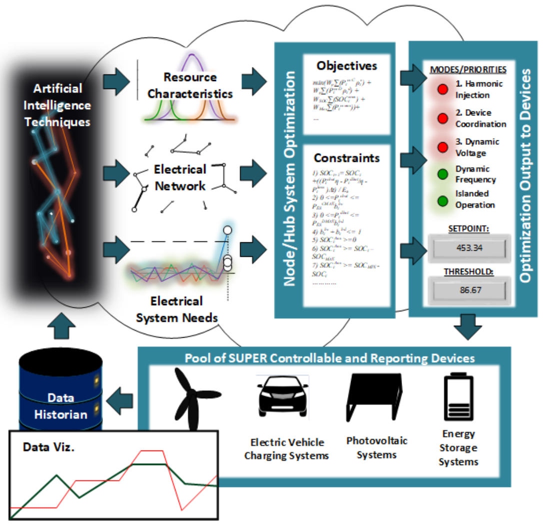
#1 Demonstration of SSPS 1.0 node with optimization framework beyond energy management



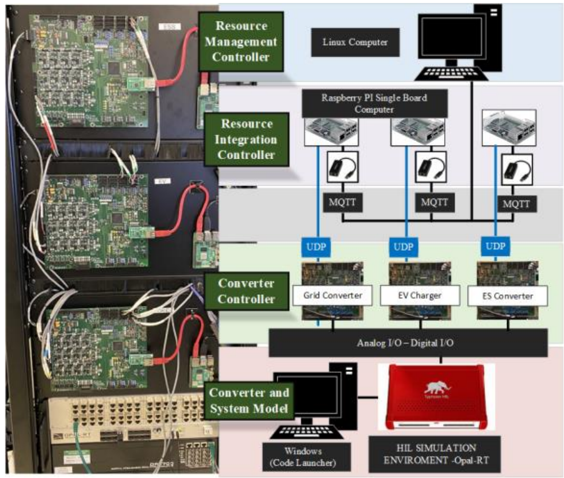
The Numbers

- DOE PROGRAM OFFICE:
  OE – Transformer Resilience and Advanced Components (TRAC)
- FUNDING OPPORTUNITY:
  Annual Operating Plan (AOP)
- LOCATION:
  Knoxville, Tennessee
- PROJECT TERM:
  10/01/2022 to 09/30/2024
- PROJECT STATUS:
  Ongoing
- AWARD AMOUNT (DOE CONTRIBUTION):
  $1,000,000/yr
- AWARDEE CONTRIBUTION (COST SHARE):
  $0
- PARTNERS:
  None

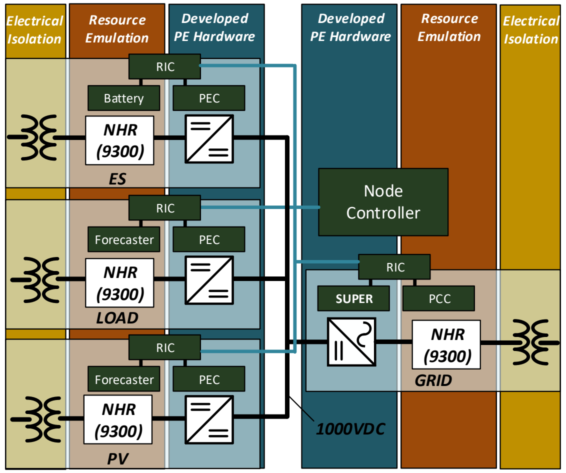
Technical Approach



Framework Establishment & Implementation



CHIL Evaluation



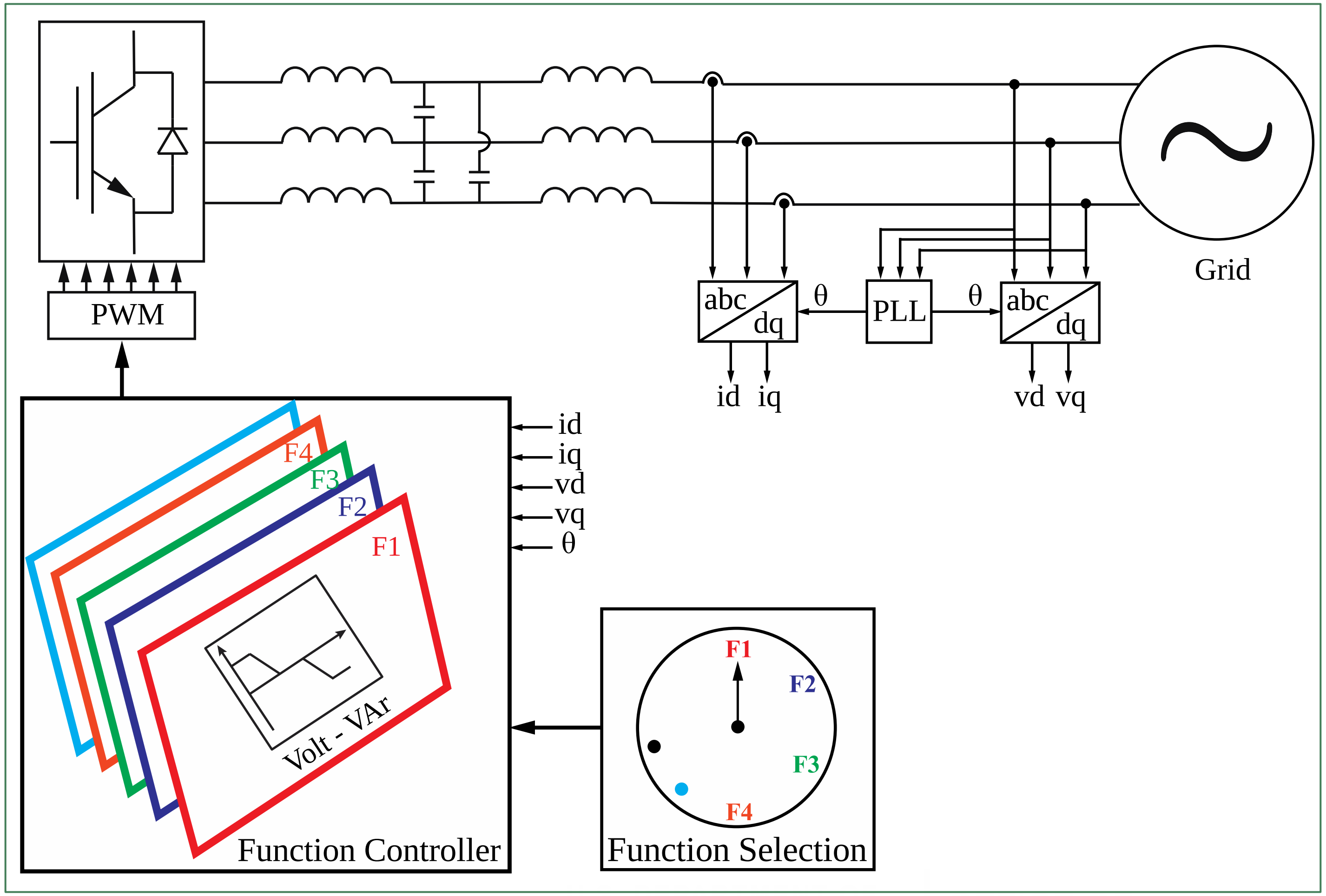
Hardware Validation

Mode Transition/Multimode Controls - Context of the Problem Being Addressed

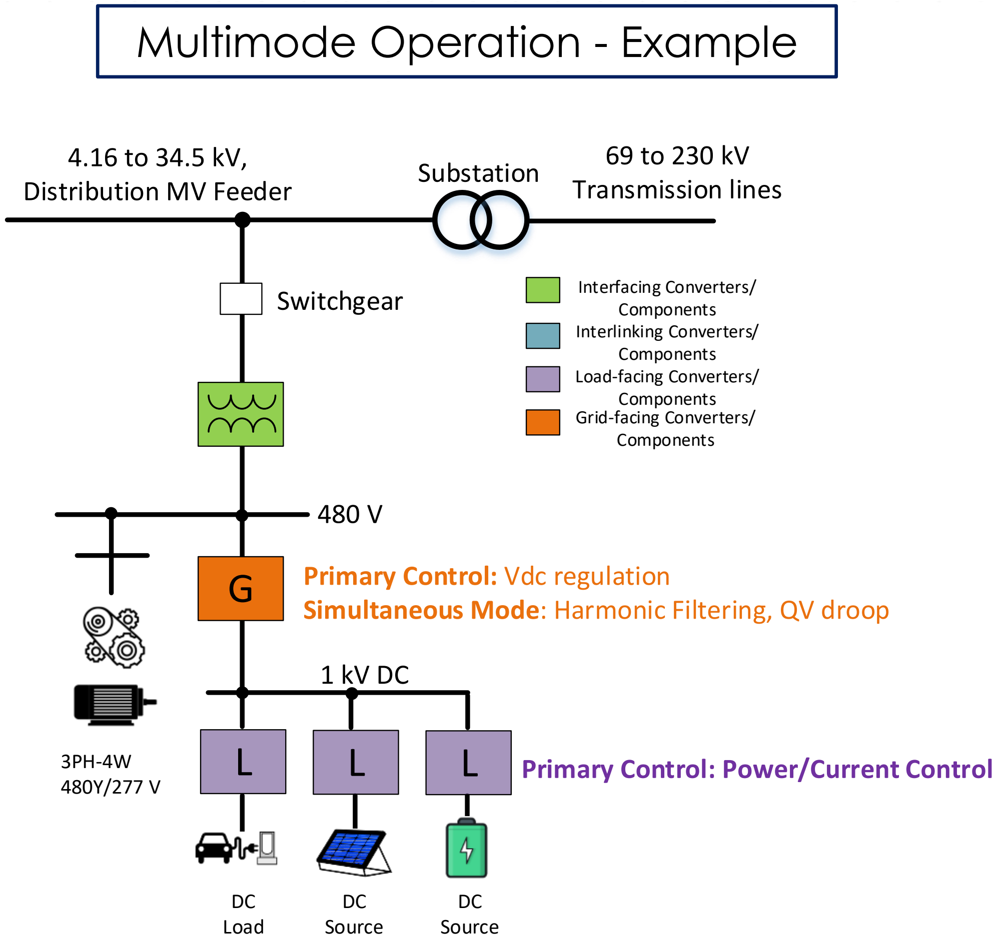
1. Inverters can be used for multitude of functions for grid services. However, **use/combination of more than one function** has not been explored in the literature for 3-ph systems

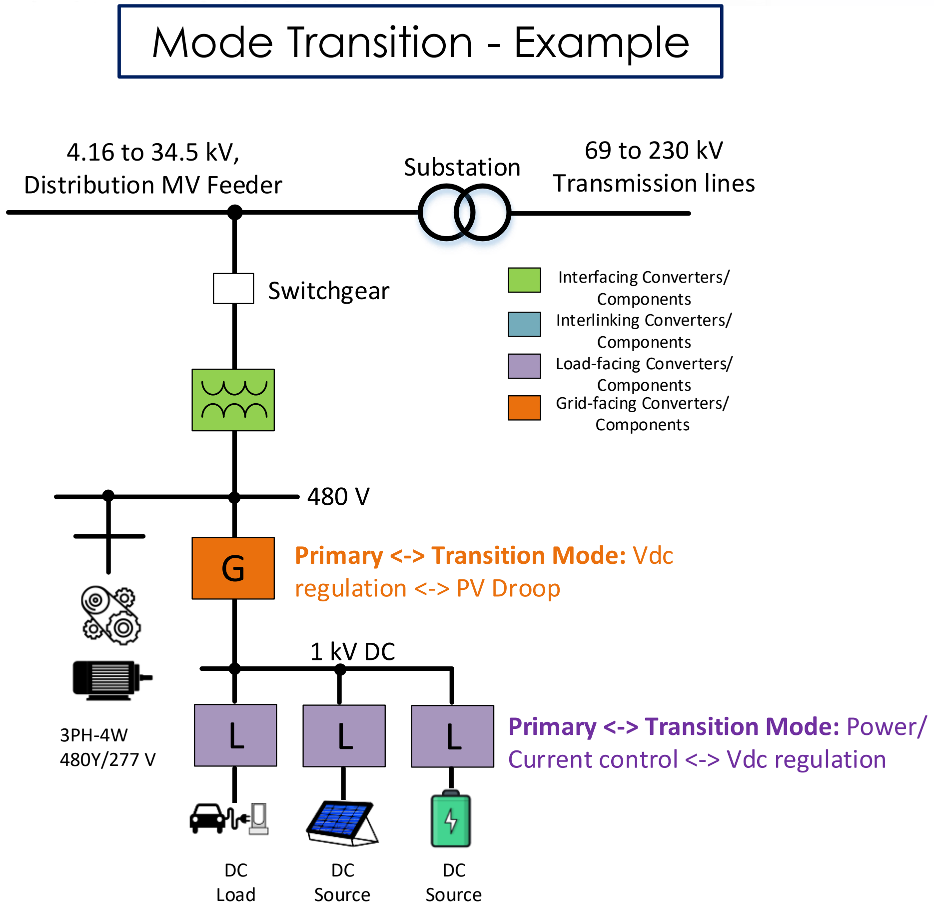
2. **Multi mode transitions** have been established only with regards to fundamental components of P & Q and not beyond & using state machines only. Plausible combinations of modes has not been explored.

3. Integration of such transitions to a hierarchical controller has not been reported



#1 – Multimode/Mode Transition Control for SSPS 1.0 Node

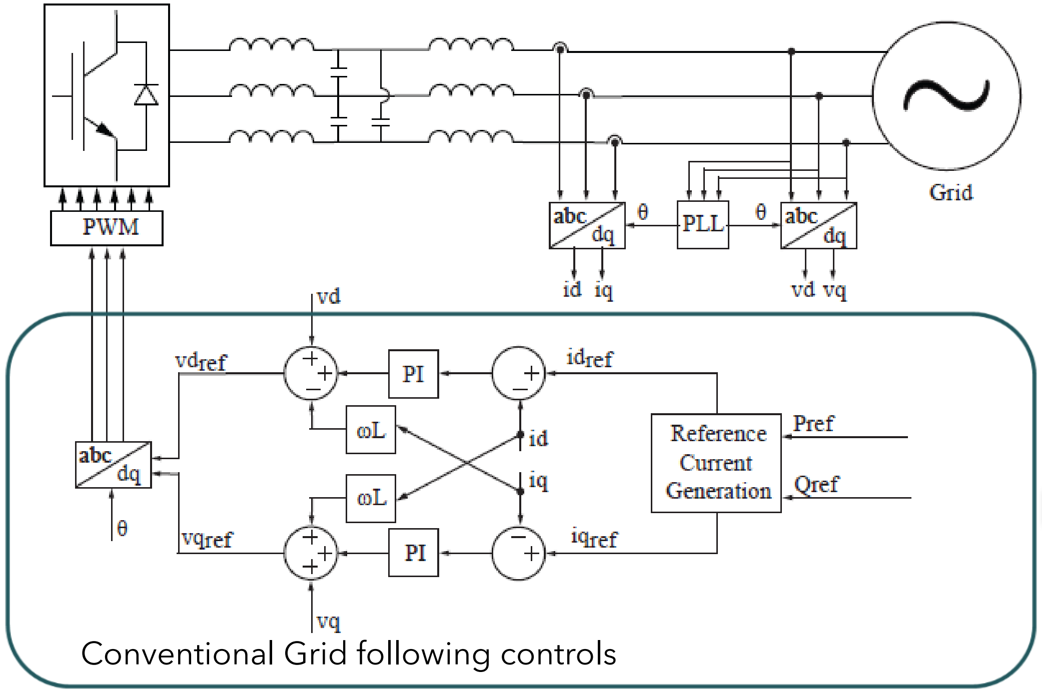




Control mode grouping as primary, transition & simultaneous is key to define multimode/mode transition controls

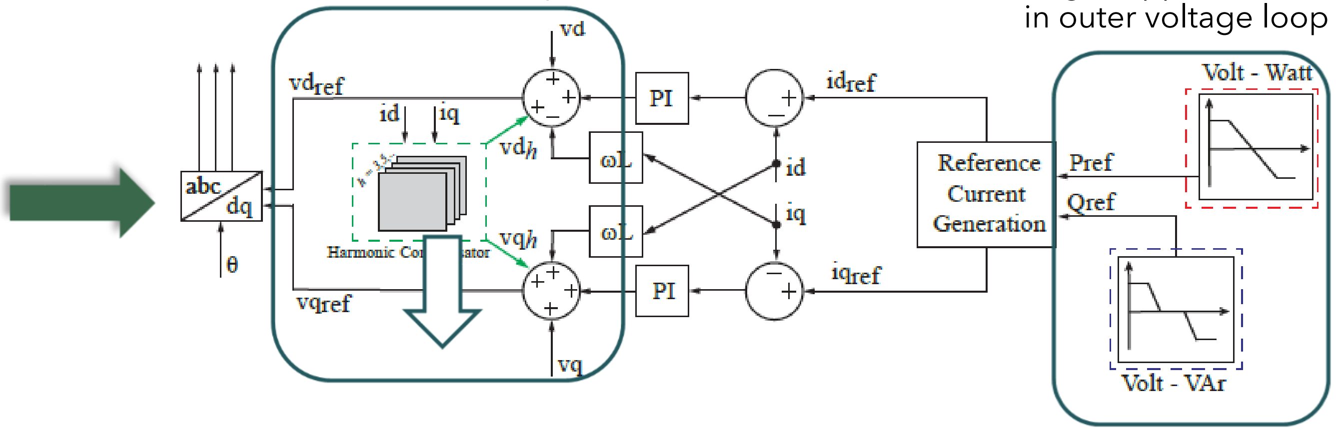
#2 - Strategy for Multimode Operation in SUPER – An Example

Multimode operation use case – 1: Power quality issue in industrial systems when there are voltage sags in the network



Harmonic control in inner current loop

Voltage support functions in outer voltage loop



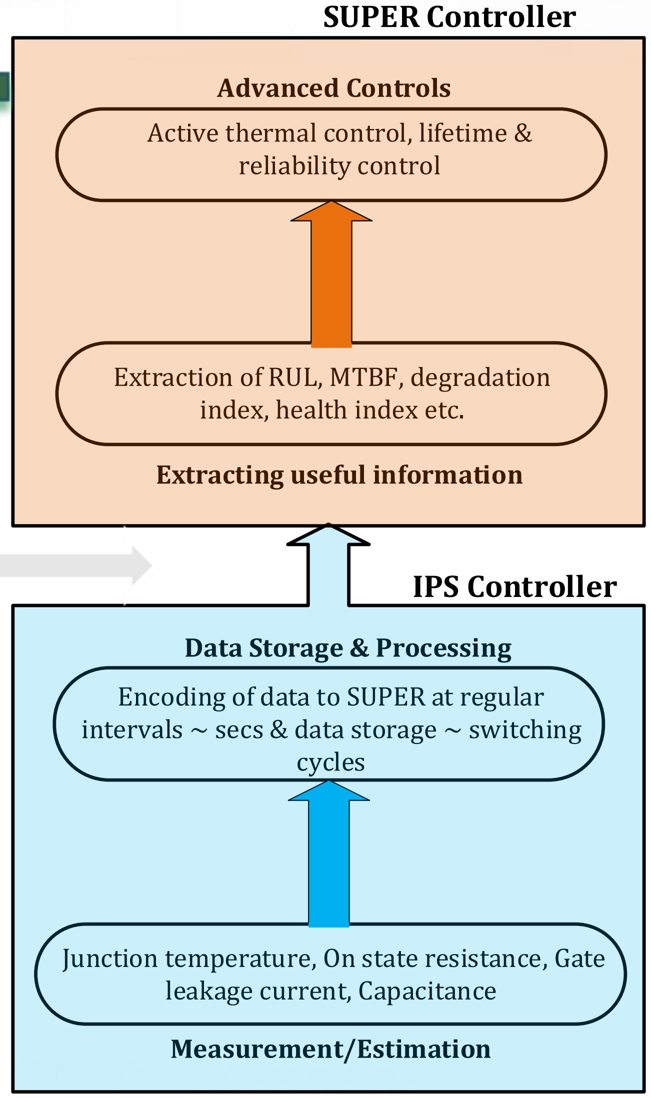
Benefit: Harmonic compensation + Voltage control = Increased Reliability of grid & downstream systems/assets

#3 – Framework for Advanced Algorithms with Health Data from Down Stream Entities

In-situ Parameter Estimation – New additions to messages from IPS to SUPER (Data Channel)	
Electronic circuit based	**Model based estimation**
1. Rds,on measurement via gate driver 2. Specialized voltage sensors for Vds,on measurement 3. Gate driver-based prognostics for gate oxide degradation	1. Sensor Fusion 2. Advanced algorithm for passives estimation 3. Digital twin - Passive estimation

SSPS 1.0 Node Objectives for performance & Maintenance

Tj, Rds,on, ΔRds, L, C, gate oxide degradation, stress/health index



- The health estimates will be streamlined from SUPER to Node controller for higher level system objective formulation for performance improvements & scheduled maintenances.
- The computational platform requirements SUPER with added computational requirements will be identified

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#4 – SSPS 1.0 Node Optimization Beyond Energy Management

Objective: *Develop optimization functions for control modes and integrate with platform.*

New Objectives !!

Objective Function

Objective = $\min(\sum \gamma_t^b P_t^{ccC} - \gamma_t^s P_t^{ccD} \quad + \sum P_t^{ccAux} \quad + \sum SOC_t^{bAux} \quad + Min(WHP\Delta P + WHQ\Delta P). + \; Health\ Objectives$

Economics — Grid PCC Limit — ES Capacity Limit — Harmonic Filtering — Health

Energy Storage Model

Energy Model

$$SOC_{t+1}^b = SOC_t^b + (P_t^{cb}\eta - P_t^{db}/\eta - P_t^{loss})\Delta t / E_b$$

Power Limits

$$0 \le P_t^{db} \le P_{MAX}^{db} b_t^{db} \qquad 0 \le P_t^{cb} \le P_{MAX}^{cb} b_t^{cb}$$

$$b_t^{cb} + b_t^{db} \le 1$$

Energy Limits

$$SOC_t^{bAux} \ge \begin{Bmatrix} 0 \\ SOC_t^b - SOC_{MAX}^b \\ SOC_{MIN}^b - SOC_t^b \end{Bmatrix}$$

Pgrid Converter

Power Limits

$$0 \le P_t^{gcD} \le P_{MAX}^{gcD} b_t^{gcD} \qquad 0 \le P_t^{gcC} \le P_{MAX}^{gcC} b_t^{gcC}$$

$$b_t^{gcC} + b_t^{gcD} \le 1$$

PV and Load

$$0 \le P_t^{pv} \le P_t^{pvforc} \qquad 0 \le P_t^{load} \le P_t^{loadforc}$$

PCC

$$P_t^{ccAux} \ge \begin{Bmatrix} 0 \\ P_t^{ccC} - P_{MAX}^{Ccc} \\ P_t^{ccD} - P_{MAX}^{Dcc} \end{Bmatrix}$$

$$0 \le P_t^{ccC} \le 10^{10} b_t^{ccC}$$

$$0 \le P_t^{ccD} \le 10^{10} b_t^{ccD}$$

$$b_t^{ccC} + b_t^{ccD} \le 1$$

DC Bus Model

$$P_t^{gcC} - P_t^{gcD} == P_t^{pv} - P_t^{load} - P_t^{cb} + P_t^{db}$$

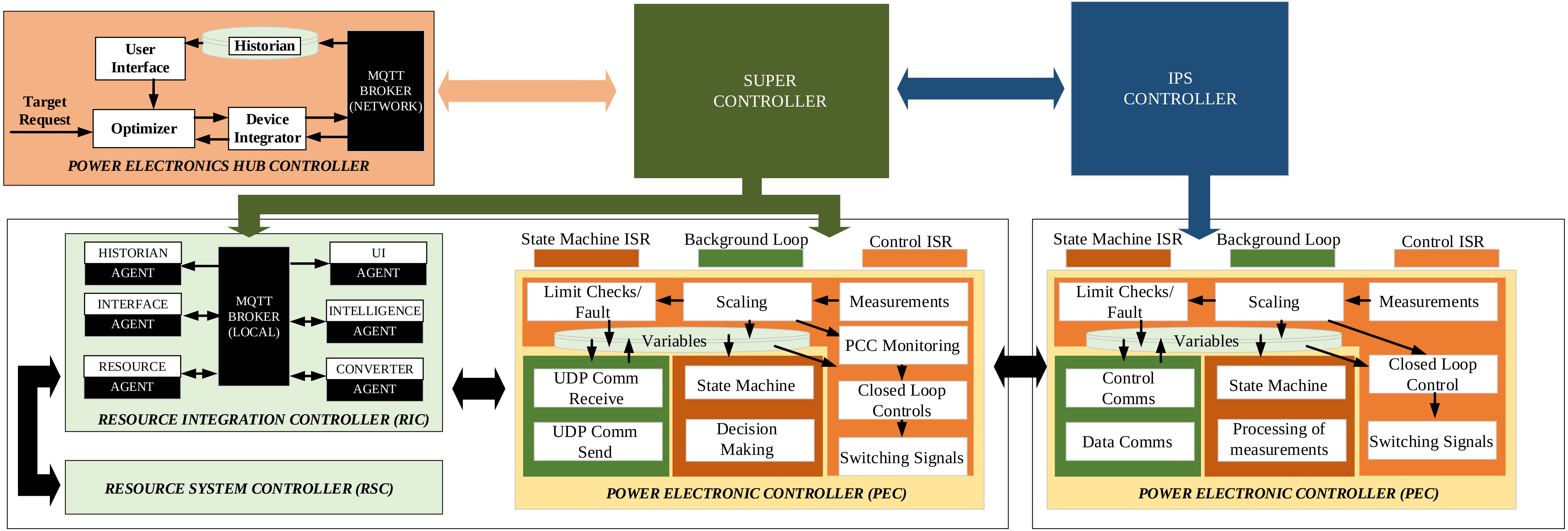
AC Bus Model

$$P_t^{ccC} - P_t^{ccD} = P_t^{gcC} - P_t^{gcD}$$

New constraints based on grid abnormalities & downstream system health

#5 – Software Architecture for SSPS 1.0 Node – CODAS-RT

2
- Streamlining of health data from SUPER -> Agent -> Node Controller
- Utilization of health data in SUPER for operational enhancement



1 Communication messages to relay regulation curves, harmonic compensation setpoints…., handshaking & data verification strategies etc.

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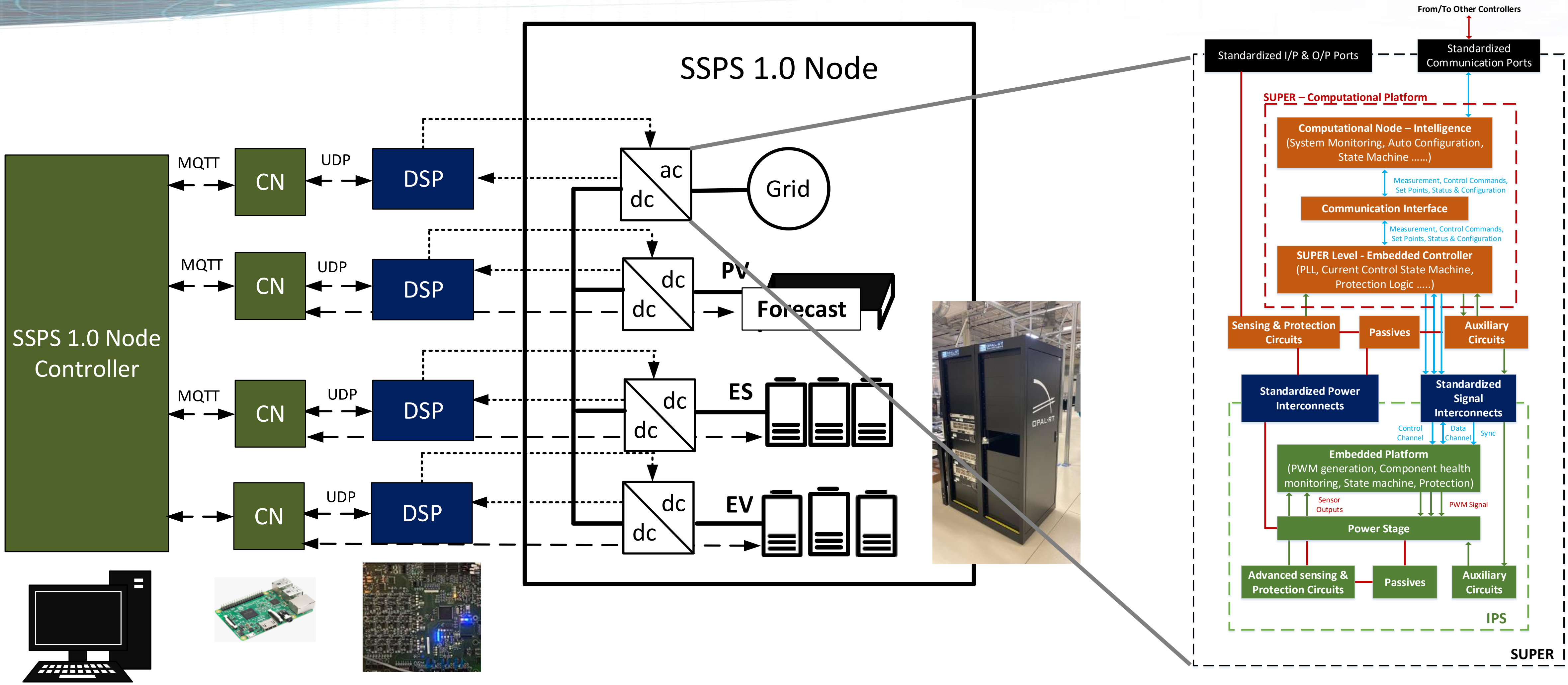
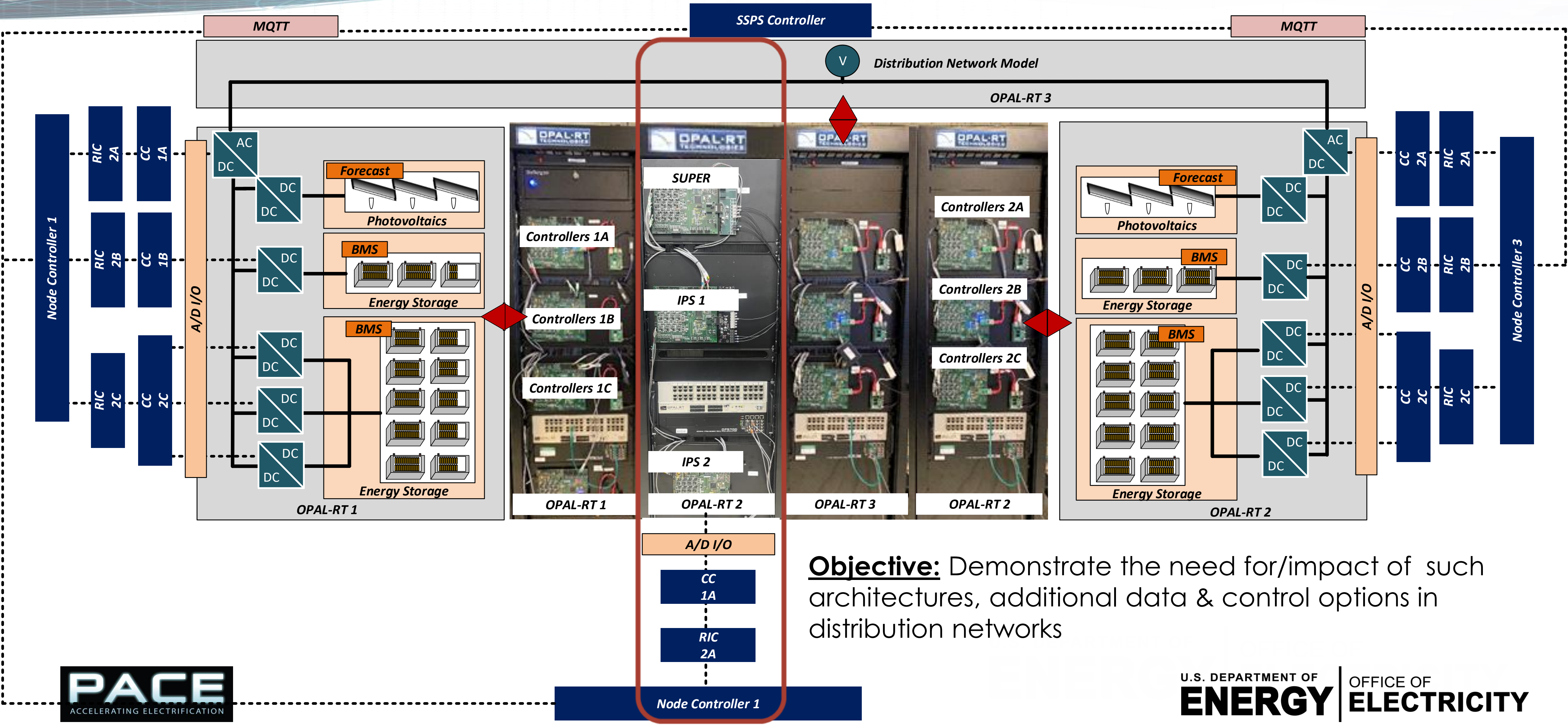
#6 – Controller Hardware in Loop (CHIL) for Framework Validation of SSPS 1.0 Node



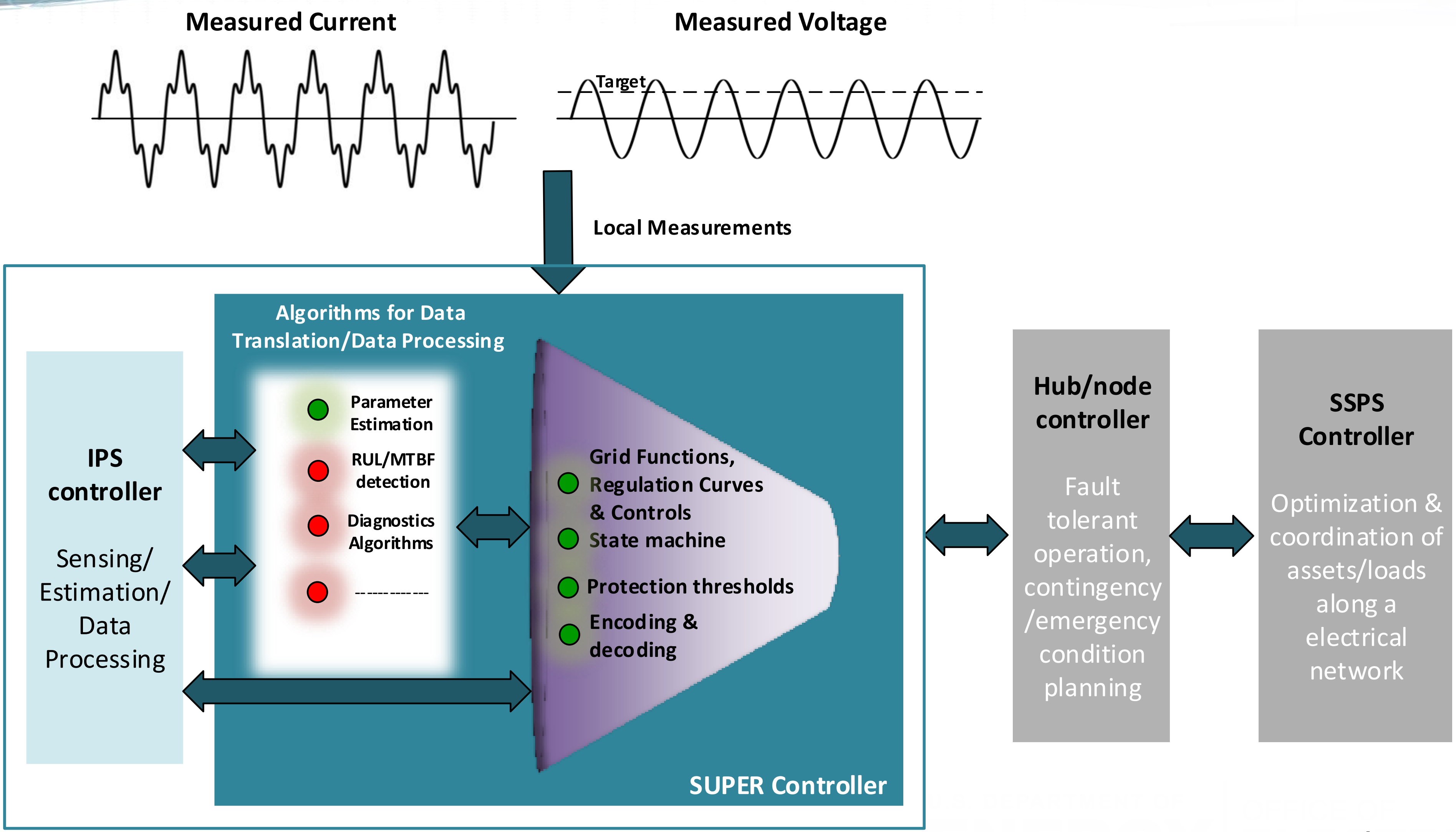
#7 – Controller Hardware in Loop (CHIL) for Framework Validation of SSPS 1.0

SSPS 1.0 node with advanced controls & health data



Objective: Demonstrate the need for/impact of such architectures, additional data & control options in distribution networks

Final Outcome



Timeline

Milestone Description (or Go/No-Go Decision Criteria)	Due	Status	Accomplishments/Notes
1.1 – Framework for SSPS 1.0 node optimization and control beyond energy management (version – 1)	BP1 – Q1 (Dec 22)	Completed	❑ The framework for SSPS 1.0 node beyond energy management (harmonic filtering) was developed.
1.2 – Development and validation of SSPS 1.0 node components	BP1 – Q2 (Mar 23)	Completed	❑ The framework for multi-mode & mode transition controls for SUPER/SSPS was developed ❑ The strategy to be verified used the communication testbed
1.3 – CHIL validation of SSPS 1.0 node	BP1 – Q3 (Jun 23)	In Progress	❑ OPAL-RT modeling and evaluation of SSPS 1.0 node is in progress.
1.4 - Integration of CHIL based node model with node controller and use case validation	BP1 – Q4 (Sept 23)	Not Started	
2.1 – Addition od additional data framework to the node controller (version – 2)	BP2 – Q1 (Dec 23)	Not Started	
2.2 – Develop and validation of SSPS 1.0 node components in hardware	BP2 – Q2 (Mar 24)	Not Started	
2.3 – Integration of SUPER with node controller	BP2 – Q3 (Jun 24)	Not Started	
2.4 – Use case demonstration: SSPS 1.0 node with SUPER (autonomous operation + data management	BP2 – Q4 (Sept 24)	Not Started	

Timeline

Risks

1. Anticipated delays in setting up the CHIL platform for the node
    a. Delays owing to purchase of new equipment for test bed expansion

Mitigation Strategy

1. Node with one SUPER can be demonstrated using addition on analog/digital cards in existing simulators (Orders placed)

Impact/Commercialization

Publications

1. R. S. K. Moorthy, M. Starke, S. Campbell, B. Dean and A. Yadav, "Multimode control strategy for SUPERs to support multiple grid functions," ***accepted*** to ECCE 2023.

Future Work

- Develop the framework for utilizing additional data from SUPER into the node controller

- Validate the mode transition/multi- mode controls in CHIL.

ORNL - TEAM

Radha Sree Krishna Moorthy
Real-Time Systems Integration

Steven Campbell
System Integration & Testing

Michael Starke
Optimization

Benjamin Dean
Communications & Software Development

THANK YOU

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Acronyms

CHIL – Controller Hardware in Loop