Overview of INL Vehicle/Grid Integration Research

Don Scoffield
John Smart
Barney Carlson

Advanced Vehicles group

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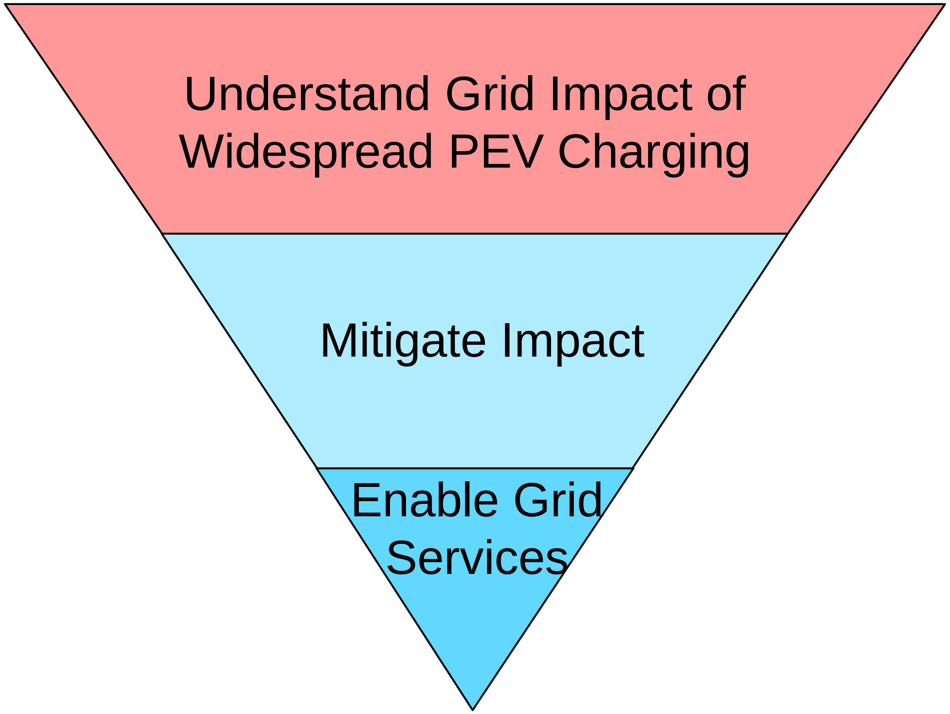
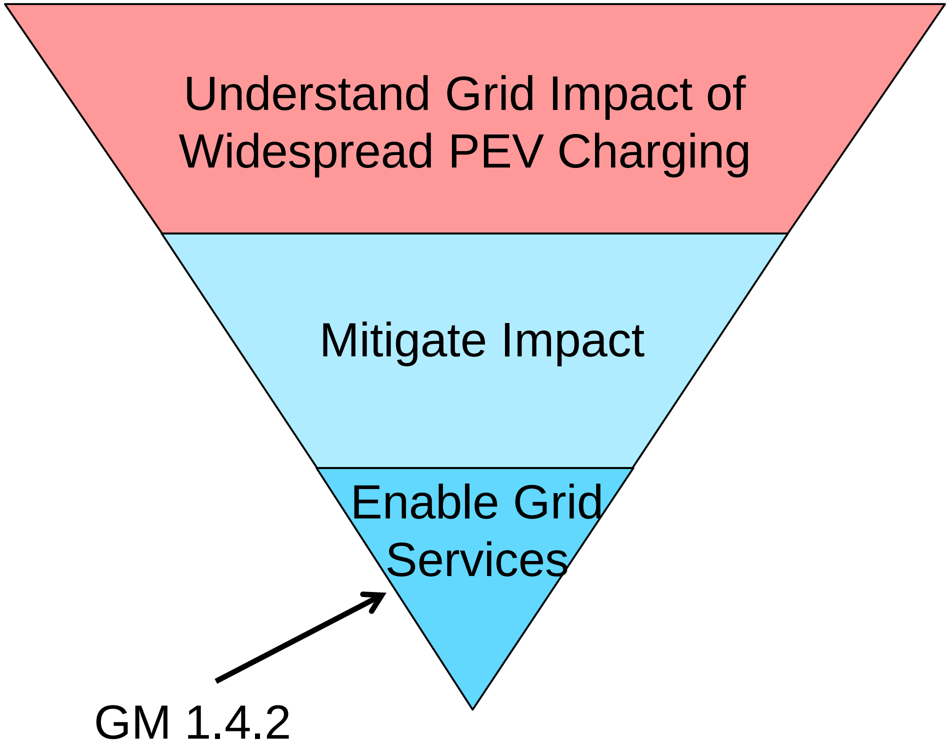
Why Vehicle/Grid Integration is Needed?



- Under what circumstances will PEV charging begin to cause grid problems?
  - PEV Penetration Level
  - Charge Rate
- What are the grid problems and cyber security risks?
- What is the best way to mitigate these grid problems?
- Can PEVs provide grid services?

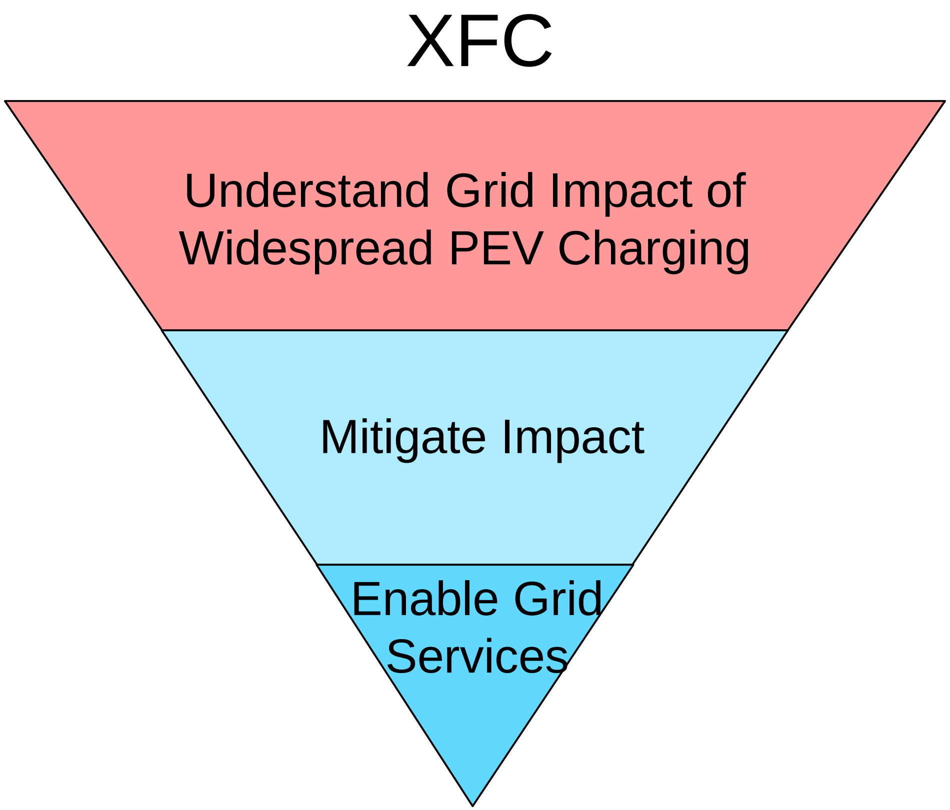
Vehicle/Grid Integration of Level 2 Charging

GM0085



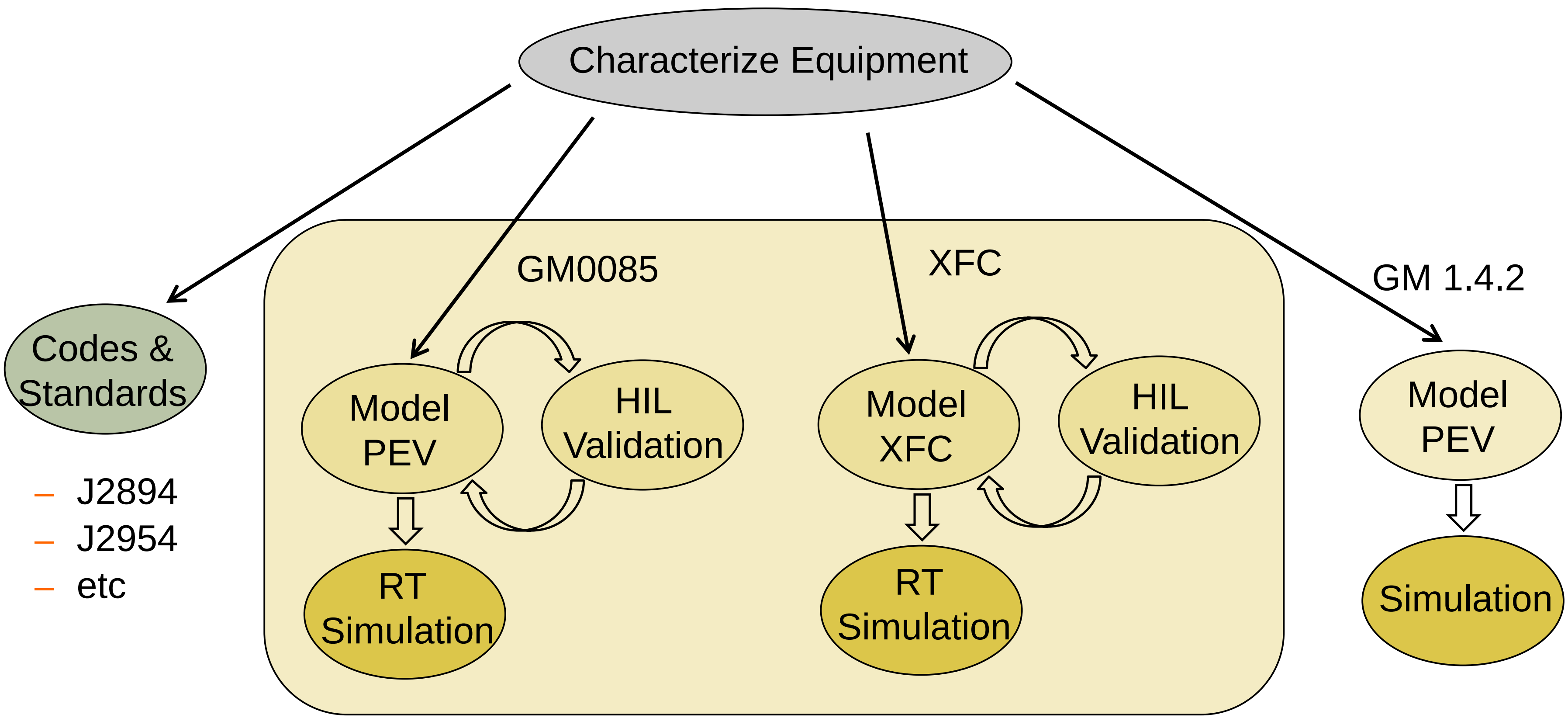
- Understand impact of *uncontrolled* Level 2 charging on the distribution feeder as PEV penetration increases
- Develop an aggregator control strategy to mitigate negative impacts
- Understand the cyber security risks associated with the control strategy
- Leverage control strategy to provide grid services

Vehicle/Grid Integration of Extreme Fast Charging (XFC)



- Understand impact of XFC on the grid as PEV penetration and charge rates increase
- Investigate ways to mitigate XFC grid impacts:
  - On-site energy storage
  - Infrastructure upgrades
  - Controlling XFC
- Understand the cyber security risks associated with XFC
- Explore potential for XFC to provide grid services

How Vehicle/Grid Integration is Studied?

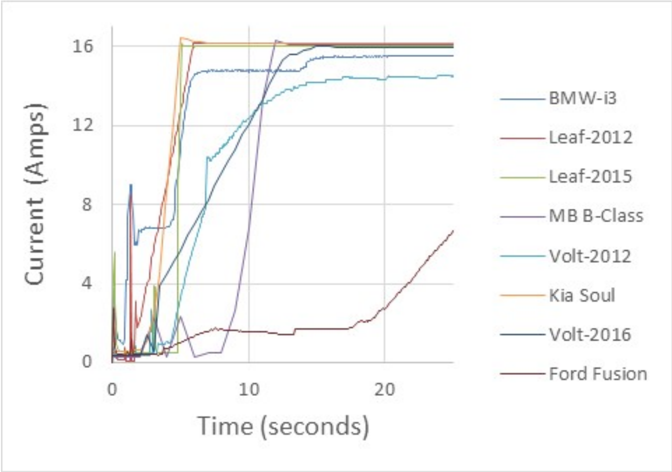


Investigate vehicle/grid electrical interactions.

Investigate grid services that PEVs can provide.

PEV Model Creation

- In a Grid Modernization Lab Consortium project (GM0085) project, we are creating vehicle-level charging models for three production PEVs:
  - 2015 Nissan Leaf
  - 2016 Chevy Volt
  - 2013 Ford Fusion
- These models will be executed in a real time environment with a Real Time Digital Simulator (RTDS)
  - Understand the impact of PEV charging on a residential distribution feeder
- The models accurately captures:
  - Charging efficiency as function of charge rate
  - Power factor as function of charge rate
  - Max charge rate as function of Battery SOC
  - Charging transitions when control pilot changes
  - Chargers power and current limits as a function of voltage



Transition from off state to charging state.

INL's Electric Vehicle Infrastructure Laboratory

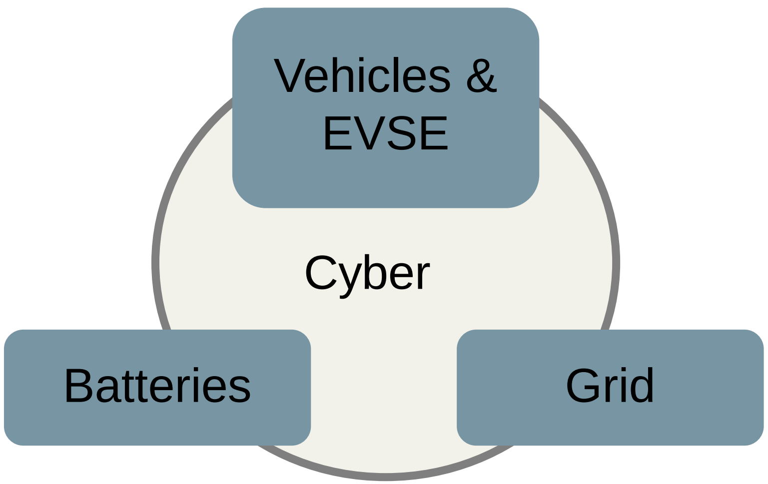
- Testing, evaluation and system characterization
  - Wireless power transfer (WPT)
  - Conductive charging systems
    - AC Level 1/ Level 2 systems
    - DC fast charging
  - Cyber security vulnerability assessment (L2 & DCFC)
- Measure performance metrics
  - Power transfer capability, efficiency, EM-field emissions, power quality
  - Steady-state characterization
  - Response to dynamic grid events and interaction with electric grid via hardware in the loop
- Wide range of input power
  - 120 VAC to 480 VAC 3ϕ
  - Up to 500 kW
  - Grid emulator enables dynamic grid event testing

https://avt.inl.gov/panos/EVLTour/?startscene=pano5141

VTO Director Tour of INL’s EVIL/RTDS Lab

- On April 18th, Michael Berube and Congressman Mike Simpson (R-ID) toured INL
- The tour highlighted INL’s capabilities for Extreme Fast Charging R&D

Electric Vehicle Infrastructure Lab (EVIL)

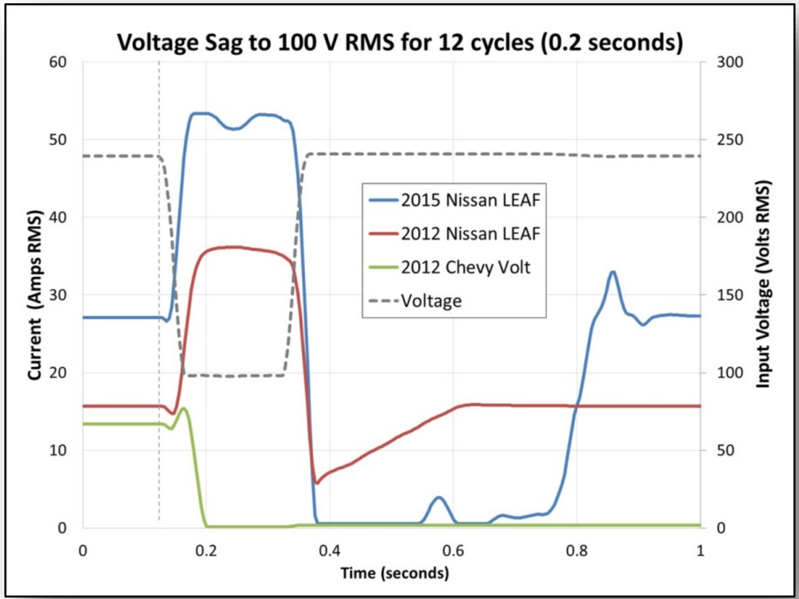


Non-destructive Battery Evaluation Lab (NOBEL)

Real-time Power & Energy Systems Lab

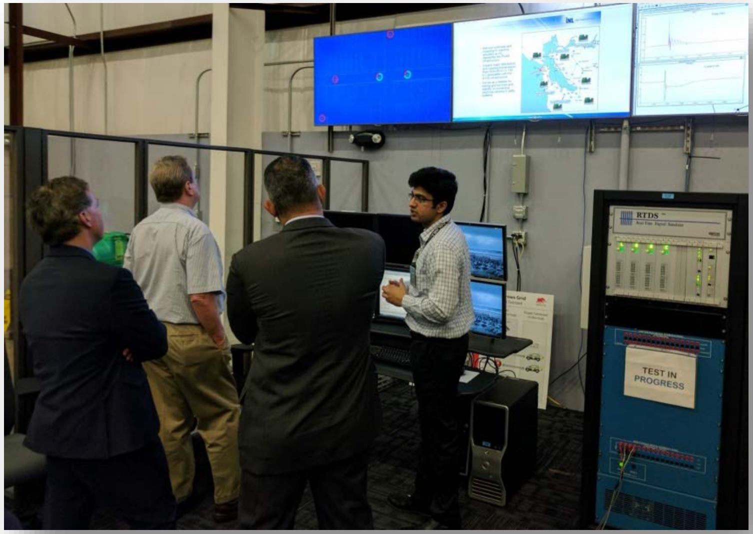
PEV Grid Impact Demo

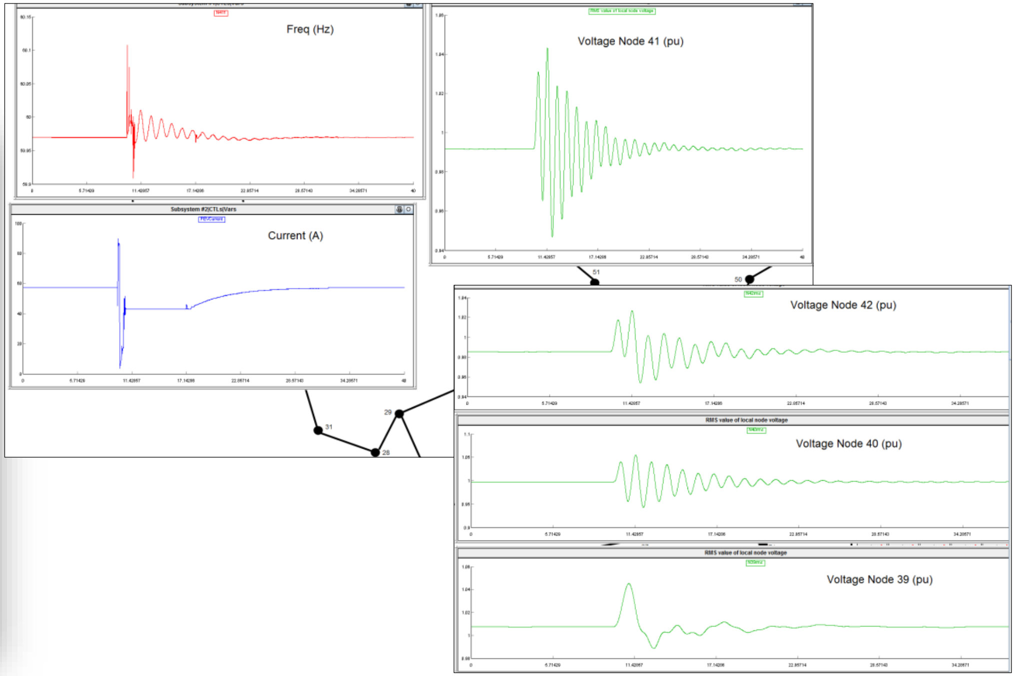
- INL staff demonstrated PEV / grid integration research capabilities using the hardware-in-the-loop platform developed under GM0085
- A 2015 Nissan LEAF, 2012 Nissan LEAF, and 2012 Chevy Volt were exposed to a voltage sag
  - Down to 100 V RMS
  - For 12 cycles (0.2 seconds)
- The response of these PEVs was measured in real time and sent to the RTDS
  - Both LEAFs increased current in attempt to maintain charge power



PEV Grid Impact Demo

- The RTDS simulated the impact on the Bay Area sub-transmission grid (PG&E) if a voltage sag occurs when 4,000 PEVs are charging
- The charge system response (from 4000 PEVs) caused a voltage fluctuation through the Bay Area that lasted for 30 seconds
  - Node 41 – San Francisco
  - Node 42 – Daly City
  - Node 40 – San Mateo
  - Node 39 – Palo Alto (30 mi away)
- **DC fast charger response impact will be greater than this Level 2 example**





Charge System Characterization

- 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 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

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

DC Fast Charger Characterization Tests

1. Complete Charge (Efficiency, Power Quality)
2. Voltage Scan Test
3. Circuit Breaker Clearing Transient on 1 Phase
4. Circuit Breaker Clearing Transient on 2 Phases
5. Circuit Breaker Clearing Transient on 3 Phases
6. Frequency Scan Test
7. Frequency Transient Test
8. Phase Magnitude Imbalance Test
9. Phase Angle Imbalance Test

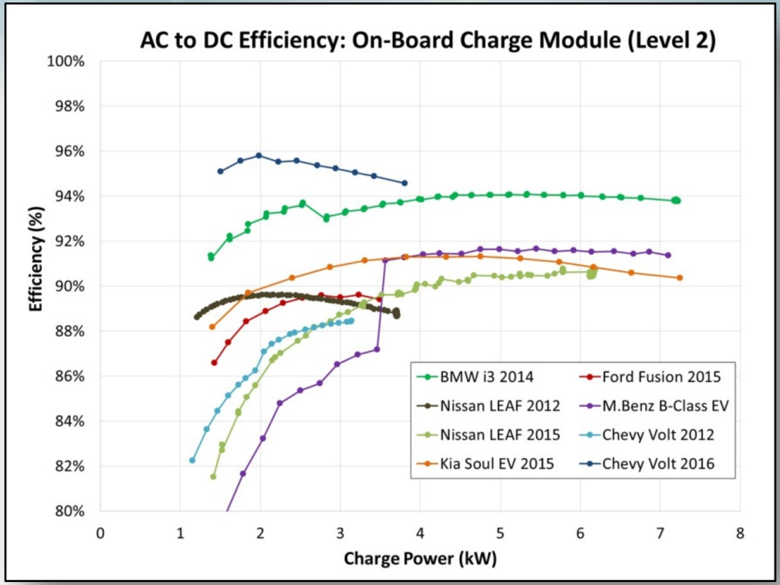
Tests Completed for DC Fast Charging

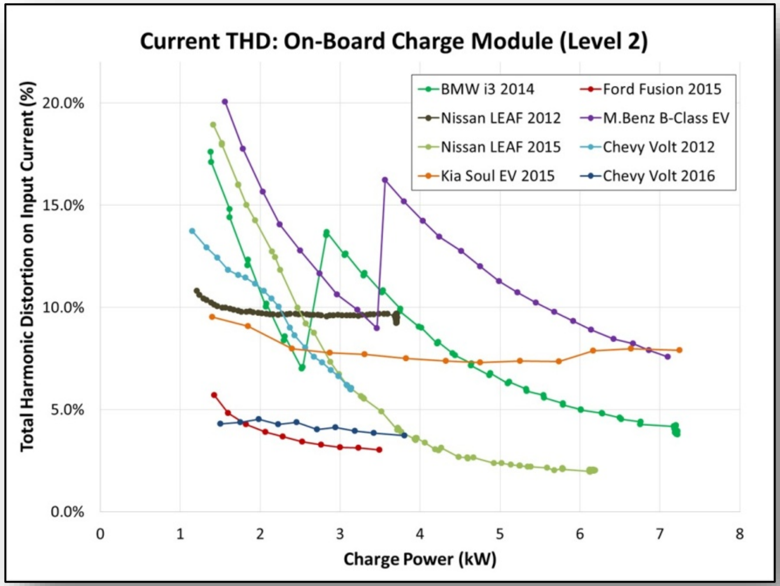
	2012 Nissan LEAF	2015 Kia Soul EV	2015 Nissan LEAF
Complete Charge - (Efficiency, Power Quality)	X	X	X
Voltage Scan Test		X	
1 Phase Circuit Breaker Clearing Transient		X	
2 Phase Circuit Breaker Clearing Transient		X	
3 Phase Circuit Breaker Clearing Transient		X	
3 Phase Momentary Outage Test		X	
Frequency Scan Test		X	
Frequency Transient Test		X	
Phase Magnitude Imbalance Test		X	
Phase Angle Imbalance Test		X	

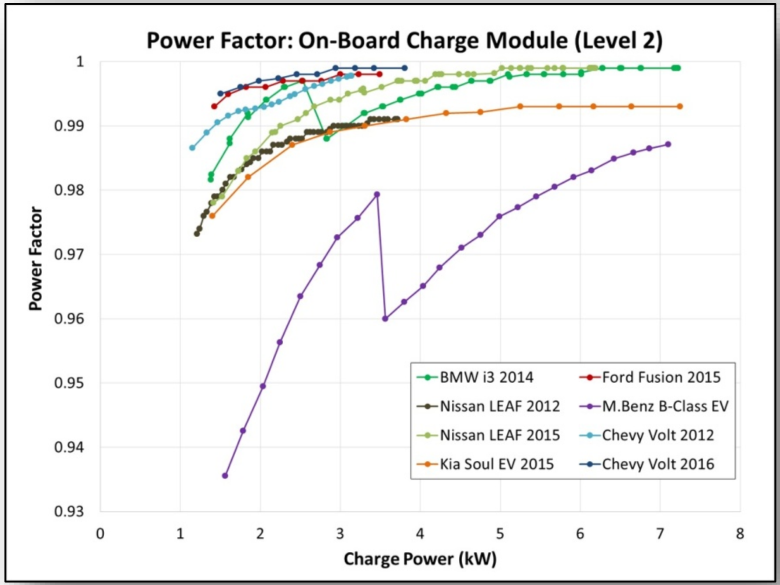
- Characterized data → dynamic model
- Dynamic model validated via HIL
  - PEV
  - DC Fast Charger
  - Grid Emulator
  - RTDS (real-time grid simulation)

Level 2 Charging Results

- Designed for best operation near full power
  – Highest efficiency and Power Factor
  – Lowest THD
- In GM0085, we are using these results to inform
  – The creation of PEV charging models
  – The charging control strategy
    - Avoids charging at low charge rate

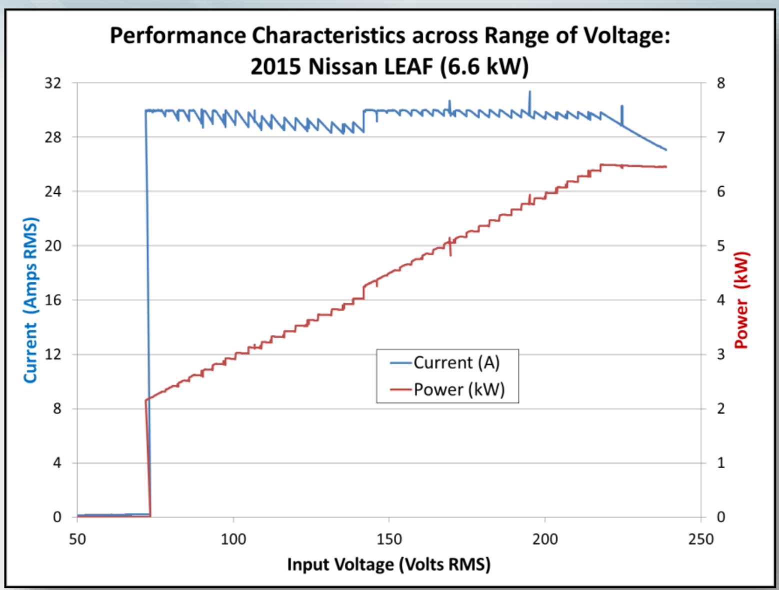


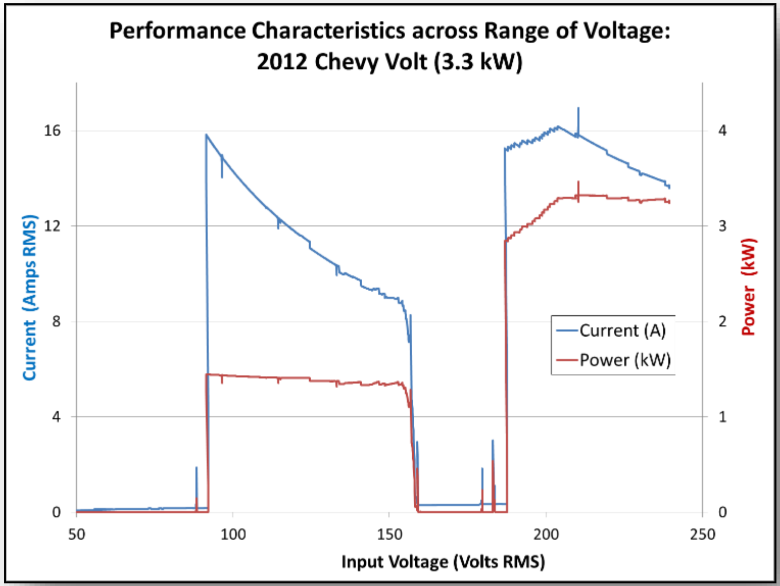


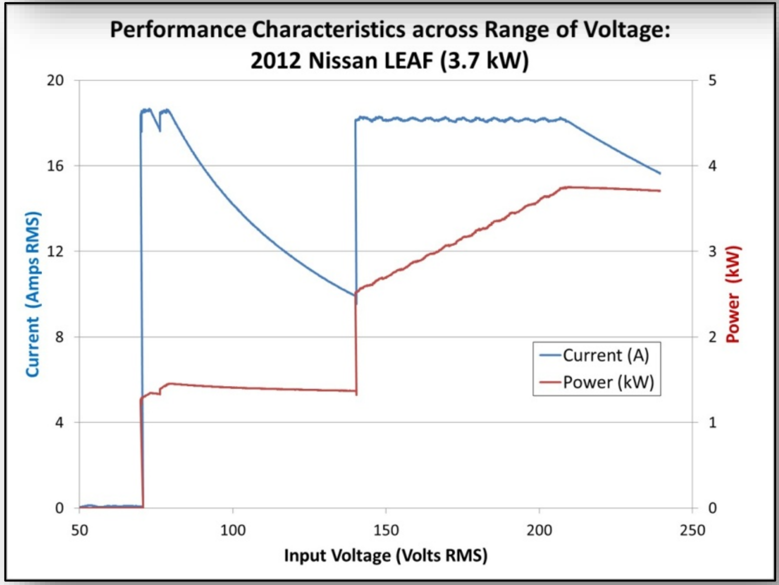


Level 2 Charging Results

- The on board charger current and power limits depend on the voltage.
  - Limits describe how charger behaves with drifting voltage
  - Limits are PEV specific
- In GM0085, we are using these results to inform the creation of the dynamic PEV charging models.

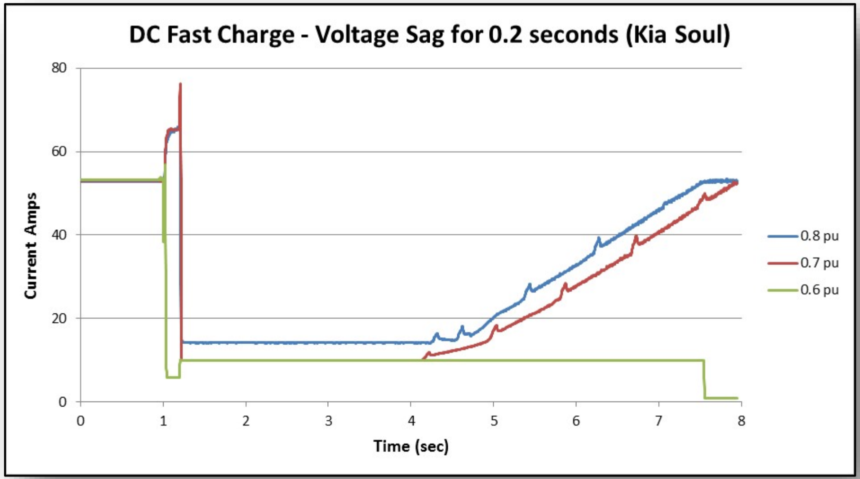




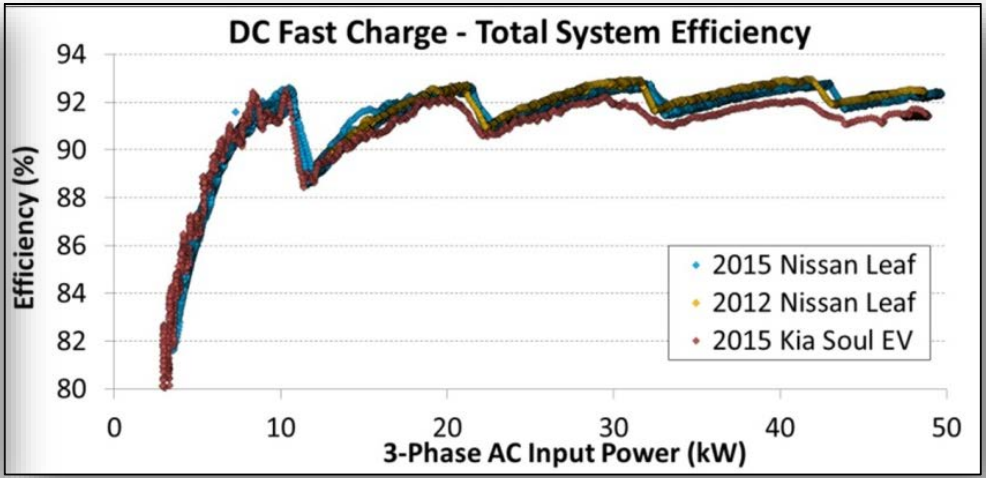


DC Fast Charger Results

- 50-kW DCFC characterization can be used to:
  - Create dynamic models for grid impact studies of today's 50-kW DCFCs
  - Extrapolate preliminary dynamic models for grid impact studies of future XFC systems



Response to voltage sag results in current increase followed by 3 second interruption



Modular design improves partial power performance

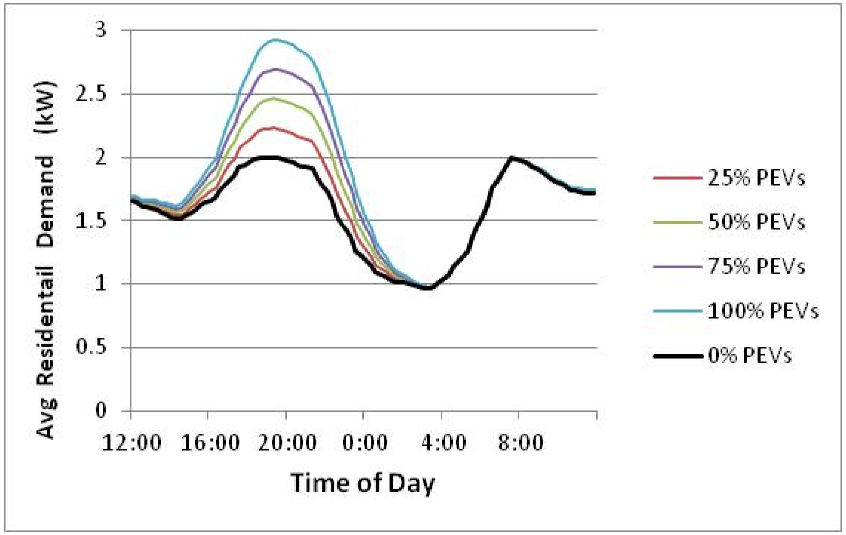
Summary

- Vehicle/Grid integration research is necessary to understand
  - The point at which PEV charging begins to cause grid problems
  - What the grid problems and cyber security risks are
  - The best ways to mitigate these grid problems
  - Explore the potential for PEVs to provide grid services
- INL does this by characterizing, modeling, validating, and simulating PEV charging infrastructure on an electric grid
- Higher power DC charging impacts and interaction with the grid should be determined using the INL EVI lab and real time hardware-in-the-loop capabilities (RTDS)
- For GM0085 we have characterized real PEVs, are in the process of creating validated dynamic models and in the near future will study grid impacts of PEV charging through real time simulations.
- The same process can be used for XFC.

Back-up Slides

Example – Widespread Uncontrolled PEV Charging

- Impact of uncontrolled PEV charging on residential loads
- Uncontrolled Level 2 charging tends to occur at same time as peak system load causing peak load to increase.
- Increase in peak can be mitigated
  - Controlling PEV charging
  - Shifting to off peak hours.
- Data in example from:
  - Typical residential load shape in Pacific Northwest from Residential Building Stock Assessment
  - PEV charging data in Seattle from EV Project

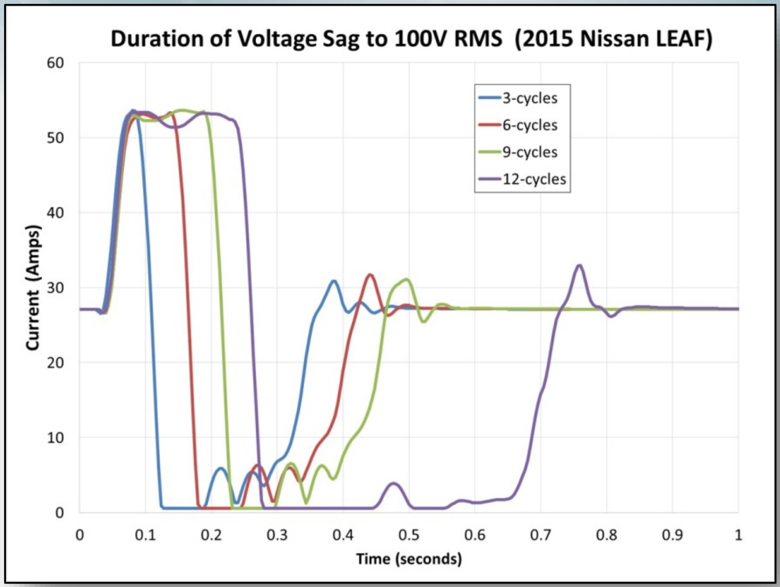


PEV Penetration	% Increase in Peak Demand
25%	12%
50%	23%
75%	35%
100%	46%

Level 2 Results:
Other Response Results

Duration of voltage sag impact:

- 2015 Nissan LEAF
  - Increases current through voltage sag to maintain charge power
  - Stops charging after voltage sag ends
  - Recovers to normal charge power within <0.5 second after end of voltage sag



Question: Can a reduced Control Pilot signal prevent the increase in current during a voltage sag event? – NO –

- 2015 Nissan LEAF
  - Current increases during the voltage sag for both control pilot settings
    - 30 Amps
    - 16 Amps