U.S. DEPARTMENT OF ENERGY
Office of Electricity

Solid State Power Substation

TRAC Program Review

US Department of Energy, Office of Electricity

Presented at Oak Ridge National Laboratory

Oak Ridge, TN

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Project Overview

- **Project Summary:**
  Design the converter topologies and identify the power electronics building block specifications (which includes controls and communication interfaces) that can scale up to 34.5 kV and 10 MW for distribution level "substation" applications.

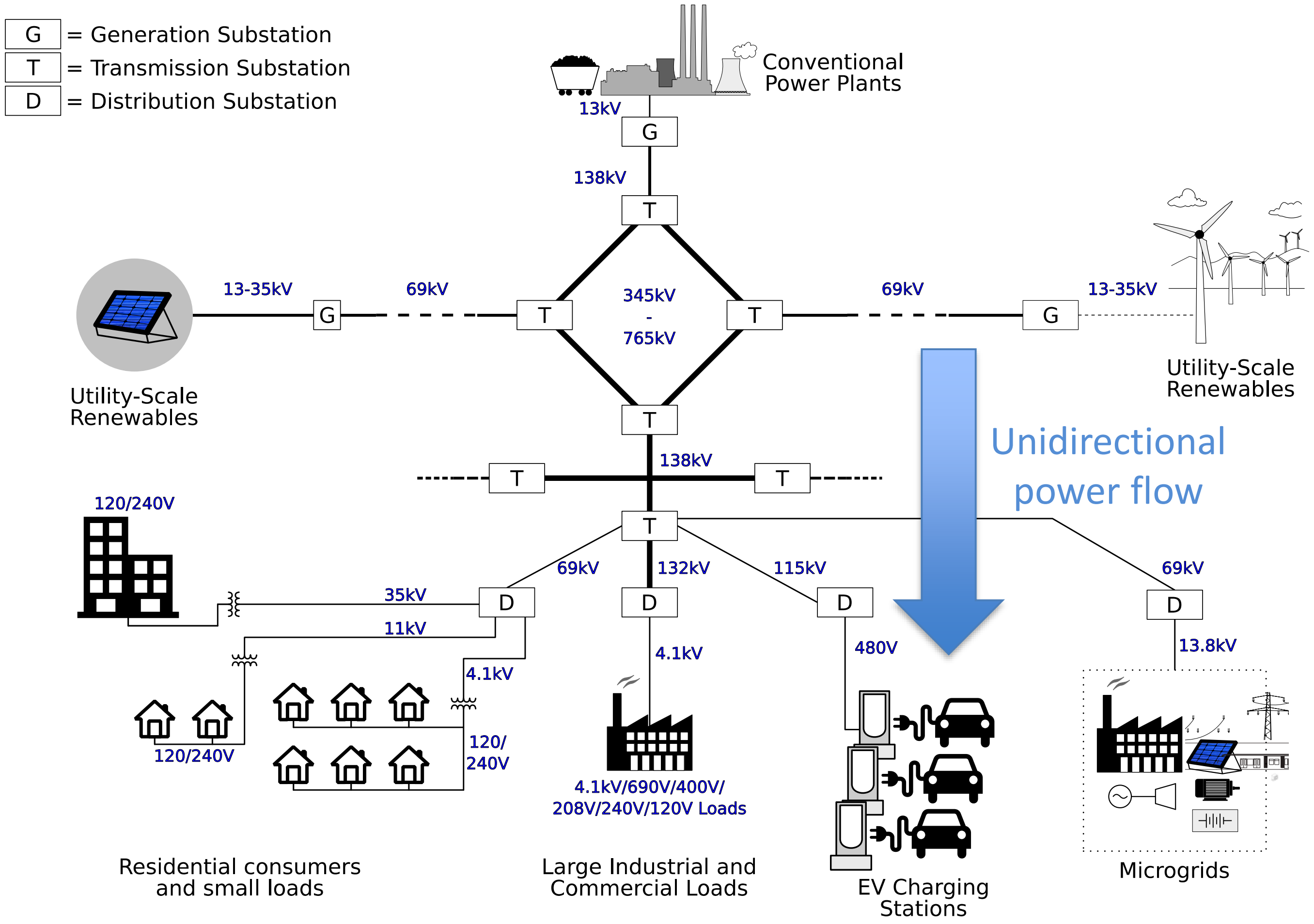
- **Total value of award: $1,000 K**

- **Period of performance: June 2019- May 2020**

- **Project lead and partners:**
  Oak Ridge National Laboratory

Context concerning the problem being addressed

- Conventional substations perform voltage translation, protection & power quality improvements.
- However, increased number of PE-grid interfaces due to higher DER penetration and load evolution will mandate a change in the concept of substation.



New substation architecture will address:

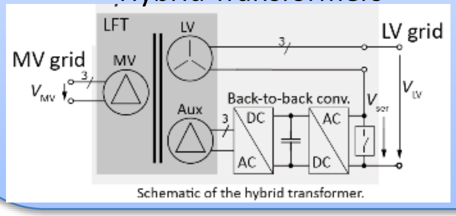
- **Multiple grid power converters :**
  - To communicate, control and coordinate and comply with grid standards
  - Reduced energy efficiency due to **multiple conversion** stages
  - Vulnerability to **cyber security threats**
- **Multiple vendors** with one-off designs, proprietary software and communications interfaces
  - High Balance of system (BOS) costs for grid-tied systems.
  - Lack of standards for communication & interfacing
- Large **computational burden** for optimization of sources and loads
- Lack of **autonomous** operating capability: trusted central master controller needed
- No transactive based **market participation**

State of the art approaches for addressing the problem

Component Based Approach

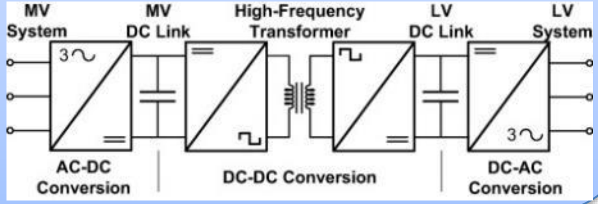
- Component based implementation based on specific functionality requirements (Voltage transformation, power factor control, etc.)
- Not designed for load or source management or other functions outside intended scope.

[1] Hybrid Transformers



Schematic of the hybrid transformer.

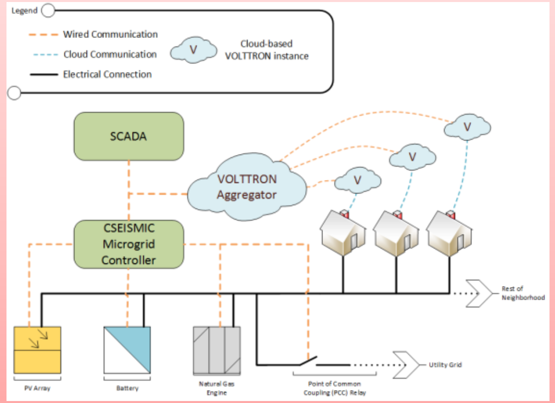
[2] SSTs



System Based Solutions

Load centric energy management

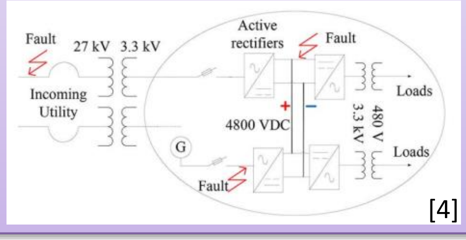
- Interface multiple sources and loads
- Needs dedicated communication links / protocols
- Can perform only load optimization and management and protections
- Cannot provide ancillary grid services



[3]

Asynchronous Microgrid interties

- Converter for power flow control usually to/from microgrids.
- Usually not designed for other features such as voltage translation, load or source management



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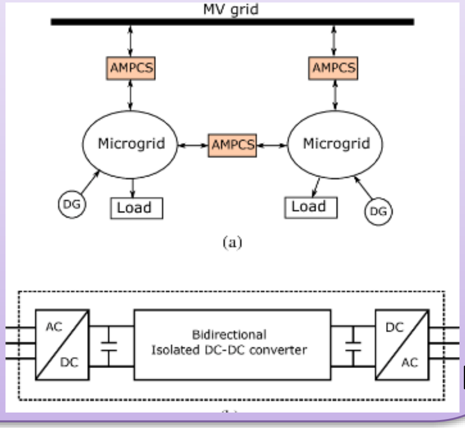

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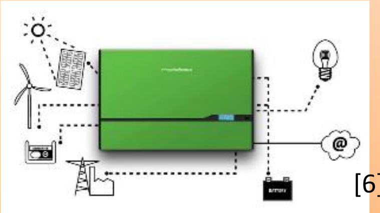
Vendor Based Solutions

Single vendor solutions:

- Preset functions in converters with centralized control
- Smart interfaces for IOT enabled loads
- Communication protocols- like open FMB



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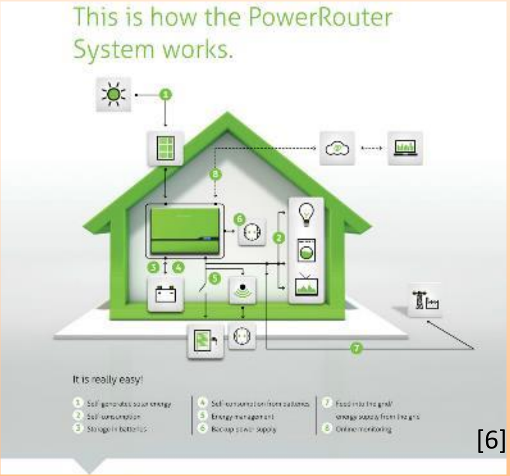

[6]

Advanced Grid Research
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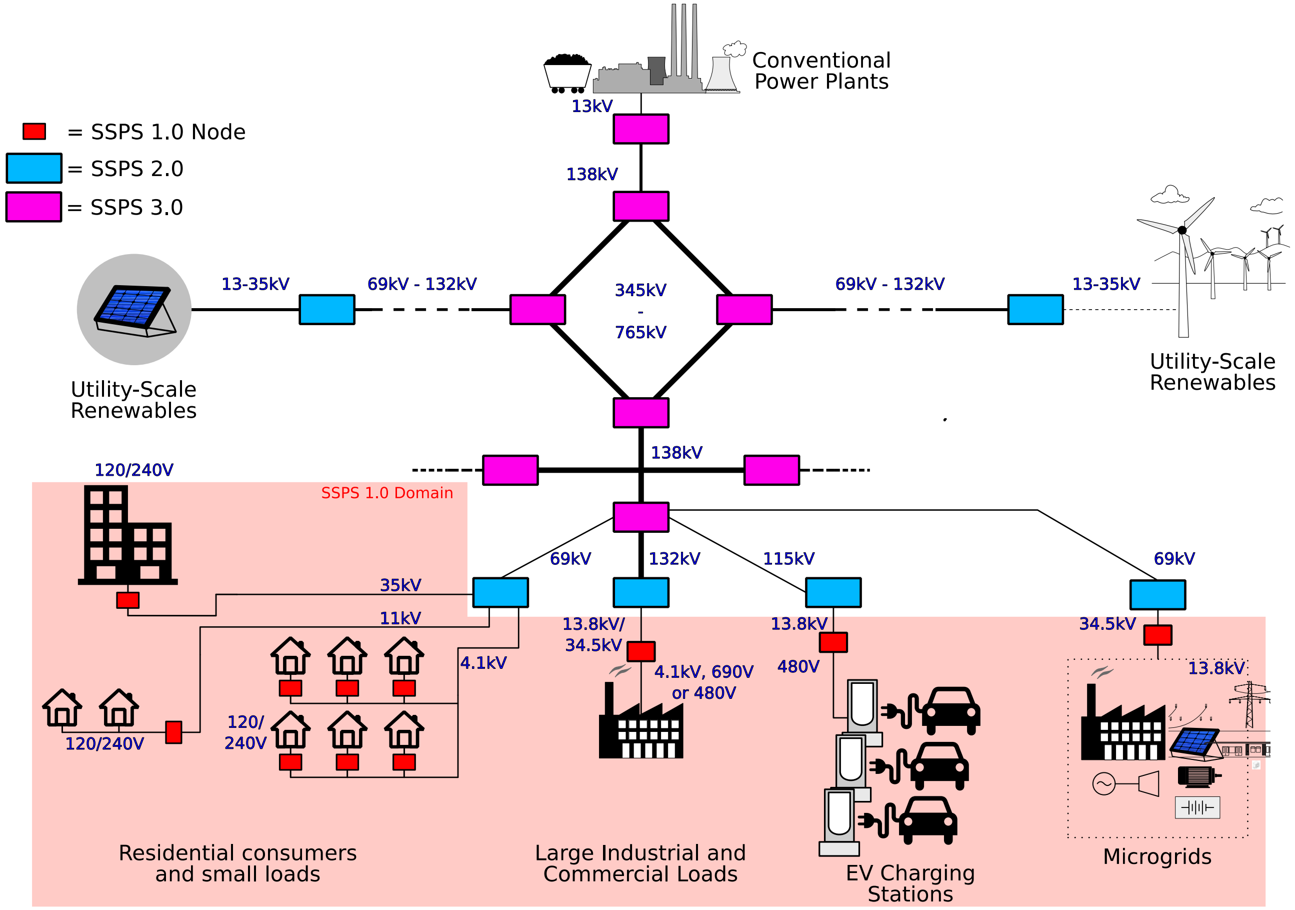
Uniqueness of the Proposed Solution – SSPS Node

SSPS node – An autonomous grid node capable of power and information exchange serving as an interface between the grid and end user.



Architectural Features

- Modular & scalable
- Increases grid security by minimizing the number of DER nodes on the grid
- Includes protection

Energy management

- Automation of energy flow between loads and sources
- Enhances power quality and provides ancillary grid services

Communications

- Interoperable / Vendor agnostic – modular and scalable agent-based software platform with real-time dynamic control of grid
- Enables coordination between multiple sources and loads

Optimization and Control

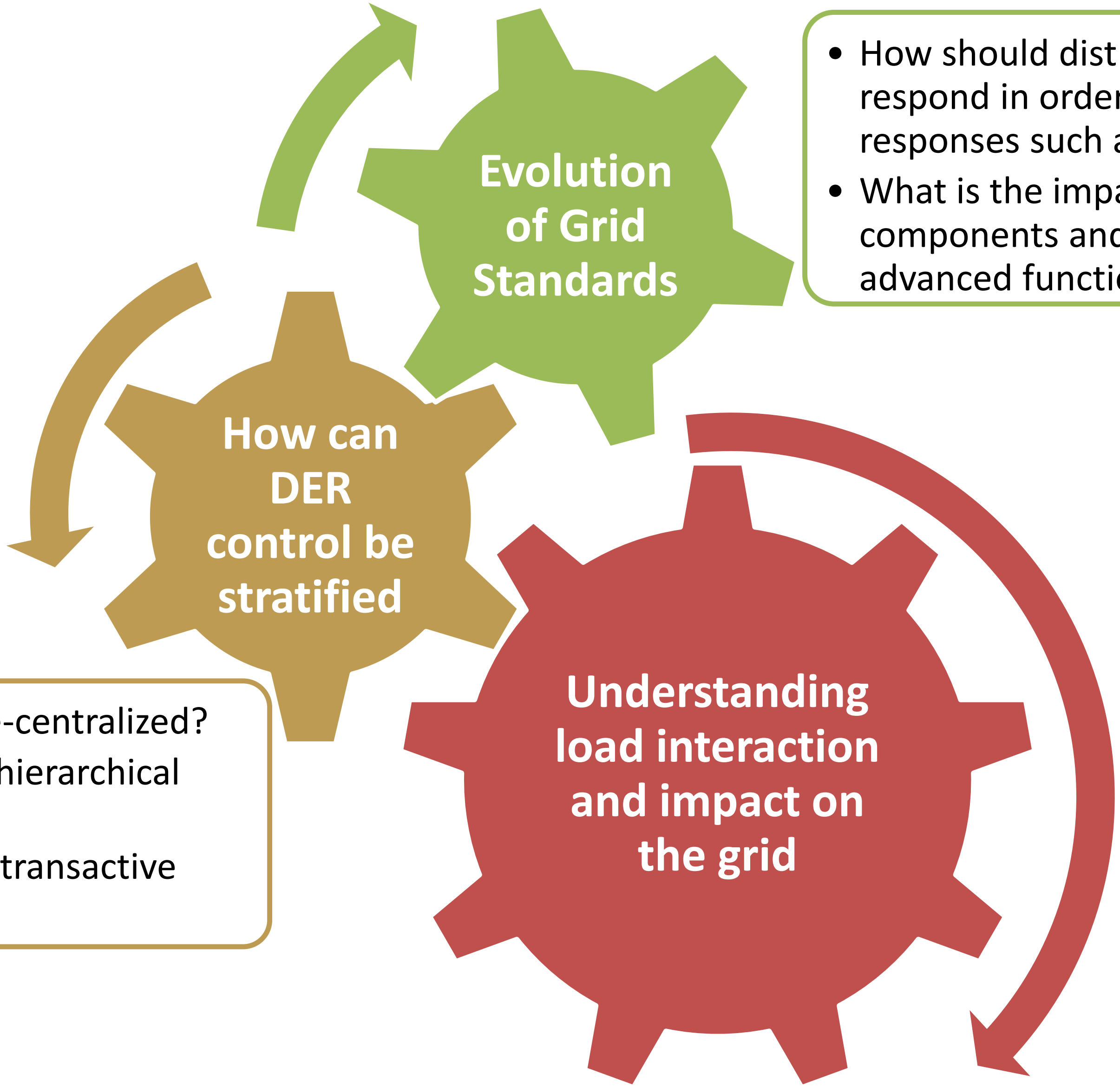
- Novel de-centralized control architecture
- Single transactive node with real-time optimization
- Single point of communication with ADMS and other utility management systems

Significance of the results, if successful

*Provide solutions for real world **grid integration** problems through advanced multi-disciplinary flexible integrated open research platforms*

- Specific use case based architectures of SSPS 1.0 nodes
- Use case based hierarchical control platforms specifications
- Modular, scalable *SMART*-PE converters
- Plug & play PEBBs : Intelligent power stages (IPS)
- Multi-team research projects to enable validation of SSPS 1.0

Specific research questions being addressed

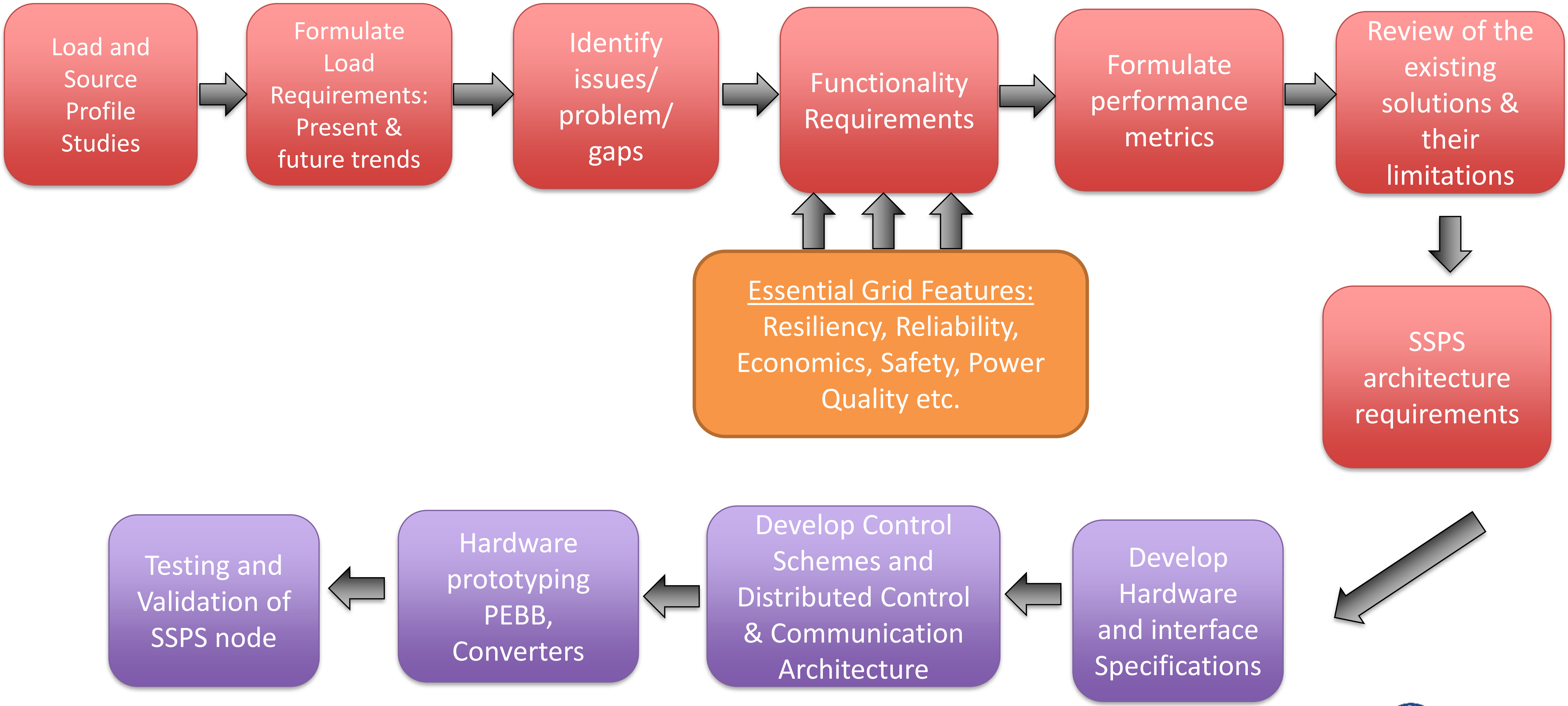


- How should distributed converters on the grid respond in order to realize widespread grid responses such as voltage support, inertia, etc.
- What is the impact on the power electronics components and hardware due to these advanced functions?

- How far can control be de-centralized?
- How should the layers of hierarchical control be organized?
- How can incentive-based transactive energy be implemented?

- What do loads need in terms of energy, power, voltage, frequency?
- How will these loads evolve?
- How do these impact the design of power electronics architectures?

Technical explanation of the proposed approach



Technical Explanation of the Proposed Approach

First load-centric approach, with thorough review of:

- Load requirements (voltage, power, energy)
- Demand profiles (diurnal, seasonal, stochastic)
- By load profile – residential, industrial, commercial & XFC
- By time horizon – immediate, short-term & long-term

Load Requirements & specifications

Residential	Commercial and Industrial	Microgrids/ spl. Loads	Next-gen EV Charging (XFC)
• Homes with and without renewables • HVAC, water heating, cooking and other bulk loads	• Medium-large establishments • e.g. hospitals, office buildings, malls, factories	• Residential or C&I • Fossil or renewable generation • Demand responsive loads	• Extremely Fast Charging • Light and Medium duty • Under 20min charging

Present Time	Near Term forecast	Long term forecast
• Now and very near future	• Load evolution within next 2 years	• Load evolution beyond 5y

Residential Use Case

Timeline	Residential Load Profile	Generation Profile
Near term	- Loads with and without intelligence - ~ 45% of non-linear loads including lighting loads [8]	Increase in penetration of centralized or distributed generation is anticipated
Short term (5 years)	- Adoption of intelligent loads - ~ 60% of non-linear loads including lighting loads [8] & EV charging loads (L1 & L2) - Small neighborhoods with < 100 residences	
Long term (10 years)	- Proliferation of intelligent loads - > 80% of non-linear loads including lighting loads & fast charging stations - Large communities (> 100 residences)	

Grid Impacts with Residential Load Evolution

Issues/ Problems/ Gaps	Functionality Requirements	Metrics	Existing solutions	Issues with existing solutions
Harmonics from increase in non-linear loads • Harmonic propagation upstream • Increase in losses in the distribution transformers • Nuisance tripping of breakers, failure of relays & CT saturation	Active filtering for power quality improvement	THD, TDD, DC current rejection	Tuned filters, passive filters	Prone to harmonic resonance, large heavy & noisy
			K-rated transformers etc.	Expensive, bulkier
Need for capacity expansion • Proliferation of residential EV chargers, Simultaneous loading: overnight EV charging • Increase in home energy use	Economics – Energy & power management to delay the need for costly upgrades	Peak load factor, Utilization factor	Load shedding	Decrease in customer satisfaction
			Energy storage units	Expensive, safety concerns
			Conservation Voltage Reduction (CVR)	Does not work with Const. Pwr. Loads
Incompatibility among loads from multiple vendors • Lack of communication interfaces • Lack of software upgrades	Ease of operation & reduced BOS cost (Economics)	Communication latency, response time, Strength of encryption	Open FMB – open source platform	Emerging standard that is not yet widely adopted
Lack of incentives for energy use & ancillary services	Resiliency – ability to perform voltage support	SAIDI, CAIDI	Voltage regulators, tap-changers, capacitor banks	High failure rates
			IEEE 1547 compliant converters	Not autonomous, rely on central trusted authority
Vulnerability to cybersecurity threats • Increase attack surface with proliferation of smart loads	Resiliency against intentional attacks; privacy of user data	Strength of encryption, authentication & authorization	• Commercially available encryption solutions	• Lack of implementation • Computational requirements • Latency issues

Grid Impacts with Large Scale Renewable Penetration

Issues/ Problems/ Gaps	Functionality Requirements	Metrics	Existing solutions	Issues with existing solutions
Islanding (intentional/ Unintentional)	• Safety of linemen & limiting energy delivered to the fault • Reliability - Low voltage ride through (LVRT) & fault ride through (FRT) capabilities for inverter based generation	• Time to disconnect/deenergize • Resynchronization - Limits on voltage, frequency & phase mismatch during reconnection	Active & passive anti-islanding (AAI) algorithms	Complicated algorithms, Needs a robust controller
			Direct transfer trip (DTT)	Costly & does not avoid a short duration island
Stability • Grid impedance variation • Impact of ramp rates of DERs • Grid inertia	Power quality - Voltage and frequency stabilization	• Rate of change of frequency (ROCOF) • Voltage and frequency limits during disturbances	Virtual inertia (Inverter control & virtual synchronous machines)	Complicated control algorithms
			Ramp rate limits	Need for energy storage (capacitors, Battery banks)
Voltage regulation at the PCC & along the feeders	Power quality - Voltage stabilization and active & reactive power control	• Stiffness factor (IutilitySC/IratedDG) • Sensitivity matrix – Voltage sensitivity for active & reactive power variations • % reduction in voltage support requirements with increasing PV penetration and use of inverters	Use of voltage regulators, tap-changing transformers & capacitor banks	Frequent use of voltage regulators & capacitor banks impacting their lifetime
Impact of higher penetration of DG on the existing utility equipment – Need for Capacity upgrades	Economics – Support integration of more renewables without requiring equipment upgrades	• Penetration factor • Curtailment	Replacement/ upgrading of existing infrastructure	Not a cost-effective solution
			Use of energy storage / curtailment of generation	Disincentivizes renewable energy deployment
Phase imbalance	Power quality – Voltage balance across phases	• Limits on percentage imbalance	Distribute load across phases & disconnect loads	Limitations on capacity & lose of power to the load

Residential Use Case

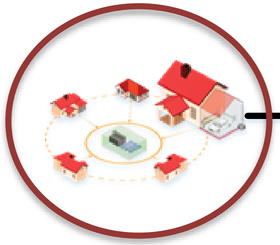
Based on Capacity expansion with load aggregation and centralized and de-centralized generation

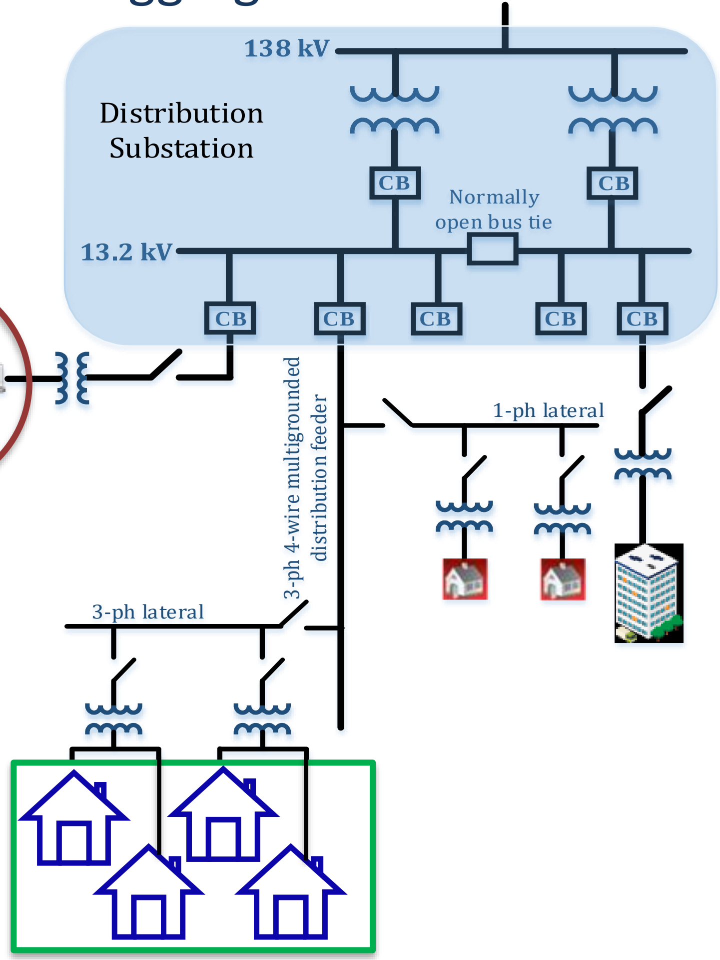
Alabama Neighborhood – Centralized Generation & aggregated load

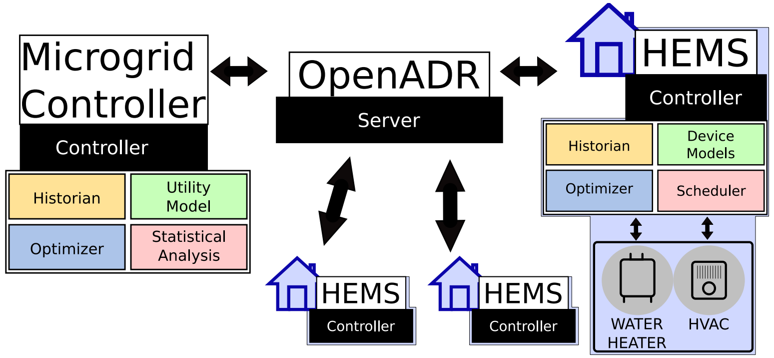
Specifications:

- 300 kW 680 kWh Li-ion battery, 330 kW solar array, 400 kW natural gas plant
- 62, 240V, 1-ph homes with controllable loads, e.g. HVACs and water heater

Existing Approach: Microgrid controller with aggregated load management





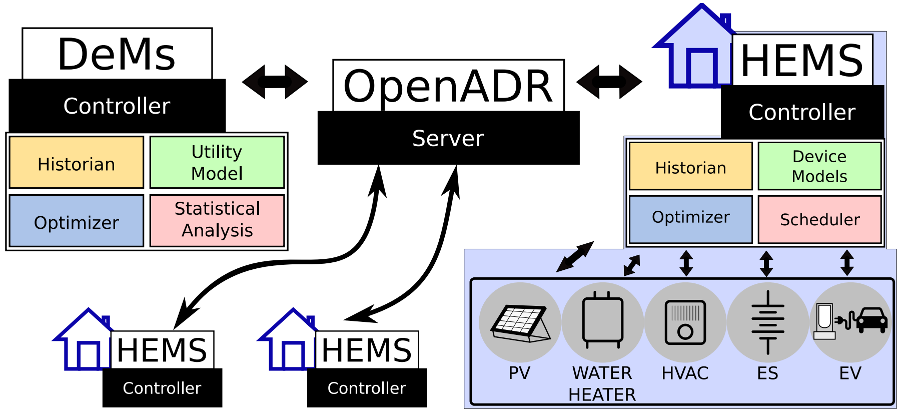


Georgia Neighborhood – Distributed Generation and distributed load

Specifications:

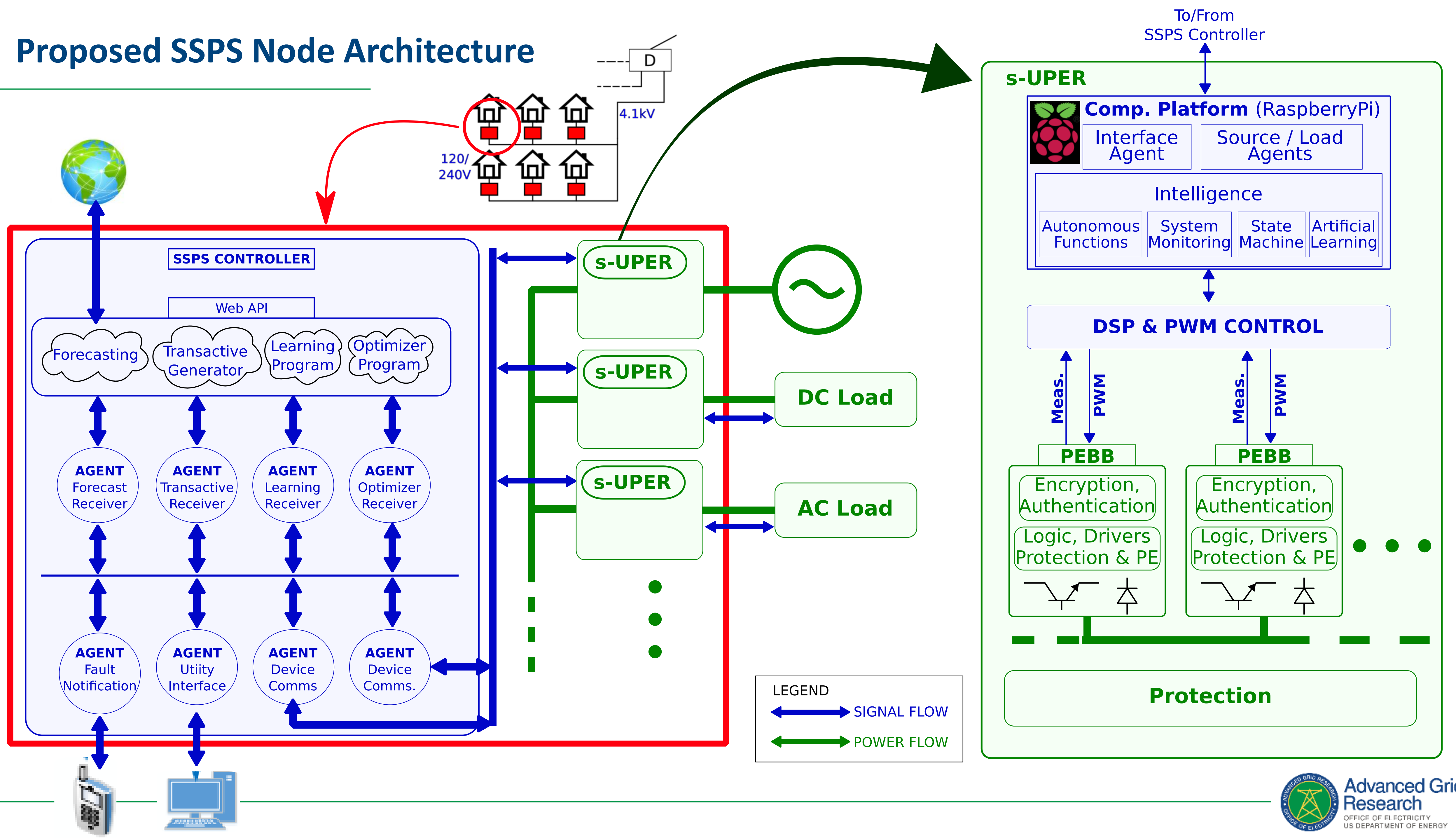
- 46 townhomes with generation & storage units per home
- 240V, 1-ph homes with controllable loads, e.g. HVACs and water heaters

Existing Approach: Multiple PE interfaces and home energy management system (HEMS) per home



NO autonomous response to grid conditions, lacks simultaneous load and source optimization

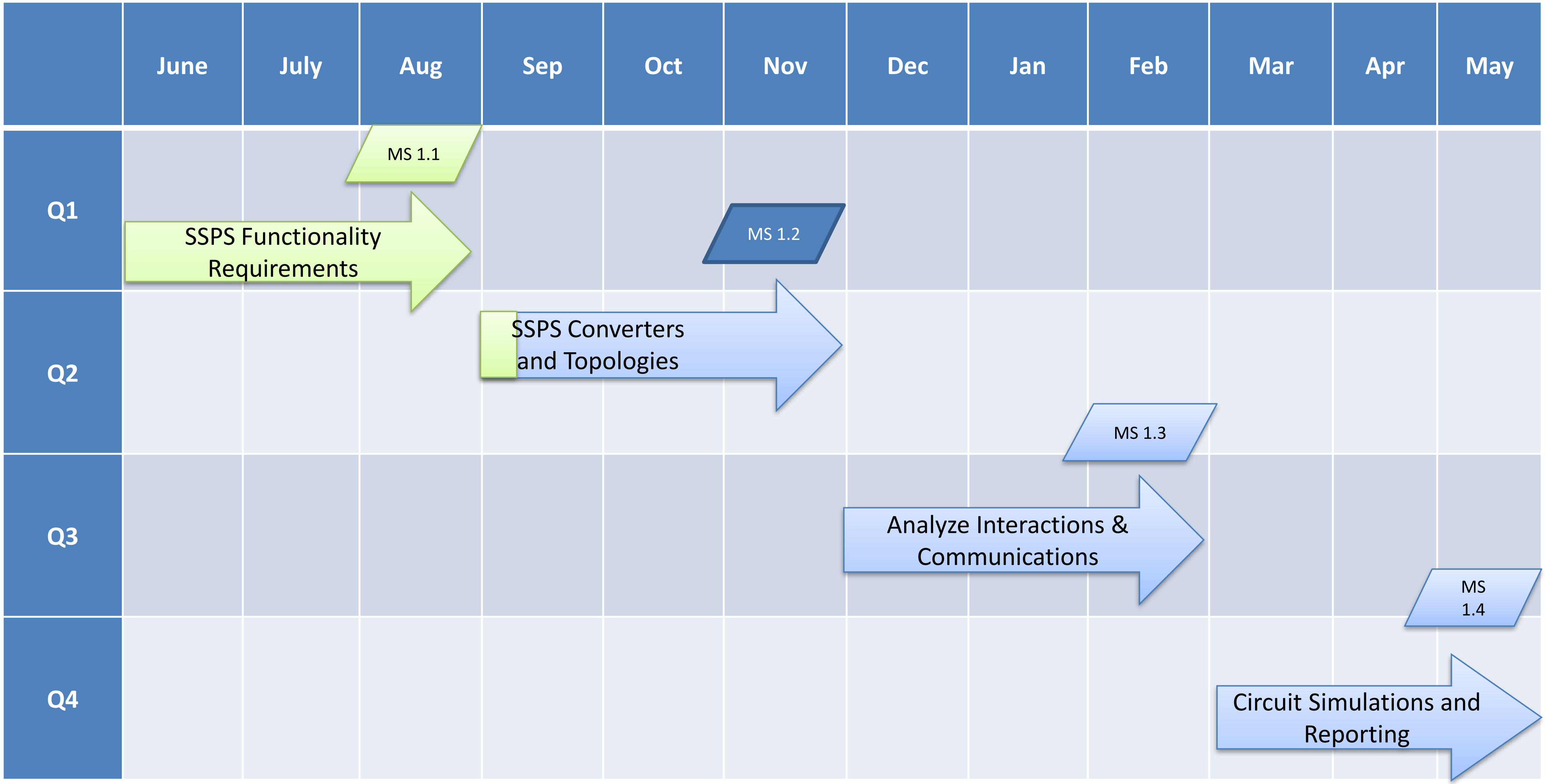
Proposed SSPS Node Architecture



Project schedule, deliverables, and current status

MS No.	Milestone Description	Due	Status	Accomplishments/Notes
1.1	Complete identification of key system specifications for distribution level "substations" and development of SSPS 1.0 and its corresponding PE converter functionality requirements	30 August 2019 Q1	Complete	Identified SSPS functional requirements based on load and source profiles studies
1.2	Complete the definition of control and protection strategies and survey of potential topologies for SSPS 1.0, converters and associated PEBBs	30 Nov 2019 Q2	In Progress (5%)	Converter specification formulation is in progress
1.3	Complete definition of interactions requirement between PEBB, converters and SSPS which includes sensor data, communication and control modes	29 February 2020 Q3	-	-
1.4	Perform circuit simulations for down-selected converter topology using the PEBB models Evaluate the SSPS 1.0 with 1 – 2 use cases. Complete the final report with the summary of the results.	30 May 2020 Q4	-	-

Project schedule, deliverables, and current status



Anticipated challenges and risk mitigation strategies

- No risks were encountered in accomplishing the objectives in this Quarter as the tasks were primarily study / literature survey.
- Project is on the track without critical path issues
- The milestone in this Quarter was achieved.
- The project will call for collaboration between industries, utilities and university partners to collaborate on developing and testing hardware, control schemes etc.

Next steps

- Based on the findings of this quarter, converter requirements and specifications will be formulated

Broader Impact

- The project will redefine the substation architecture that can be realized through advancements ranging from materials to system integrations for all levels of the grid
- The project will address some of the hardware limitations and set up guidelines for hardware architecture standards.
- The project will provide a framework for pilot projects which can enable technology transfer
- The project will close the gap between low level grid impact studies and hardware implementation
- The project will speed up power electronics deployment on the grid in collaboration with industries utilities

Contact Information

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