GM0085 Progress to Date and Re-Scope Update

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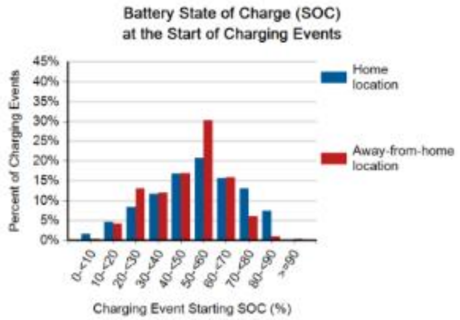
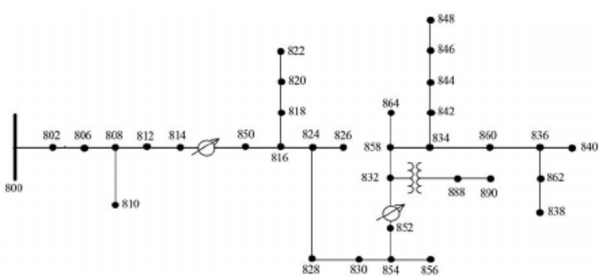
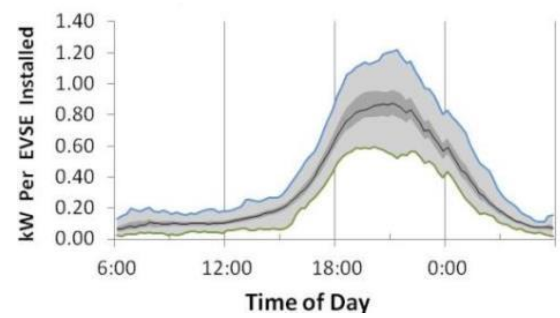
INL/MIS-18-45354

Project Objectives

- Determine the feasibility of PEVs providing grid services via an aggregator at the electric utility distribution level
- Develop a methodology for controlling PEV charging
- Quantify the benefits of controlling PEV charging
  - Cost savings of avoided distribution feeder upgrades
  - Avoided capacity of new generation

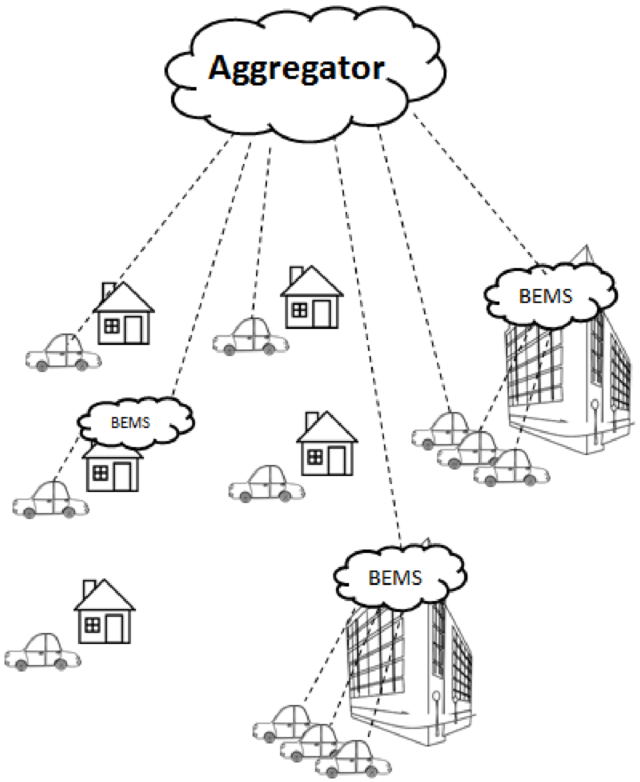






Approach

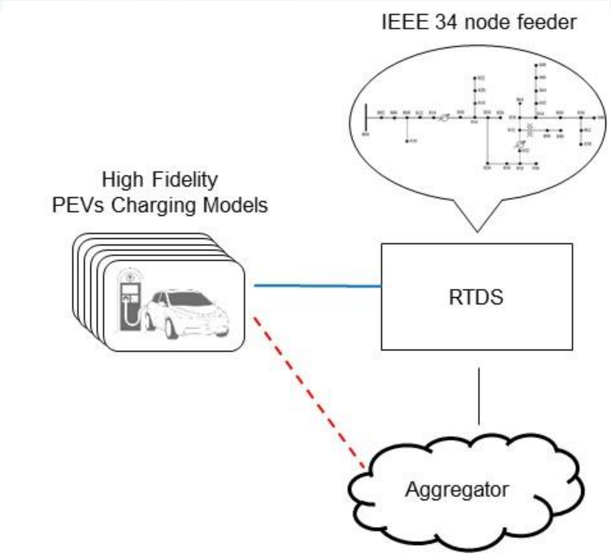
- Develop an aggregator that can be used to coordinate charging of PEVs to provide grid services
  - Coordinate with buildings
  - Coordinate with PEVs directly
- Use aggregator platform to study effectiveness of aggregator to provide benefit to the grid
- Study PEV charging in two contexts:
  - Charging at commercial buildings
  - Charging at residences



Approach Refocused

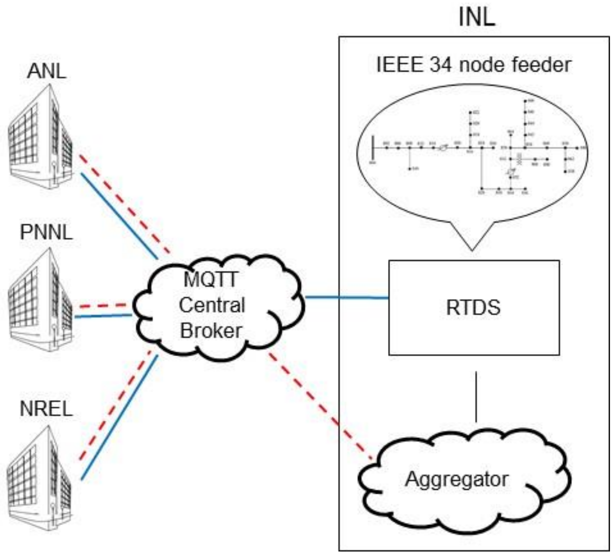
Original focus

- Residential Distribution Feeder
- Aggregator controls PEV charging directly
- Create high fidelity PEV charging models
- Focus during FY17 and1st half FY18



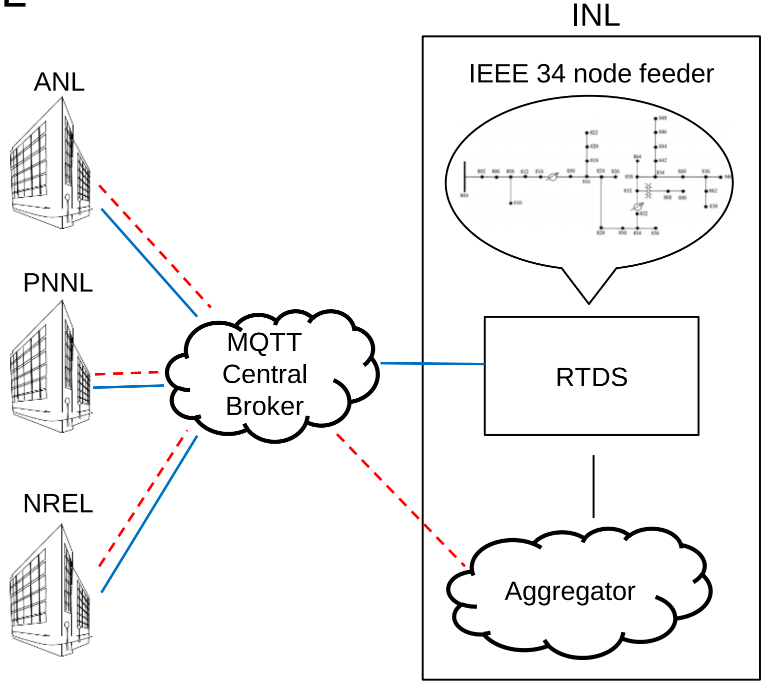
Focus going forward

- Workplace charging at commercial buildings
- Building directly controls PEV charging
- Aggregator communicates with buildings and coordinates their response across the distributio feeder
- Focus 2nd half FY18 and FY19



Charging at Commercial Buildings (FY18)

- Working closely with "Vehicle to Building Integration Pathway" (GM0062)
- As part of the GM0062 project, the hardware, communication, and controls needed to integrate PEV charging into buildings have been implemented in buildings located at ANL, PNNL, and NREL
- These buildings will interact with real-time digital simulator (RTDS) and aggregator located at INL
- Each building directly controls the PEV charging of all PEVs located at the building
- The aggregator communicates with the buildings and coordinates their response across the distribution feeder



This platform will study the ability of PEVs charging at commercial buildings to provide grid services

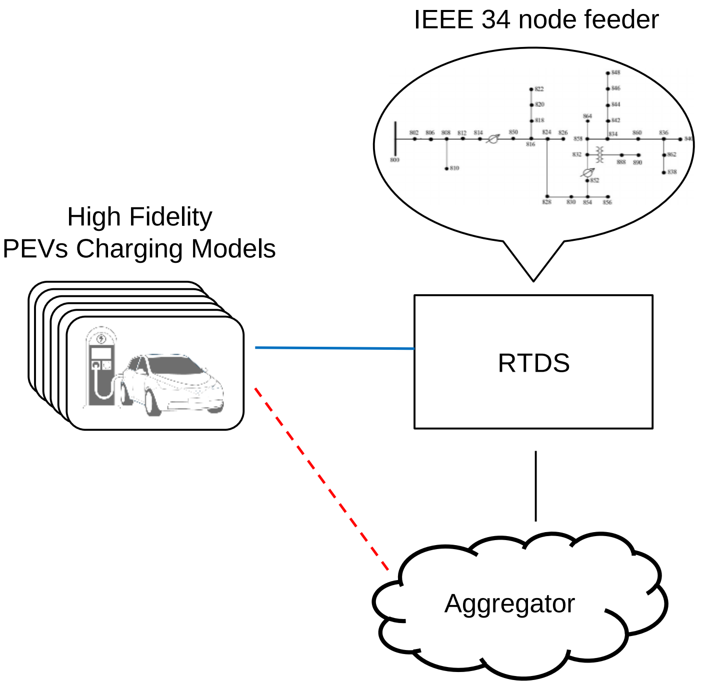
Next Steps and Expected Outcomes

- Develop an aggregator to communicate with buildings and coordinate their response across a distribution feeder to achieve a grid objective or provide a grid service
- Develop communications platform to exchange information between the aggregator and distribution feeder simulation located at INL, and building control systems located at ANL, PNNL, and NREL
- Use hardware-in-the-loop platform to study the ability of PEVs charging at commercial buildings to provide grid services
- Quantify the benefits of controlling PEV charging using the following two metrics:
  - Avoided cost of distribution feeder upgrades when charging is controlled
  - Avoided capacity of new generation when charging is controlled

Results to Date

Charging at Residences (FY16, FY17)

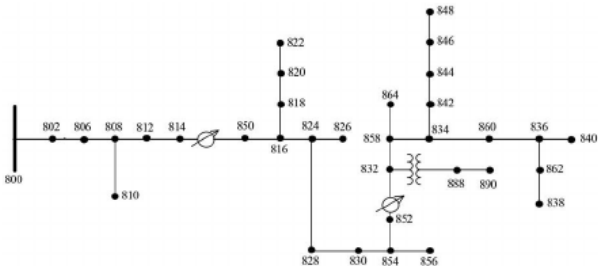
- Understand the charging of 10,000's of PEVs on a residential distribution feeder
- High-fidelity PEV charging models interact with the RTDS simulation
- PEV charging is controlled via aggregator.
- End Objectives:
  - Determine feasibility of PEVs to provide grid services
  - Quantify benefits of controlling PEV charging

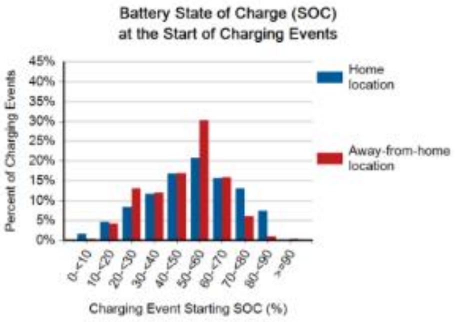


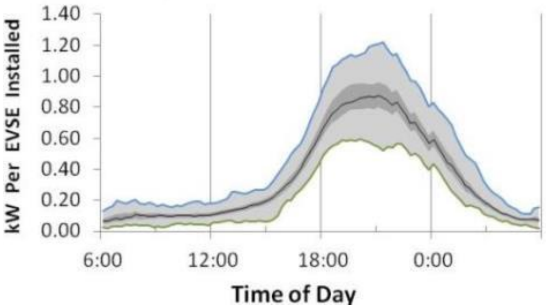
This platform will study the ability of PEVs charging at residences to provide grid services

Key Building Blocks

- Characterize charging of production PEVs
- Create High Fidelity PEV charging models
- Develop a PEV charging control strategy



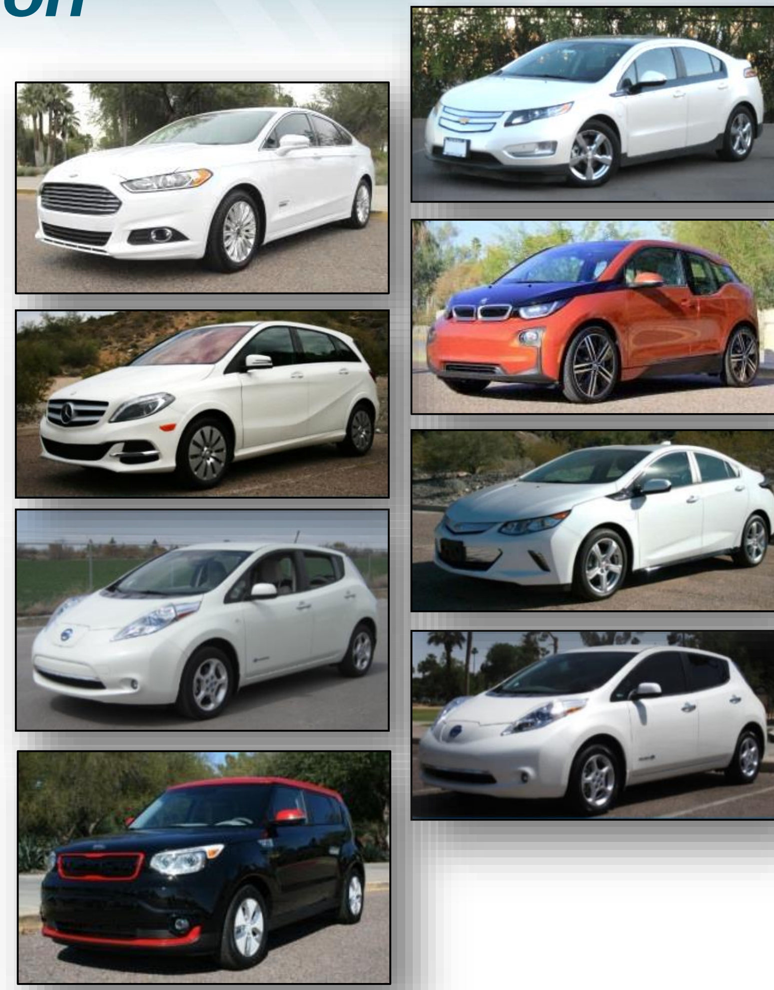




Characterize PEV Charging

Charge System Characterization

- Characterization results basis for:
  - Creating high fidelity PEV charging models
  - Developing PEV charging control strategy
- Charge systems evaluated: vehicles leveraged from AVTE fleet (Intertek)
  - Level 2
    - 2012 Chevy Volt
    - 2013 Ford Fusion
    - 2014 BMW i3
    - 2015 Mercedes B-Class
    - 2016 Chevy Volt
  - Level 2 and DCFC evaluation
    - 2012 Nissan Leaf
    - 2015 Nissan Leaf
    - 2015 Kia Soul



INL Photos and Photos courtesy: Intertek CECET

Level 2 Charger Characterization Lab Tests

- Control Pilot Tests
  1. Control Pilot Transition Test
  2. Control Pilot Charge Start/End Test
  3. Control Pilot Ramping Test
  4. Control Pilot Soft Start Test

- Voltage Deviation Tests
  5. Voltage Scan Test
  6. Long Notch Voltage Transient
  7. Delayed Voltage Recovery Transient
  8. Circuit Breaker Clearing Transient
  9. Momentary Outage Test

- Frequency Deviation Tests
  10. Frequency Scan Test
  11. Frequency Transient Test

- Voltage Distortion Tests
  12. Individual Harmonic Test
  13. Harmonic Profile Test

- Interrupt Charging Tests
  14. PEV Timeout Test
  15. Stop/Resume Charging Test

- Other Tests
  16. Power Limit Test
  17. Inrush Current Test
  18. Complete PEV Charge

Lab Tests Completed for Level 2 Charging

	Without Grid Emulator		With Grid Emulator					
	2014 BWM i3	2015 Merc. Benz B-Class	2012 Chevy Volt	2012 Nissan LEAF	2015 Nissan LEAF	2013 Ford Fusion	2015 Kia Soul EV	2016 Chevy Volt
Control Pilot Transition Test	X	X	X	X	X	X	X	X
Control Pilot Charge Start/End Test	X	X	X	X	X	X	X	X
Control Pilot Ramping Test						X	X	X
Control Pilot Soft Start Test						X	X	X
Voltage Scan Test			X	X	X	X	X	X
Long Notch Voltage Transient			X	X	X	X	X	X
Delayed Voltage Recovery Transient			X	X	X	X	X	X
Circuit Breaker Clearing Transient			X	X	X	X	X	X
Momentary Outage Test			X	X	X	X	X	X
Frequency Scan Test			X	X	X	X	X	X
Frequency Transient Test						X	X	X
Individual Harmonic Test						X	X	X
Hamonic Profile Test						X	X	X
PEV Timeout Test							X	X
Stop/Resume Charging Test	X	X	X	X	X	X	X	X
Power Limit Test	X		X	X	X	X	X	X
Inrush Current Test		X	X	X	X	X	X	X
Complete PEV Charge	X			X	X	X	X	X

Capabilities to develop and automate tests were created over time

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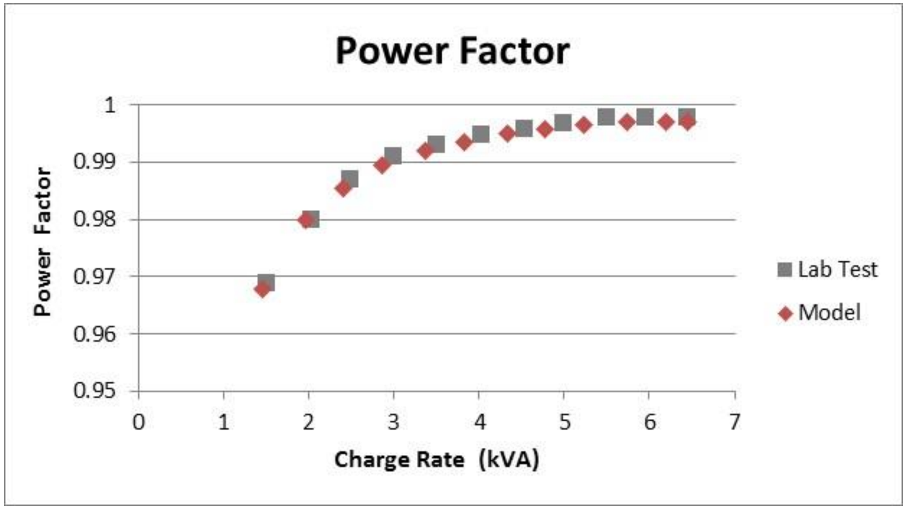
High Fidelity PEV Charging Models

High Fidelity Charging Models

- Models accurately represent the charging of production PEVs.
- Created charging models for the:
  - 2015 Leaf
  - 2016 Volt
  - 2013 Fusion
- Charging models were validated by comparing model output to lab tests.

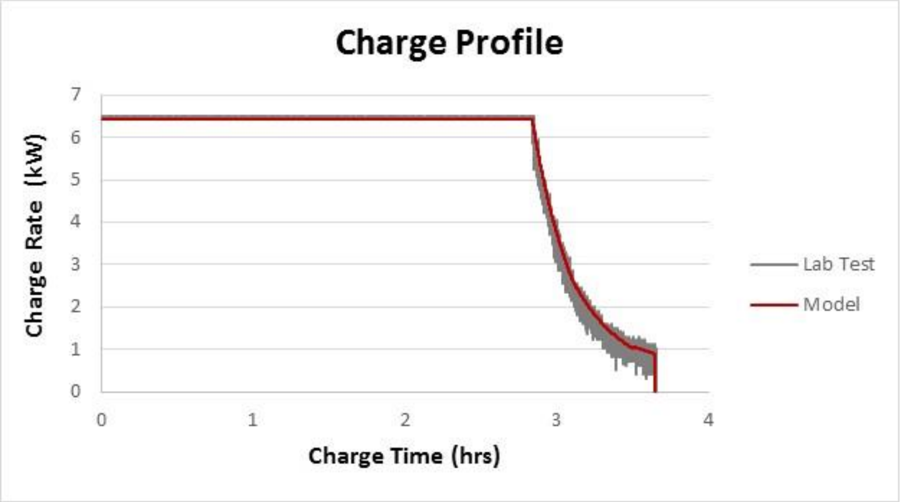
2015 Leaf Model Comparison with Lab Tests

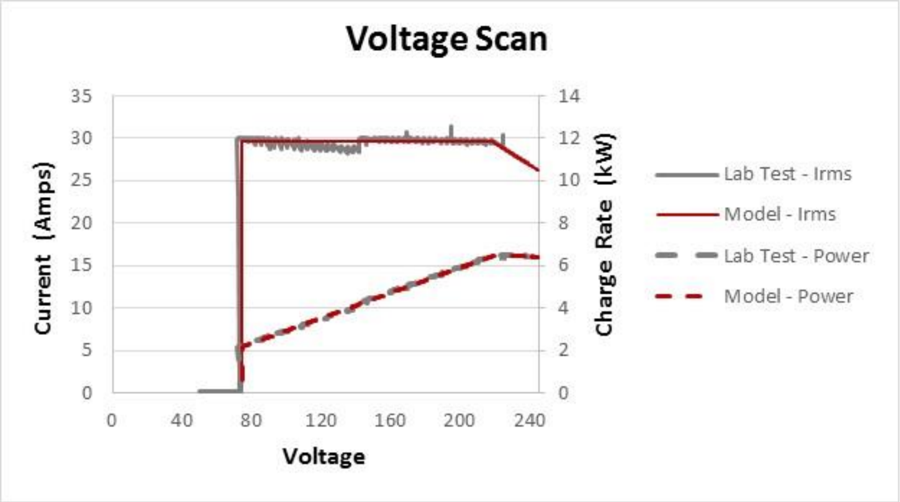
- Efficiency
  - Decreases with charge rate
  - Charge efficiency best at high charge rates
- Power Factor
  - Decreases with charge rate
  - Power factor close to unity at high charge rates
- When developing PEV charging control strategy PEVs only allowed to charge at high charge rates.
  - Ensure maximum efficiency and power quality



2015 Leaf Model Comparison with Lab Tests

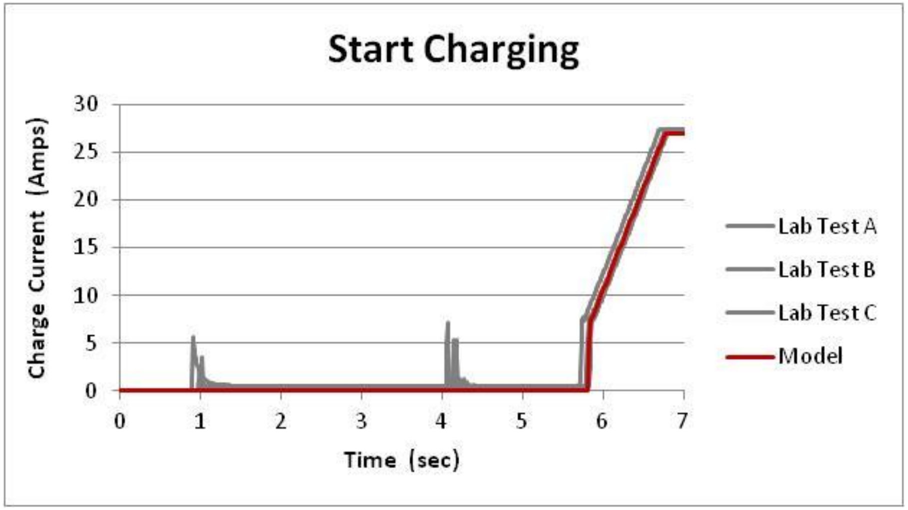
- Charge Profile
  - Describes the charger's max charge rate as a function of SOC
  - Charge rate decreases at high SOC when battery charged in constant voltage mode.
- Voltage Scan
  - Describes the behavior of the PEV charger as grid voltage changes
  - Describes the charger's max power and max current as a function of voltage

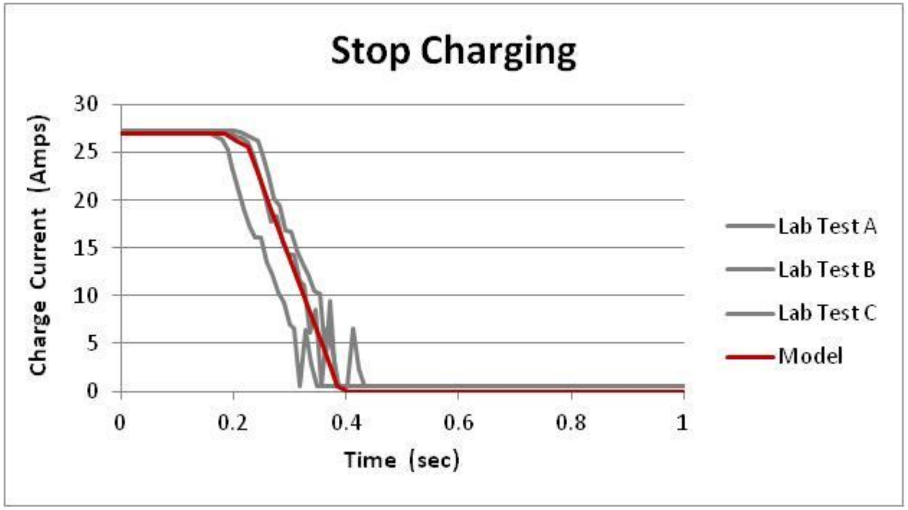




2015 Leaf Model Comparison with Lab Tests

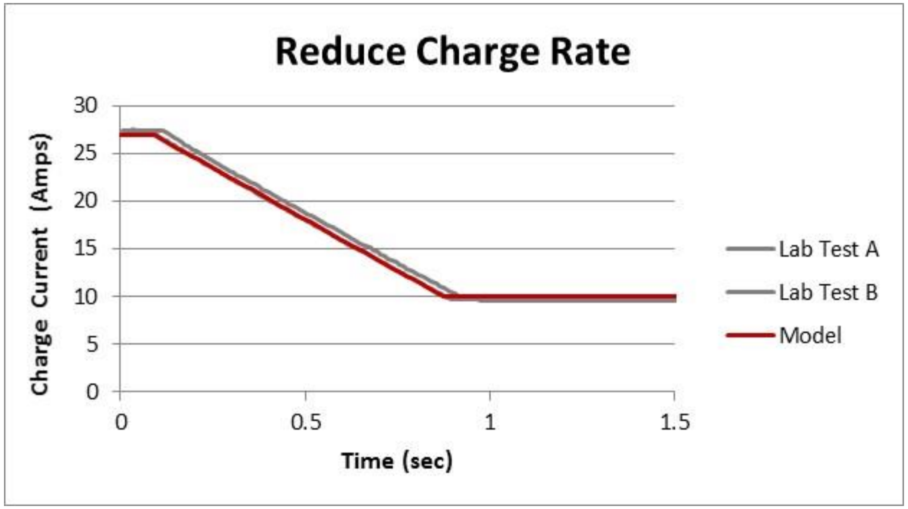
- Start Charging
  - Describes the transition from the off state to the on state
- Stop Charging
  - Describes the transition from the on state to the off state
- Accurately modeling the timing of transitions is important
  - Determining if PEVs can provide grid services that require fast response
  - Developing and testing PEV charging control strategies

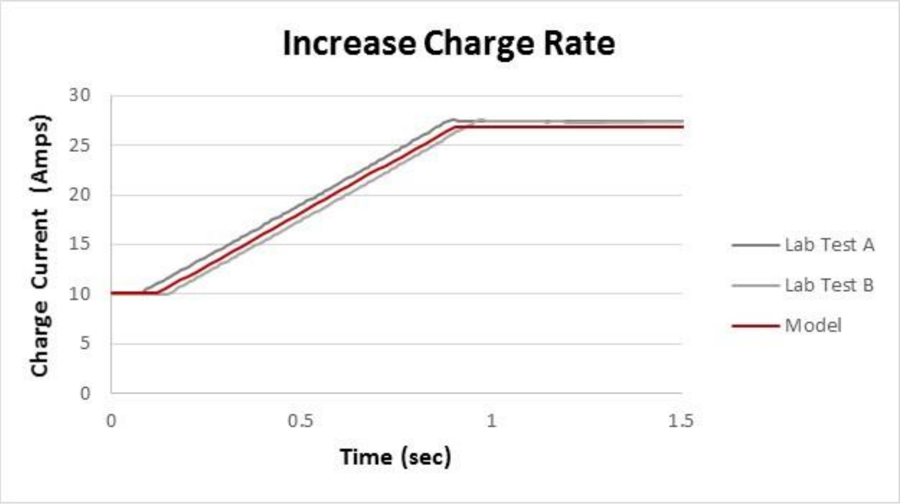




2015 Leaf Model Comparison with Lab Tests

- Reduce Charge Rate
  - Charging current transitions from 27 to 10 amps
- Increase Charge Rate
  - Charging current transitions from 10 to 27 amps
- Accurately modeling the timing of transitions is important
  - Determining if PEVs can provide grid services that require fast response
  - Developing and testing PEV charging control strategies

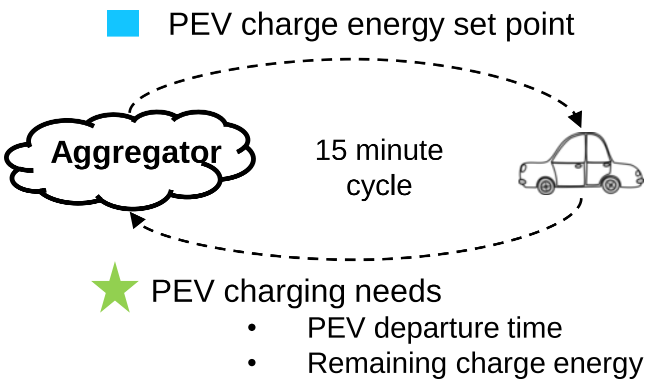


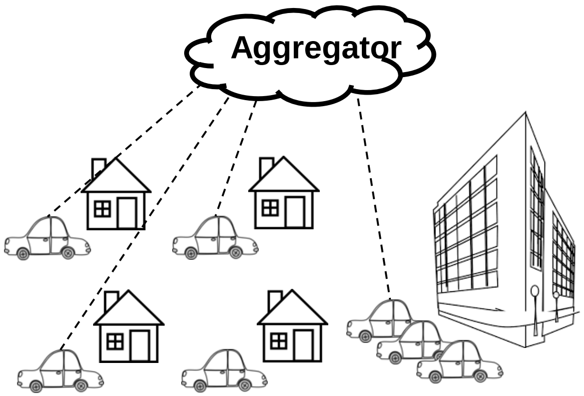


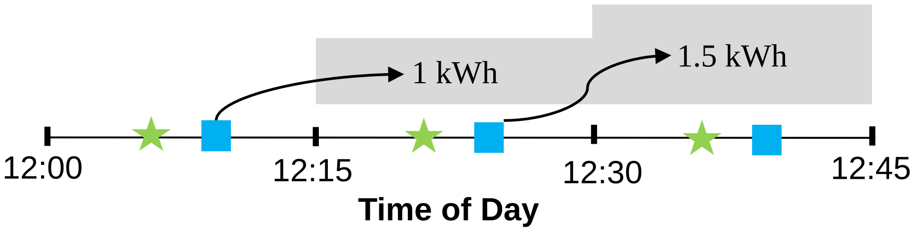
Direct Control Strategy

Overview

- Charge control strategy optimally allocates PEV charge energy over time to provide benefit to the grid.
- The following steps between the aggregator and PEVs occurs every 15 minutes:
  1. Each PEV sends its charging needs to aggregator
  2. Aggregator calculates each PEVs energy set point for next time step
  3. Aggregator sends energy set points to each PEV
- Charge control strategy is not sensitive to internet latency
- Does not require low latency communication between the aggregator and PEVs

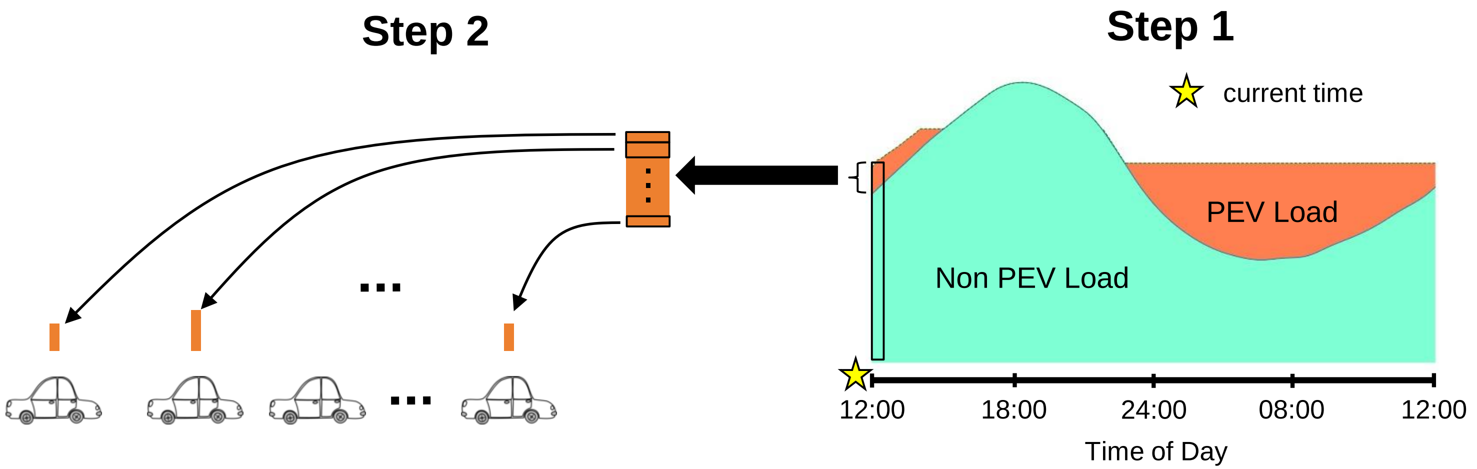






Two Step Control Strategy

- There are two steps in the charge control strategy
    1. Optimally allocate the total charging energy for all PEVs over next 24 hours
    2. Divide total PEV charging energy for the next time step between all PEVs
- The size of the optimization problem is determined by the number of times steps in a day.
- The size of the optimization problem is independent of the number of PEVs
- The charge control strategy is scalable and computationally efficient.



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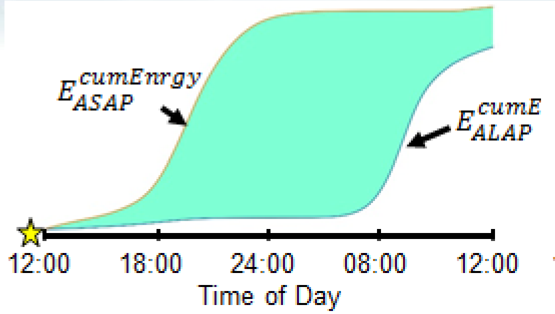
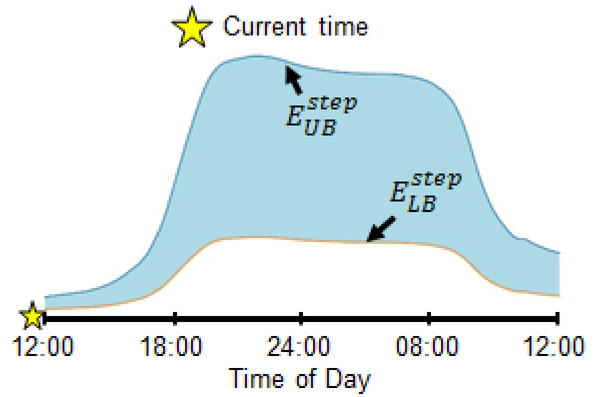
Two Step Control Strategy – Step 1

- **Step 1: Optimally allocate total charging energy for all PEVs over next 24 hours**
- Individual PEV charging constraints are combined into a single set of aggregate charging constraints
  - Only 96 decision variables when time step is 15 minutes
  - Reduces size of optimization problem
  - Making optimization problem independent of number of PEVs
- Constraints bound all possible ways PEVs can be charged
- Constraints help ensure PEV charging needs are met





Optimization Model

$$\min \quad f(E^{step}[i])$$

$$s.t. \quad E_{ALAP}^{cumEnrgy}[\mathrm{i}] \leq \sum_{j=0}^{i} E^{step}[\mathrm{j}] \leq E_{ASAP}^{cumEnrgy}[\mathrm{i}]$$

$$E_{LB}^{step}[\mathrm{i}] \leq E^{step}[\mathrm{i}] \leq E_{UB}^{step}[\mathrm{i}]$$

$$E^{step}[\mathrm{i}] + D_{net}[\mathrm{i}] \leq Feeder_{EnrgyLmt}^{step}$$

$$i = 0, \dots, N-1$$

Objective Functions

Peak Shave / Capacity Deferral

$$f(E^{step}[i]) = \sum_{i=0}^{N-1} (E^{step}[\mathrm{i}] + D_{net}[\mathrm{i}])^2$$

Reduce Ramping

$$f(E^{step}[i]) = \sum_{i=0}^{N-2} \left((E^{step}[\mathrm{i}+1] + D_{net}[\mathrm{i}+1]) - (E^{step}[\mathrm{i}] + D_{net}[\mathrm{i}]) \right)^2$$

Two Step Control Strategy – Step 2

- **Step 2: Divide total PEV charging energy for the next time step between all PEVs**

- Energy is allocated to PEVs based on each PEVs Charge Priority
  - $\text{ChargingPriority} = \frac{\text{MinTimetoCharge}}{\text{RemainingParkTime}}$
  - Charge Priority = 0.7 -> PEV must charge 70% of remaining park time.

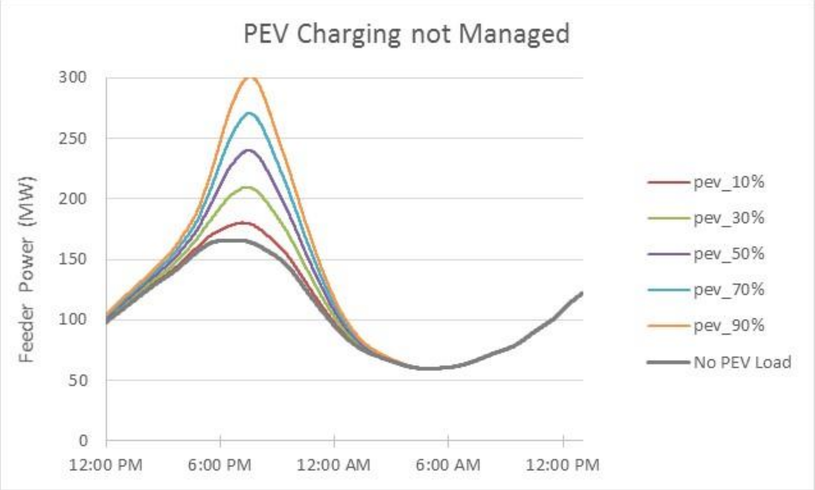
- PEVs with larger charge priority are charged before PEVs with a smaller charge priority.
- The strategy helps ensure that the PEVs charging needs are met.
  - PEVs that require a lot of energy in a short amount of time are allowed to charge before PEVs that require less energy or have more time to charge.

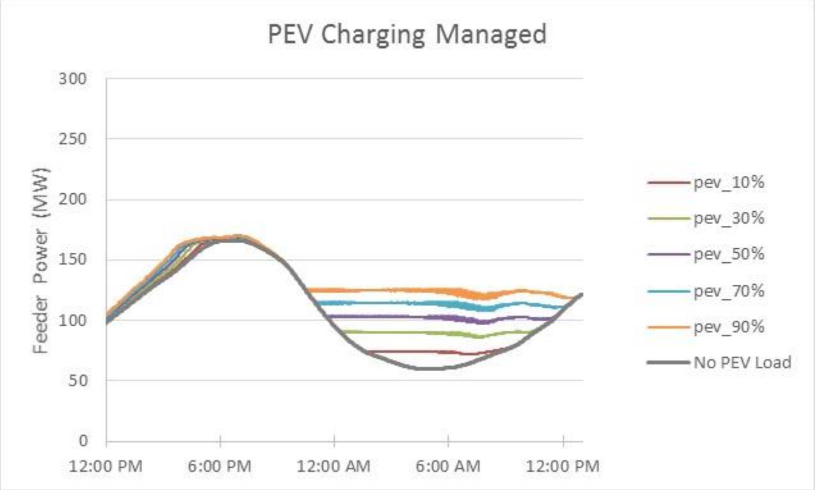
Testing Control Strategy - Setup

- System Composition
  - 100,000 residential homes
  - Penetration scenarios (percentage of homes with PEV)
    - 10%, 30%, 50%, 70%, 90%
- PEV charging model
  - 2015 Nissan Leaf charging model
- PEV charging behavior data
  - aka. park start time, park end time, charge start time, charge energy, …
  - Derived from actual charging data of PEV owners in the PG&E service territory
    - Data collected during the EV Project
- Non PEV Load data
  - Used the typical residential PG&E load data for 2016
    - Downloaded from PG&E website
    - Selected the day with the highest peak load

Testing Control Strategy - Results

- Unmanaged Charging
  - Aligns the PEV peak with the non PEV peak load.
  - Increases the ramping and variation in load shape.
- Managed Charging
  - Shifts PEV charging to off peak hours.
  - Flattens the load shape.
    - Mitigates the need for capacity upgrades.
    - Prevents PEVs from causing voltage regulation issues.





Peak Load (MW)

	No PEV Load	pev_10%	pev_30%	pev_50%	pev_70%	pev_90%
Not Managed	166	180	210	240	271	302
Managed	166	166	167	168	169	170
Increase in Peak		8%	25%	43%	60%	77%

Control Strategy Benefits

- The control strategy maximizes PEV charging efficiency and power quality

- The control strategy helps ensure that the PEVs charging needs are met.

- The control strategy is not sensitive to internet latency.

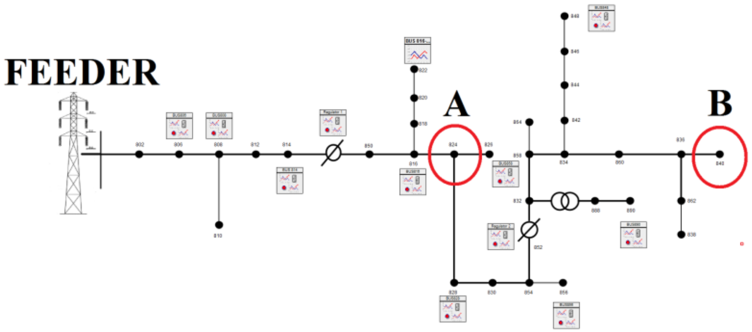
- Control strategy is scalable and computationally efficient.
  - Implemented strategy on desktop PC
  - Controlled charging for 1,000,000 vehicles
  - Took about 10-15 seconds to solve

Simulation Results

Results: Charging at Residences

Scenario: 50% PEV Penetration

- Ran a simulation on RTDS using high-fidelity PEV charging models
- System Composition
  - 75,000 Homes
  - 50% of homes own PEV
  - IEEE 34 node test feeder
- PEV Charge Model
  - 2015 Nissan Leaf charging model
- PEV Charging Behavior
  - aka. park start time, park end time, charge energy
  - Derived from actual charging data of PEV owners in PG&E service territory
- Non PEV feeder load
  - 2016 typical residential PG&E load data
  - Downloaded from PG&E website
  - The day in 2016 with the highest peak load used

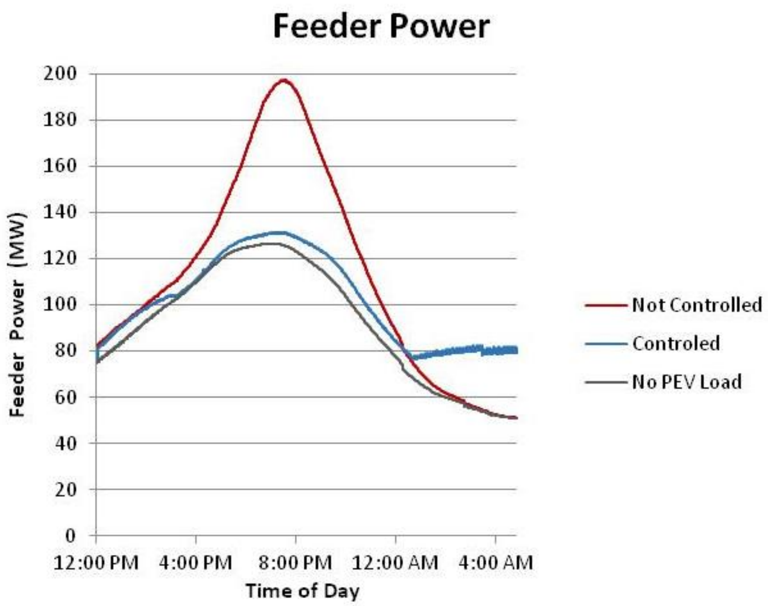


Source: INL

Results: Charging at Residences

Scenario: 50% PEV Penetration
Grid Service: Capacity Deferral

- PEVs provide capacity deferral when charging is coordinated with an aggregator
  - 65 MW of capacity deferred in this example
- Uncontrolled Charging
  - Aligns the PEV peak with the non PEV peak load
  - Increases the ramping and variation in load shape
- Controlled Charging
  - Shifts PEV charging to off peak hours
  - Flattens the load shape mitigating the need for capacity upgrades



Feeder Peak:

127 MW -> No PEV Charging

132 MW -> Controlled PEV Charging

197 MW -> Uncontrolled PEV Charging

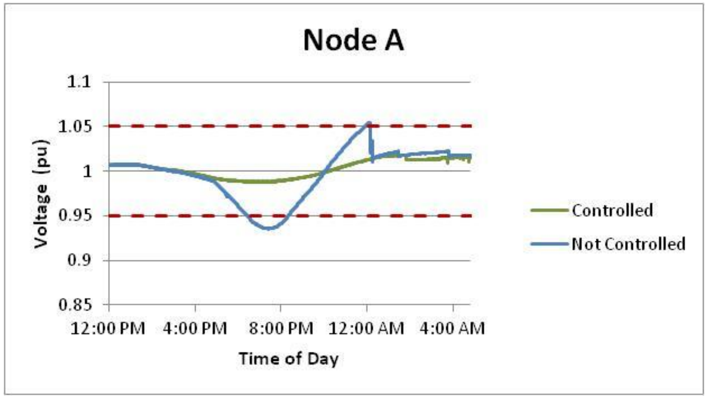
Controlled Charging requires 4% increase in capacity

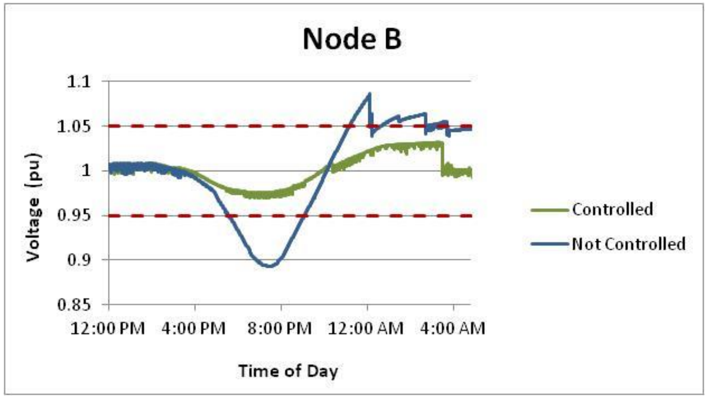
Uncontrolled Charging requires 55% increase in capacity

Results: Charging at Residences

Scenario: 50% PEV Penetration
Grid Service: Voltage Support

- PEVs provide voltage support when charging is coordinated with an aggregator
- Voltage profile is flatter when PEV charging is controlled
- Uncontrolled Charging
  - Voltage deviates outside normally accepted limits (+/- 5% of nominal)
  - This requires utility upgrades to address the issue
- Controlled Charging
  - Voltage is within normally accepted limits (+/- 5% of nominal)
  - No utility upgrades needed



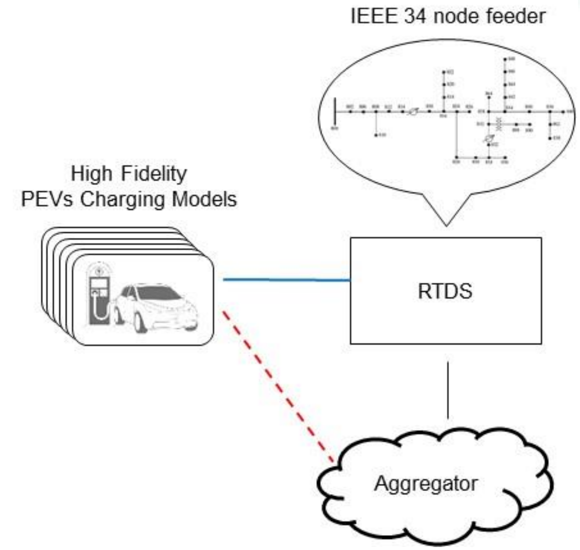


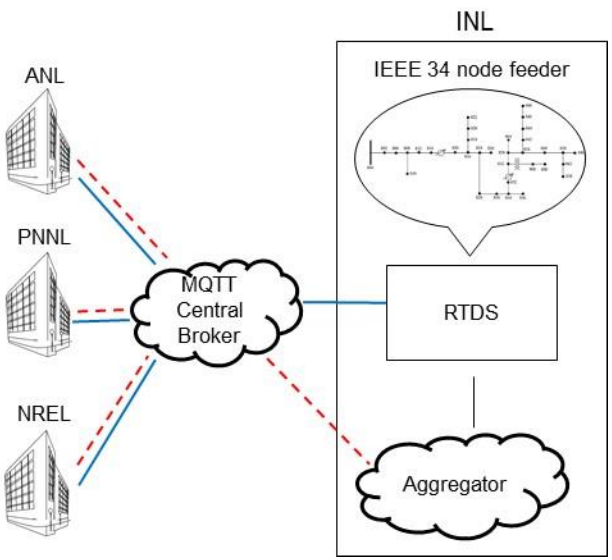
Node A is closer to the feeder substation than Node B causing Node A to have less variation in the voltage profile than Node B.

Summary

Summary

- PEV charging at Residences (initial work)
  - Aggregator optimally allocates PEV charge energy over time to provide benefit to the grid.
  - Controlling PEV charging can provide voltage support and capacity deferral.
  - **To do:** Quantify the benefits of controlling PEV charging at residences
- PEV charging at commercial buildings (future work)
  - Study the ability of PEVs charging at commercial buildings to provide grid services
  - Modify aggregator to coordinate PEV charging at many buildings across a distribution feeder
  - Quantify the benefits of controlling PEV charging at commercial buildings:
    - Avoided cost of distribution feeder upgrades when charging is controlled
    - Avoided capacity of new generation when charging is controlled





Questions