ORNL Dynamic Wireless Power Transfer System Demonstration with Electrochemical Energy Buffers

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Power Electronics and Electric Machinery Group

Oak Ridge National Laboratory

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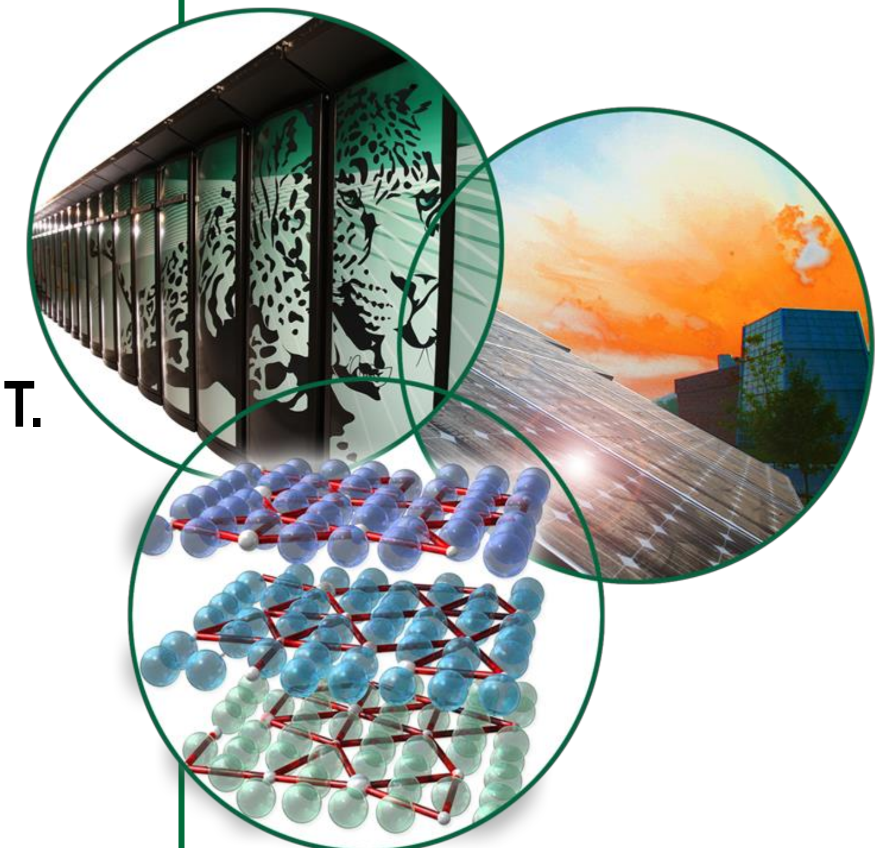

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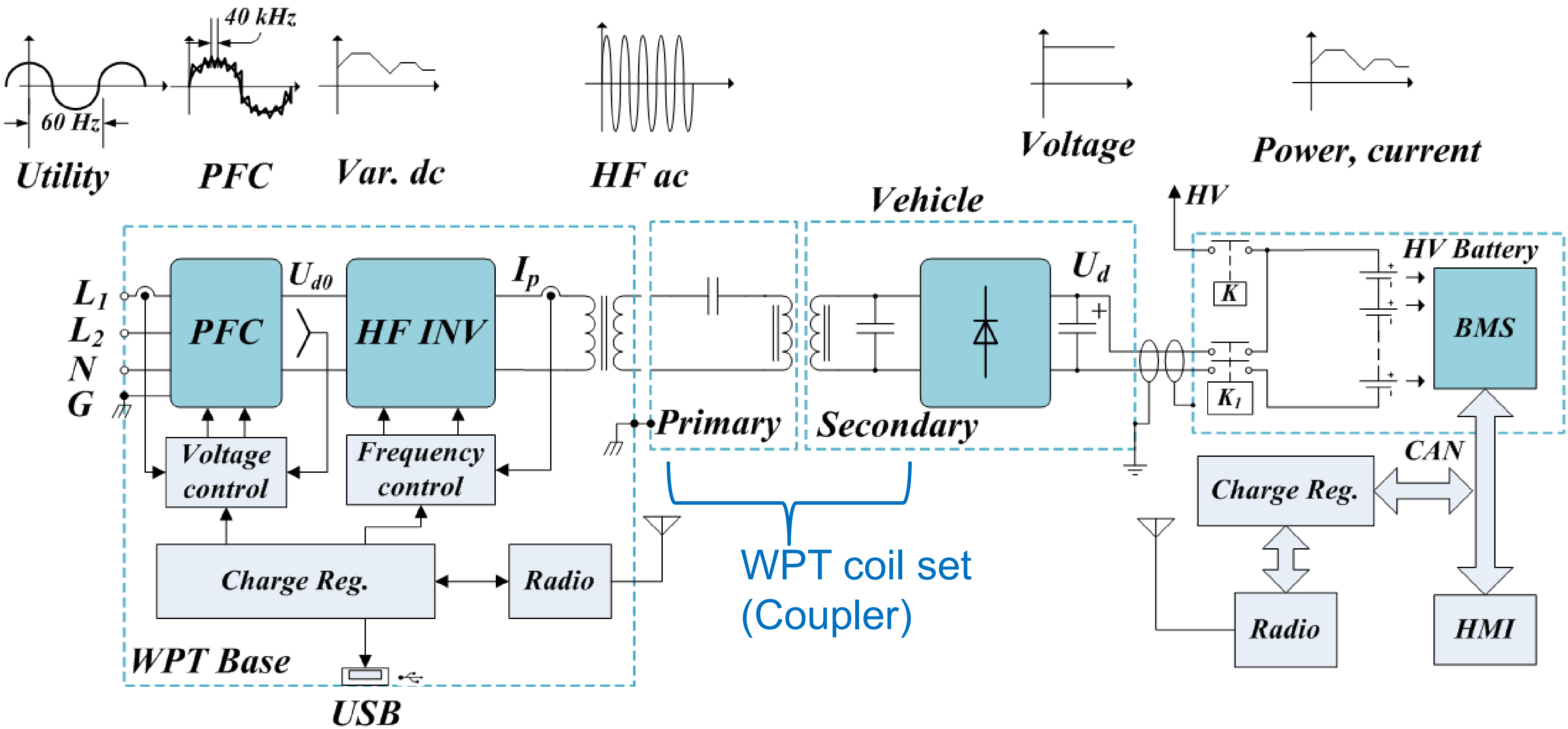
Outline

- Introduction and hardware system description
- Elements of wireless power transfer (WPT) system control
- Case study of ORNL's in-motion WPT
- Vehicle and grid side power smoothing with electrochemical energy buffers
- Experimental test results

Introduction and System Description

- Overall system functional block diagram
- 5 cascaded power conversion stages, ensuring safety and control flexibility



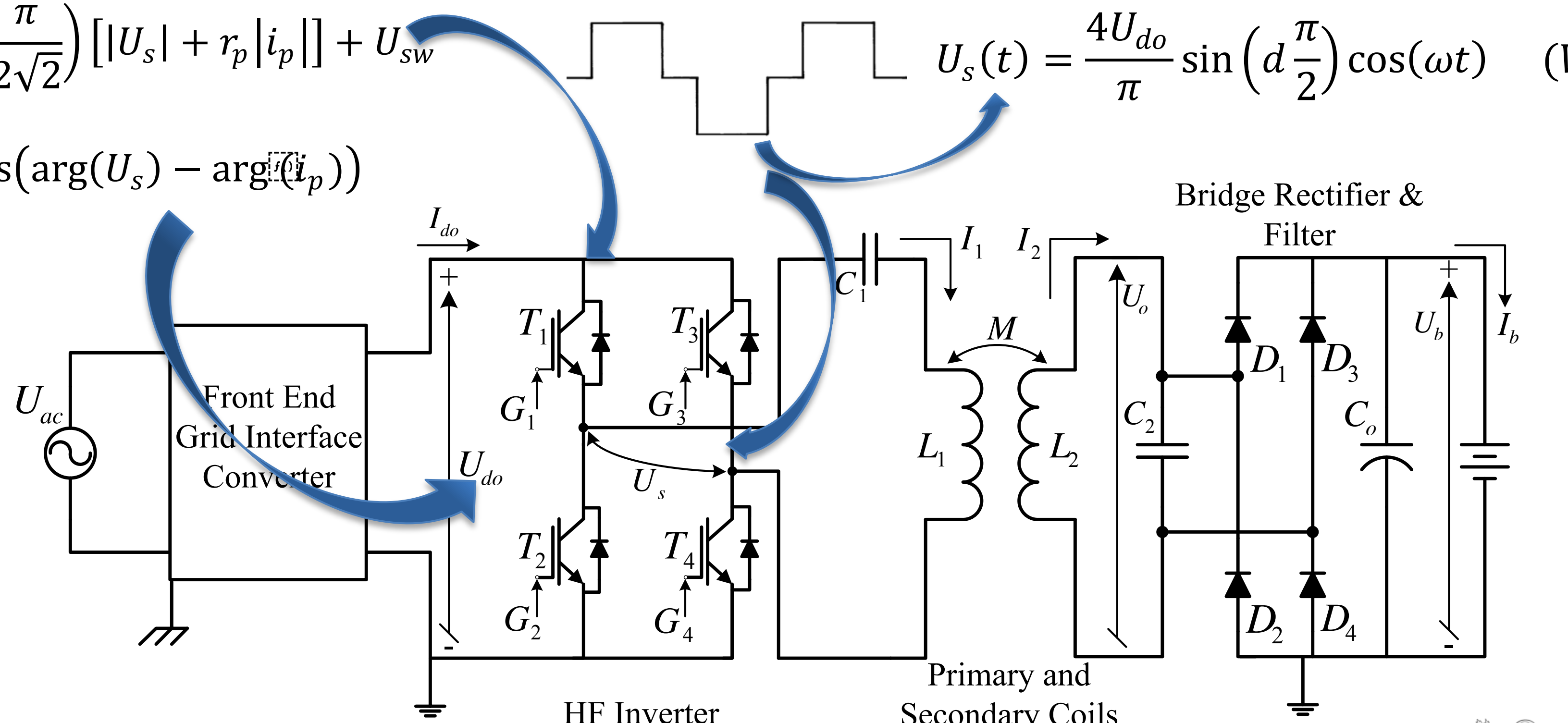
Elements of WPT System Control

- Inverter duty cycle, *d*, pulse width modulation,
- Voltage control, U_{dc}, with active front-end rectifier with power factor correction,
- Frequency control for reactive power minimization due to load (battery SOC), gap (*z*), and misalignment changes.

$$U_{do} = \left(\frac{\pi}{2\sqrt{2}}\right)\left[|U_s| + r_p|i_p|\right] + U_{sw}$$

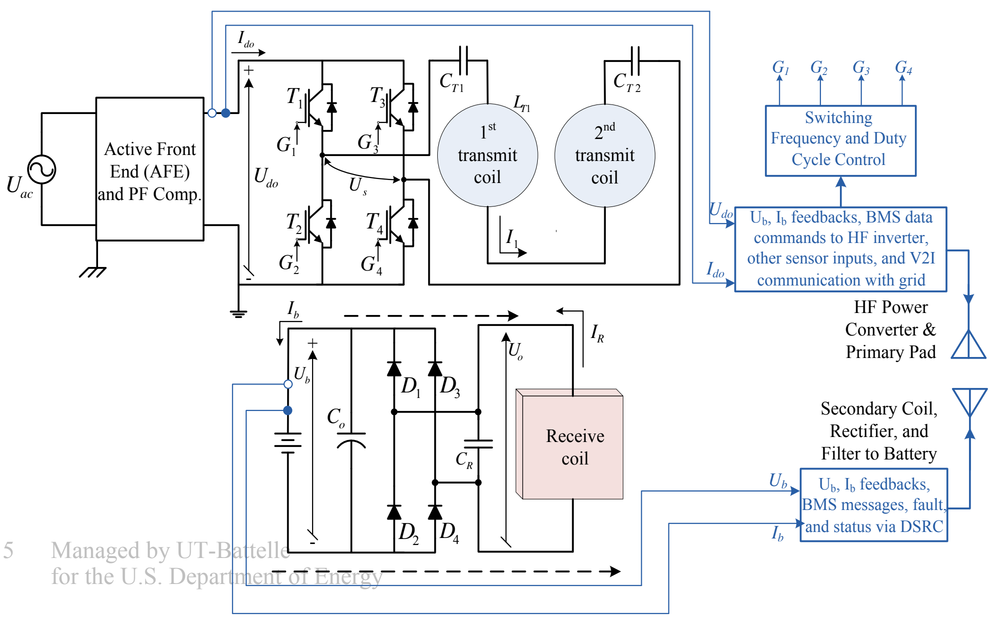
$$U_s(t) = \frac{4U_{do}}{\pi}\sin\left(d\frac{\pi}{2}\right)\cos(\omega t) \quad (V_{rms})$$

$$PF = \cos\left(\arg(U_s) - \arg(i_p)\right)$$



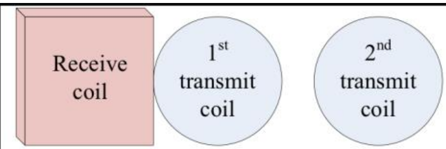
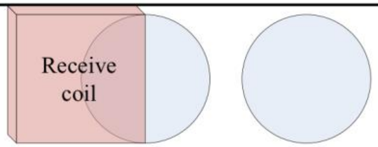
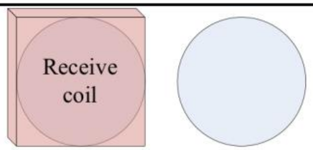
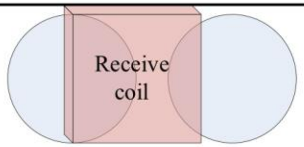
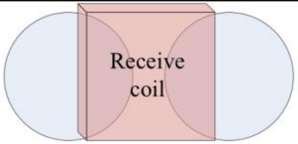
Case Study of ORNL's In-motion WPT

- Initial 2-coil track, upgraded to 6-coil track for internal funded in-motion wireless charging system
- System uses a Zylinx ZP24D-250RM 2.4GHz Radio Modem and optical sensors for communications and relative vehicle position determination.

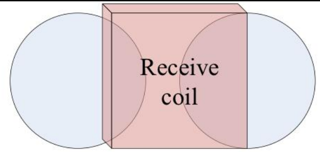
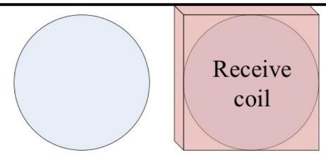
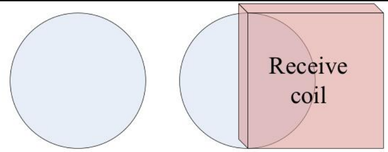
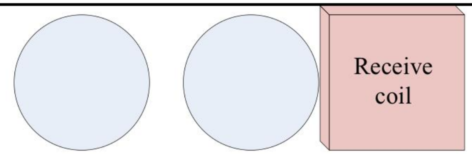


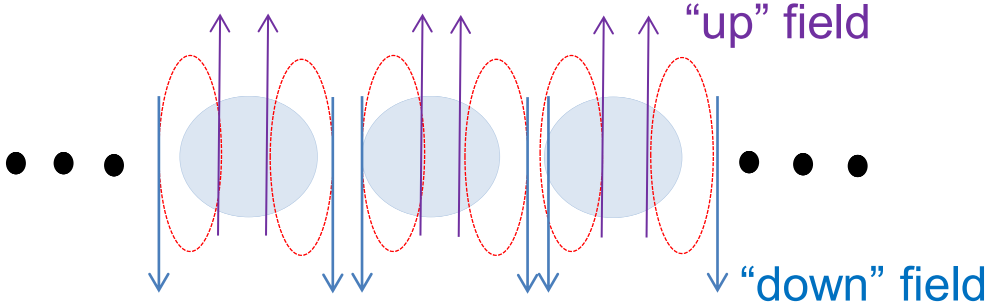
Case Study of ORNL's In-motion WPT

- **Definition of vehicle secondary coil relative to track coils**

Position 1: Right before alignment with the first transmit coil; edge to edge.		
Position 2: 50% aligned with the first transmit coil.		
Position 3: Perfectly aligned with the first transmit coil.		
Position 4: 50% misaligned with the first transmit coil, towards the second transmit coil.		
Position 5: Right in between two transmit coils.		

Case Study of ORNL's In-motion WPT

Position 6: 50% aligned with the second transmit coil.		
Position 7: Perfectly aligned with the second transmit coil.		
Position 8: 50% misaligned with the second transmit coil.		
Position 9: Right after alignment with the second transmit coil; edge to edge.		



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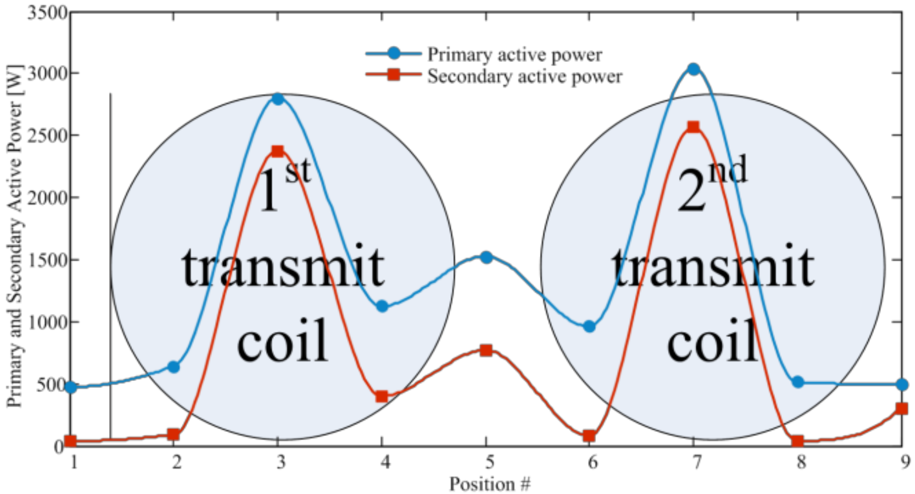
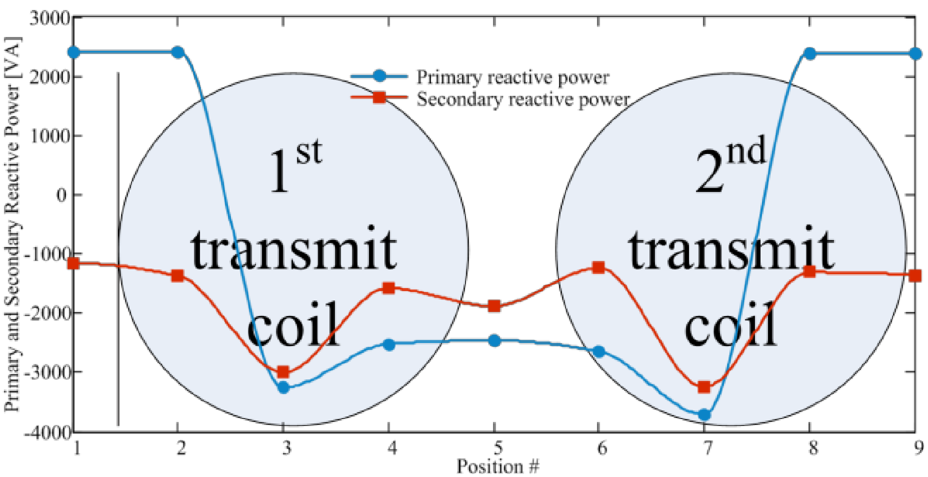
Case Study of ORNL's In-motion WPT

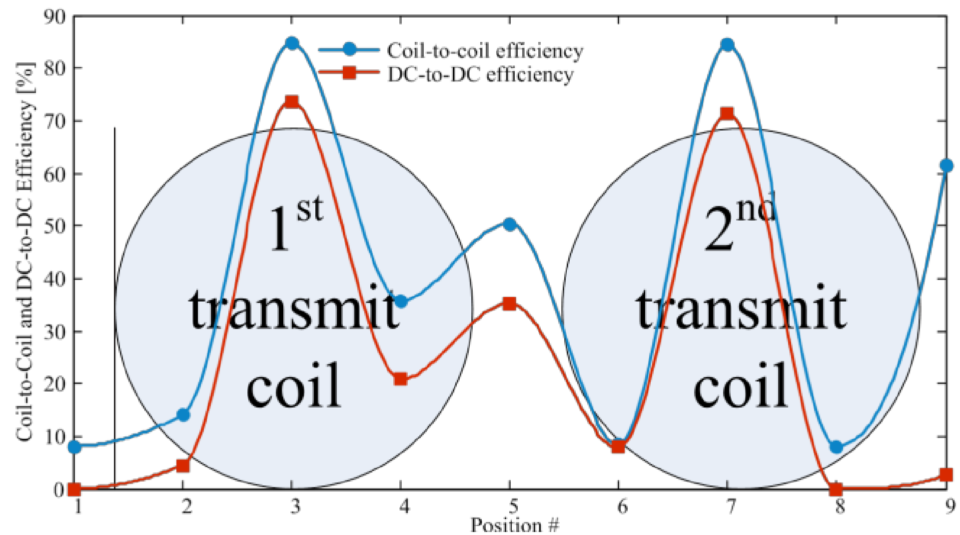
- Drastic reversals of power flows during vehicle pass-over.



- Active power variation over the track when vehicle is moving.

- Reactive power variation over the track when vehicle is moving.

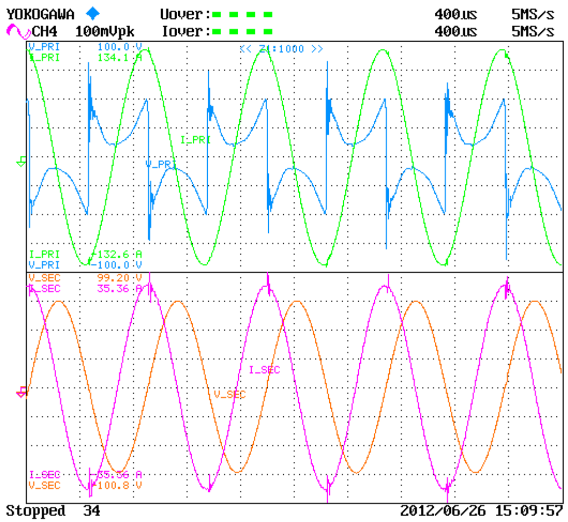


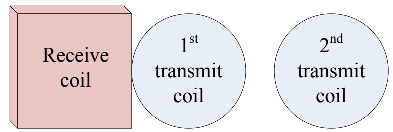


- DC-to-DC and coil-to-coil efficiency when vehicle is moving.

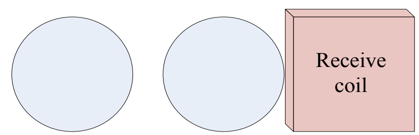
Case Study of ORNL's In-motion WPT

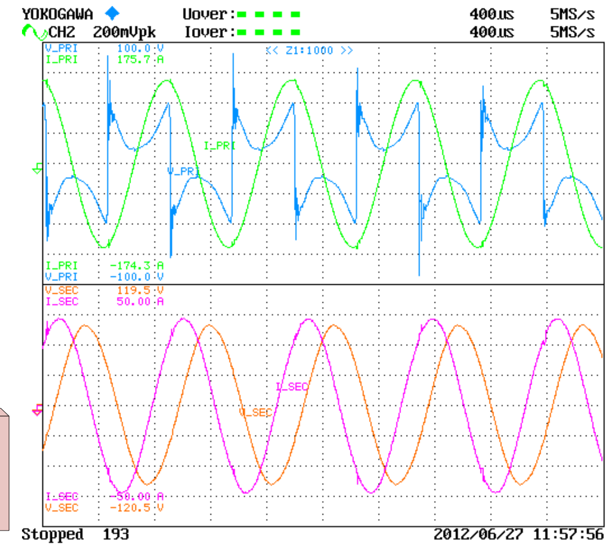
- Waveforms for positions #1 (left) and #9 (right) – right before alignment and right after alignment (vehicle goes over duel coils)



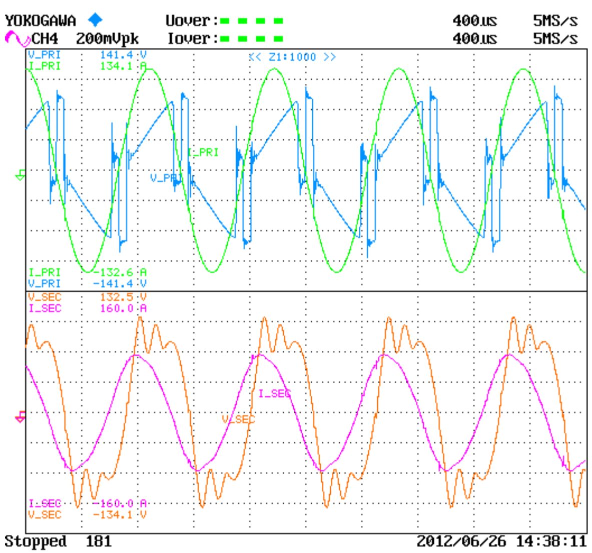


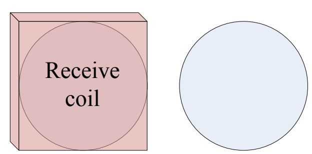
- High reactive power content of inverter output.



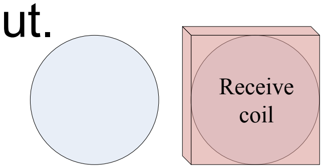


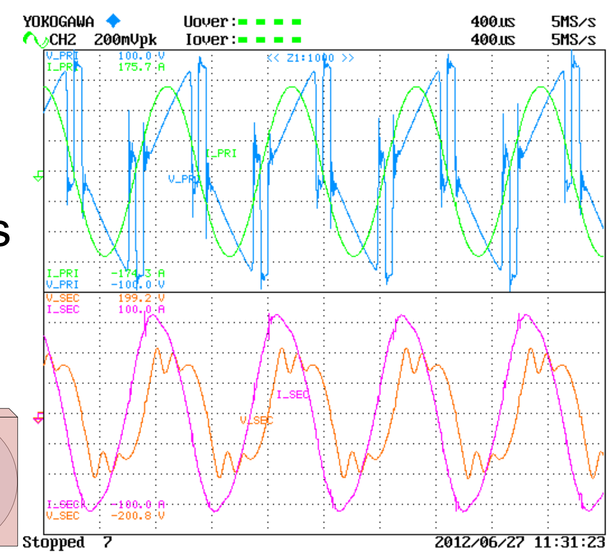
- Waveforms for positions #3 (left) and #7 (right) – Perfectly aligned with first and second coils.





- Higher coupling factor, less magnetizing current, more active power content of inverter output.

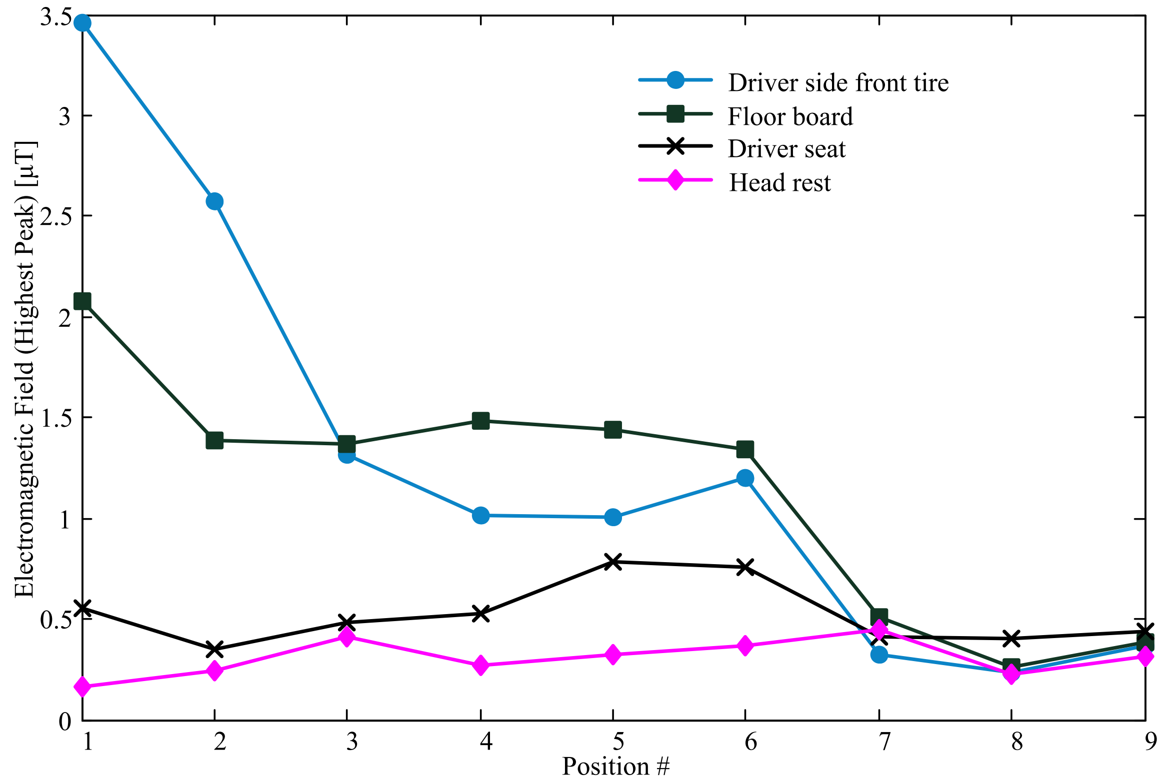




Case Study of ORNL's In-motion WPT

- Magnetic field measurements using NARDA EHP-50D E&H field analyzer near driver side front tire, floor board, driver seat, and head rest, all less than 6.25uT for all relative vehicle positions.

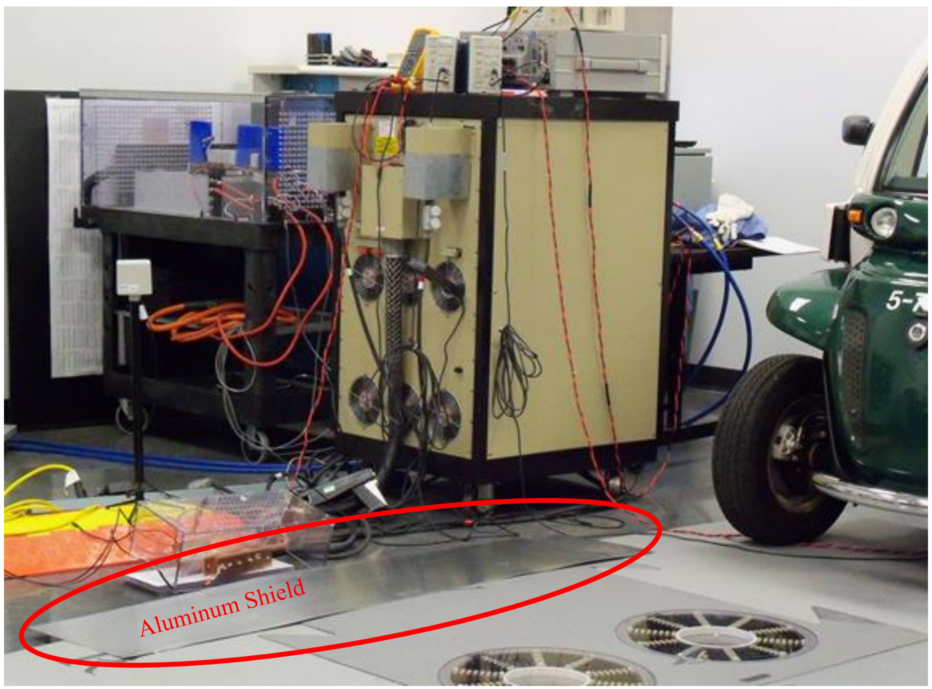
Car floor board on the acceleration pedal

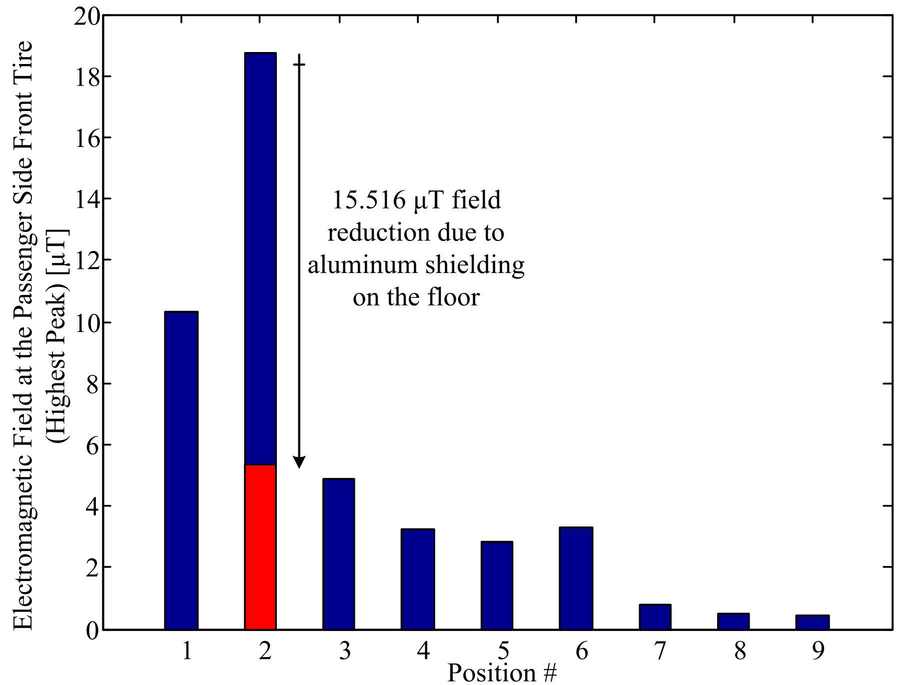


Driver Seat

Case Study of ORNL's In-motion WPT

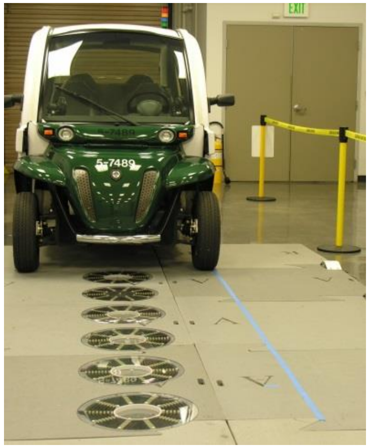
- Aluminum shielding reduces the Electromagnetic Field to safer levels on the passenger side front tire.
- Effective when grid side units have to be away from the primary pad; reduces emissions from high frequency wires from inverter to the primary coil.





In-motion Wireless Charging Demonstration

- World's very first in-motion wireless charging system using coils (not using rails or long wire loops as in previous technologies) with power smoothing.
- Dynamic Wireless Power Transfer (WPT)
  - ORNL demonstration: GEM EV and 6-coil track
  - Also addressed motion dependent power pulsations

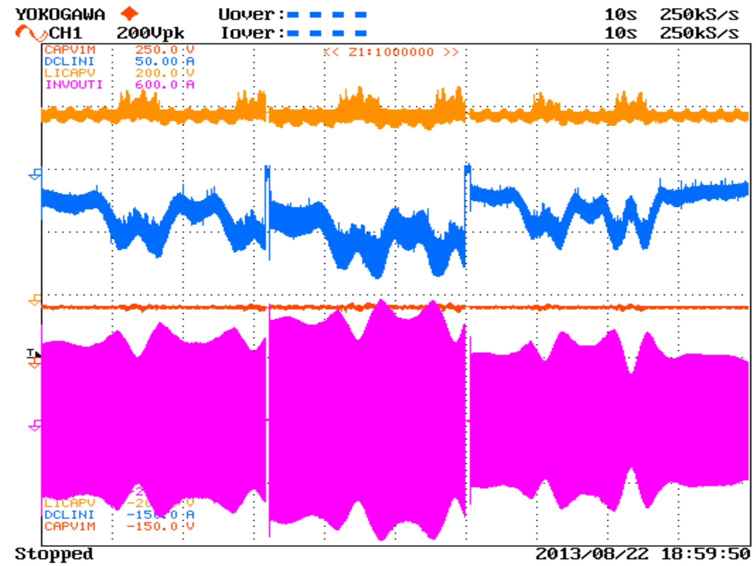



- Achieved 3 industry firsts: 1) in-vehicle charge power smoothing using carbon ultracapacitors, 2) grid side power smoothing using lithium-capacitors (LiC), 3) both in combination

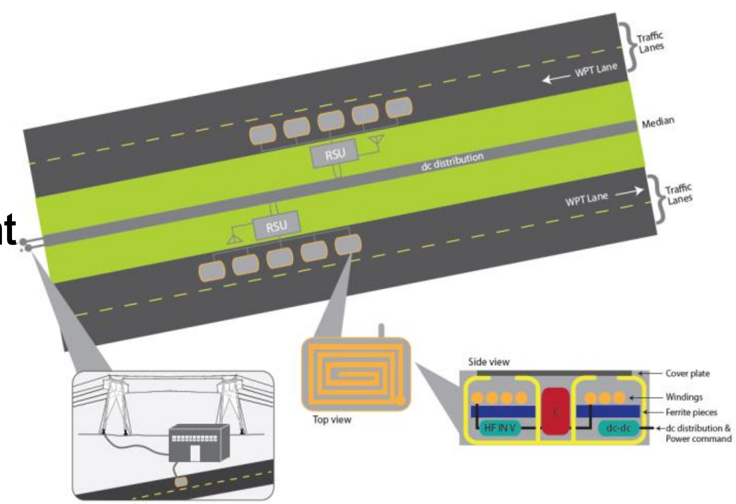
ORNL Dynamic WPT Demonstrator

- Dynamic Wireless Power Transfer (WPT) Experimental Results
  - Illustration of system hardware
  - Power flow as function of vehicle position

HF inverter system with HF transformer and self contained thermal management system

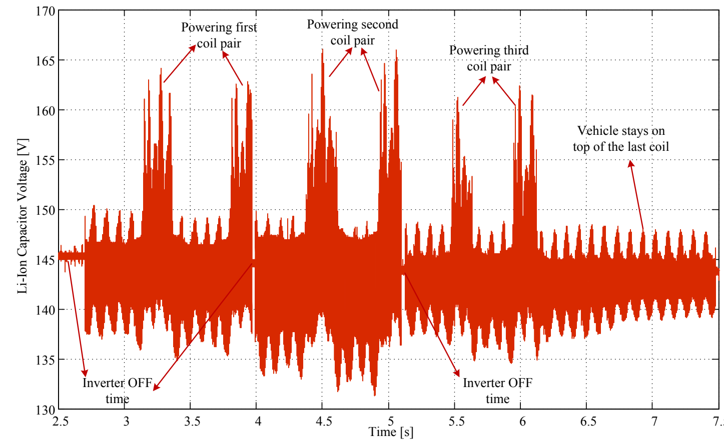


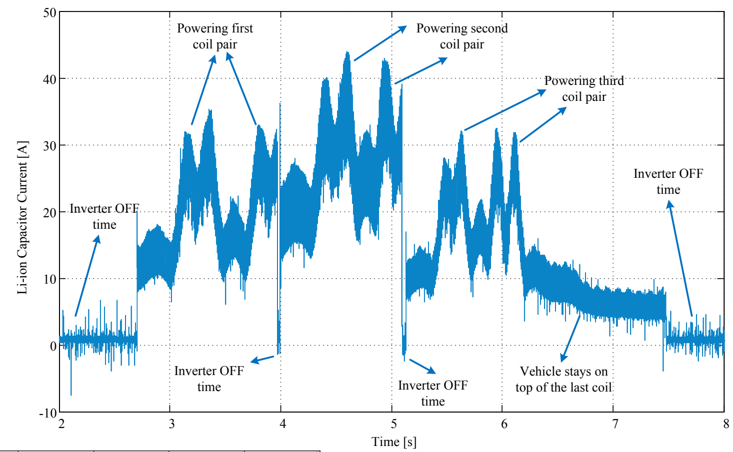
  - Future directions in dynamic WPT
    - Infrastructure issues (roadway integrity)
    - Communications requirements (latency)
    - Grid power distribution (intermittency)
    - Coil sequencing and power modulation & alignment
    - Local energy storage (smoothening)
  - Promote dc distribution along highway
  - Highly distributed vs. centralized HF stage

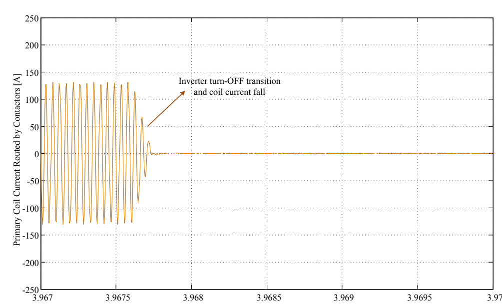


ORNL Dynamic WPT Demonstrator

- DWPT Experimental Results
- GEM vehicle driving across roadway coils







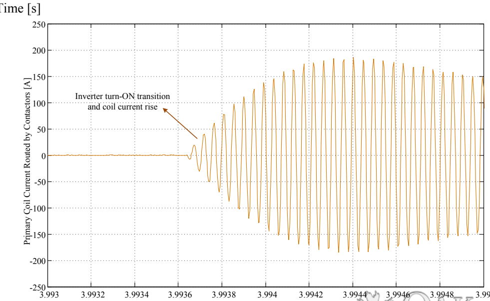
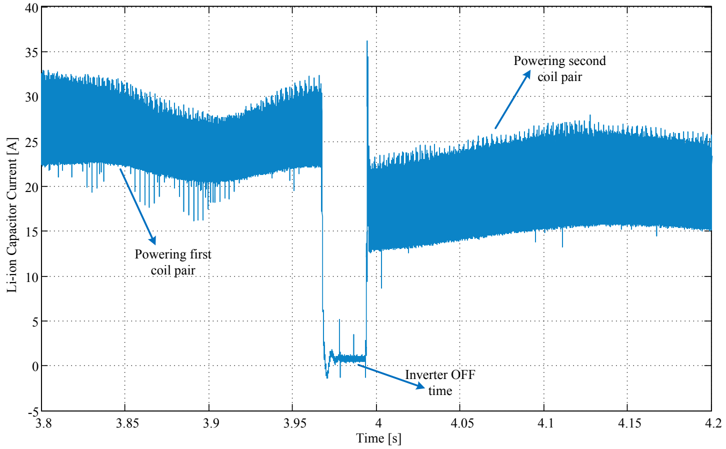


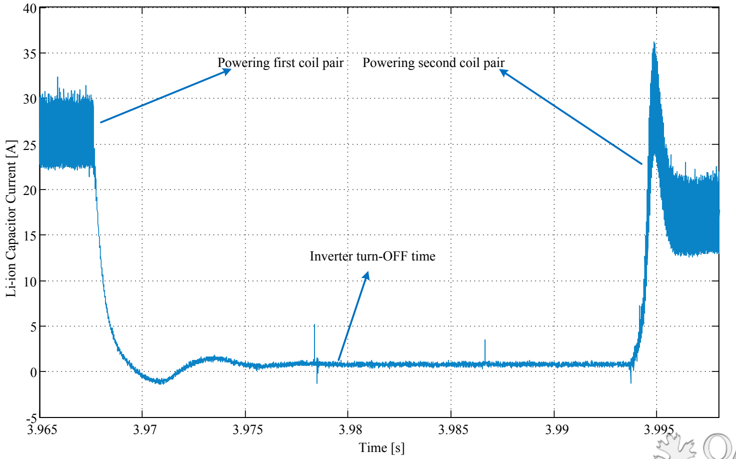
Illustration of roadway coil current quenching (0.2ms) and inverter turn-ON coil current ring-up (1.4ms)

ORNL Dynamic WPT Demonstrator

- Feedback from electrified roadway optical sensors are utilized to turn the inverter ON and OFF depending on the vehicle tire positions.

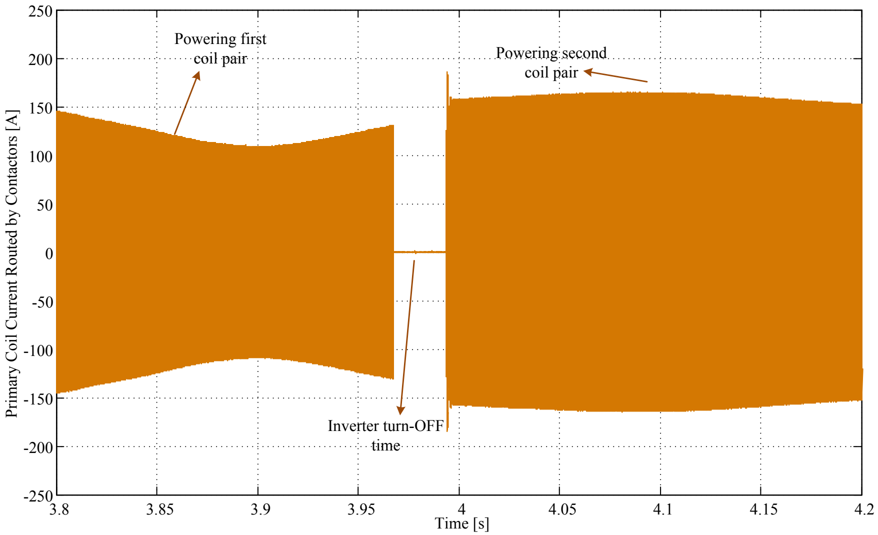
- Contactors are also controlled to direct the power from the inverter to the particular set of coils.

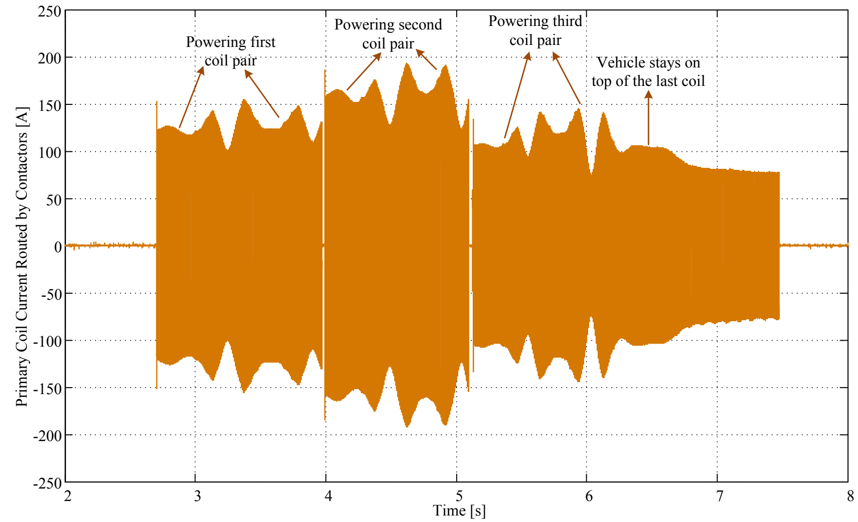


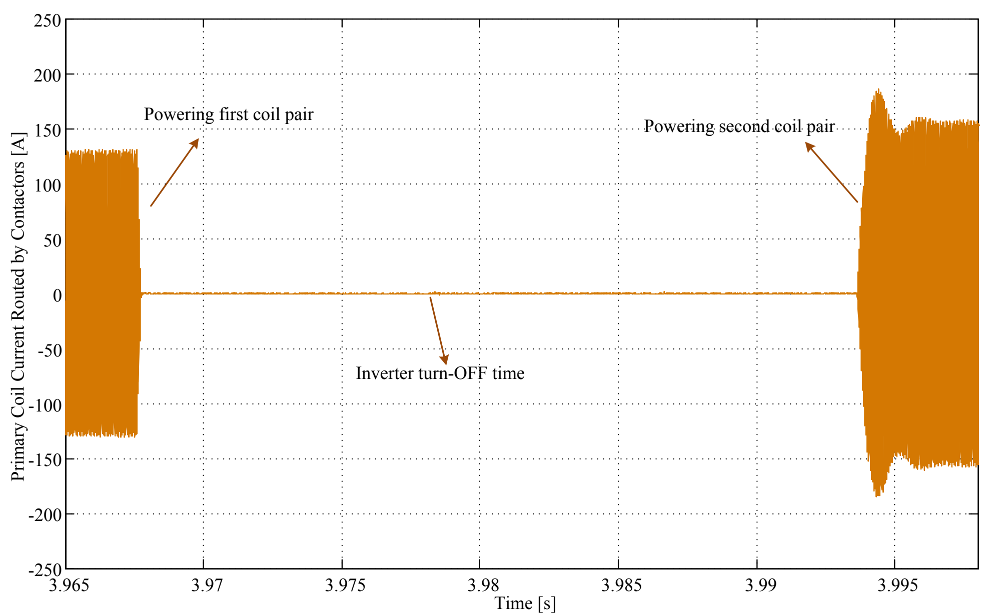


ORNL Dynamic WPT Demonstrator

- Primary coil current due to inverter turn OFF and ON and coil sequencing

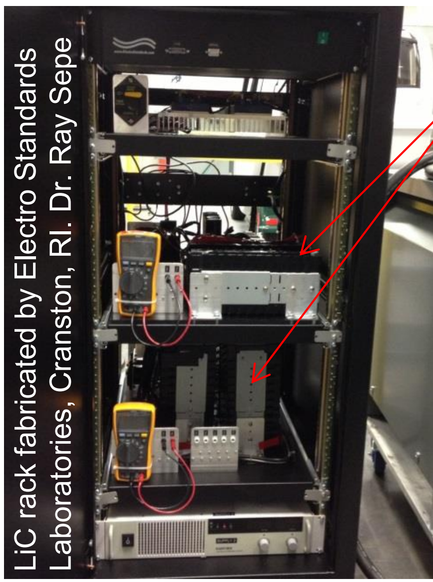






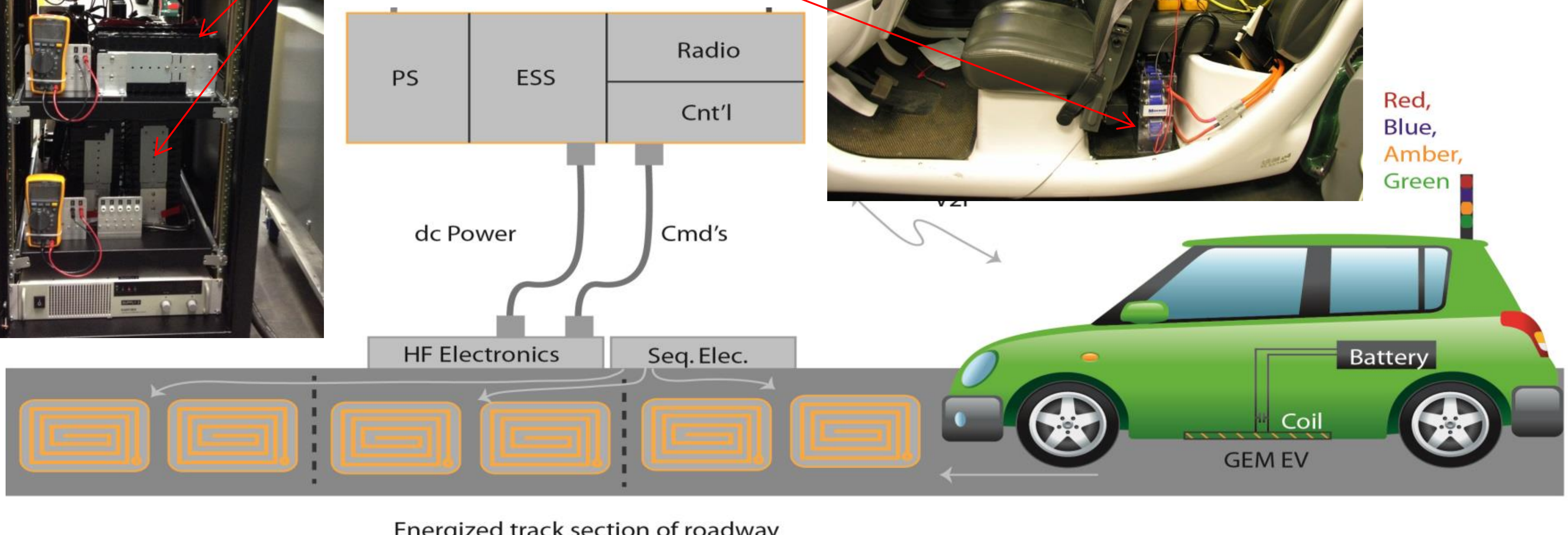
ORNL Developments in WPT Charging

- The need for energy buffer:
  - We keep saying dynamic WPT can reduce the vehicle ESS.
  - However, high power is needed for effective energy transfer to the vehicle.
  - Energy storage capacity can be reduced, but power rating of the ESS should be increase.
  - How?
  - Decoupling power and energy components of the vehicle ESS
  - Also effectively reduces the vehicle battery and grid side power ripples.



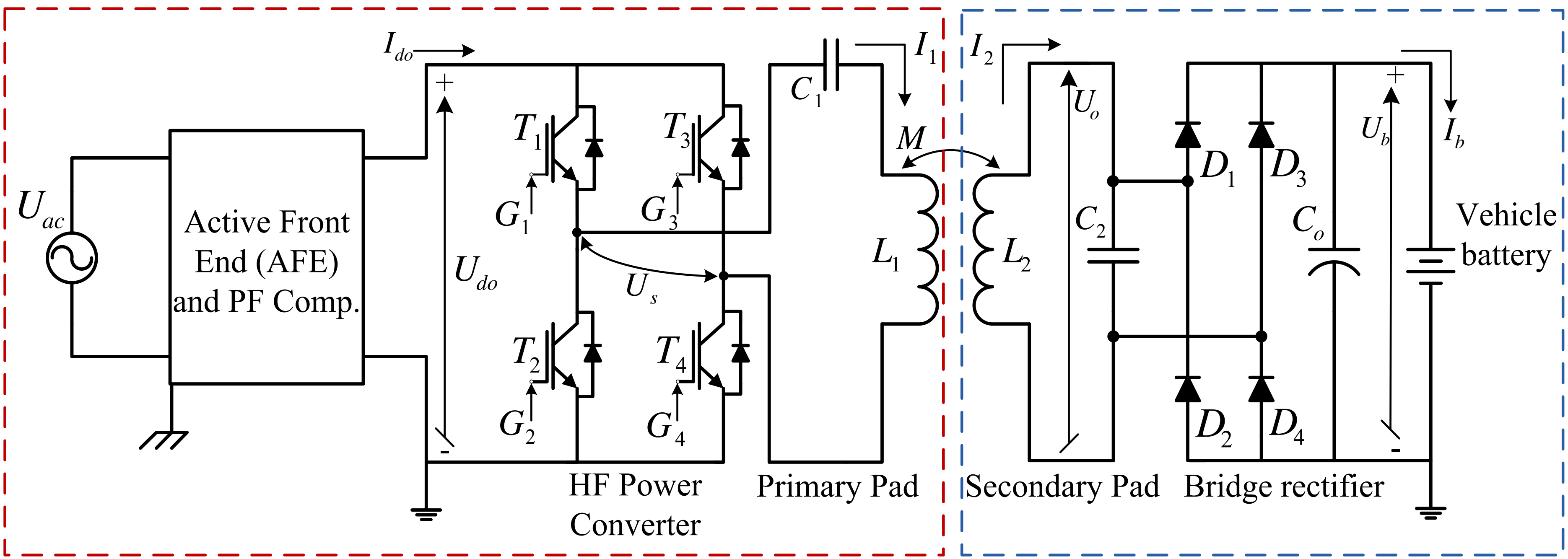
Grid side LiC

Vehicle side carbon UC



Dual ESS Hybridization for in-motion WPT

- **Employing fast response EC based energy storage buffers have not been applied for wireless power transfer systems.**
- **Particularly for in-motion wireless applications, using EC energy storage systems for the purpose of grid support or vehicle battery current ripple reduction makes use of a high power capable buffer available for both transmit and receive sides of the system.**
- **Both transmit side and the receive side have component that are relatively sensitive to the fast transients or high ripples.**



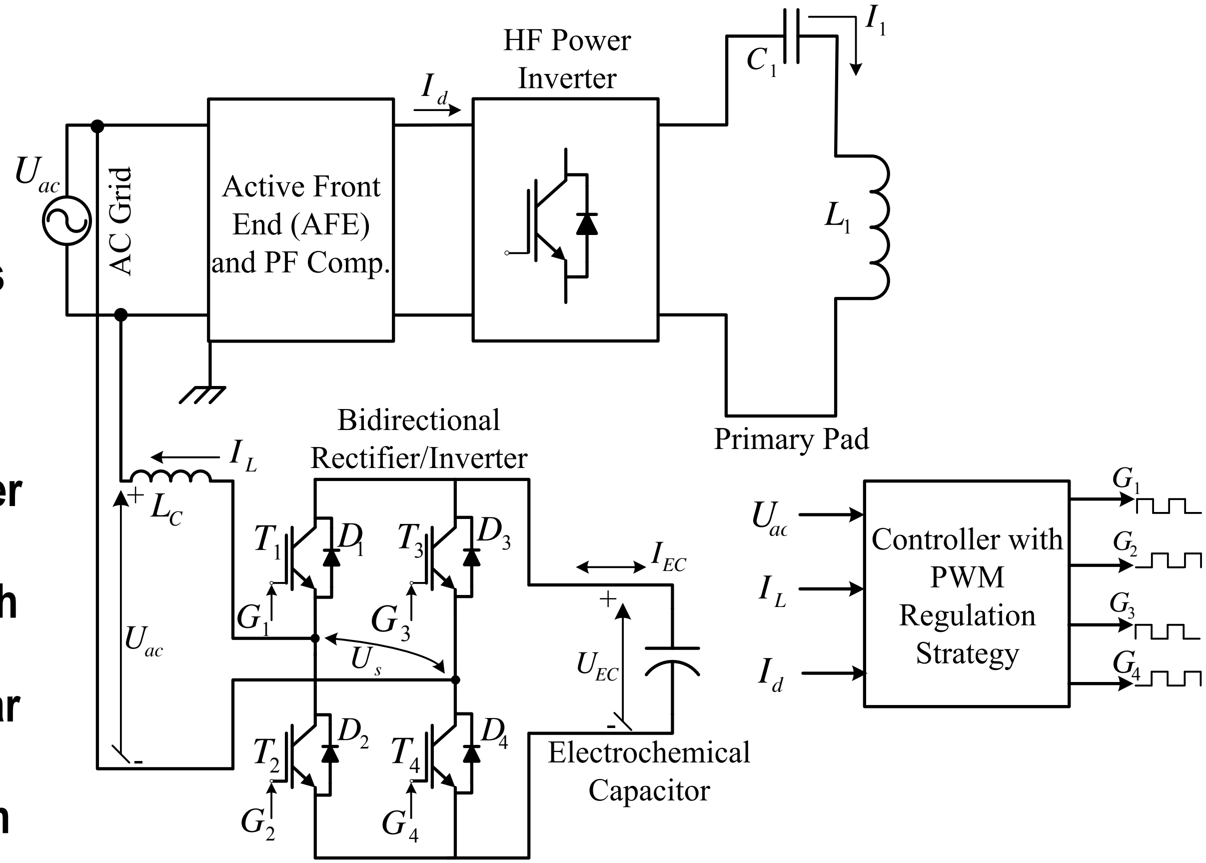
Grid side circuit

Vehicle (motional) side circuit

Grid-side energy buffering/peak current reduction

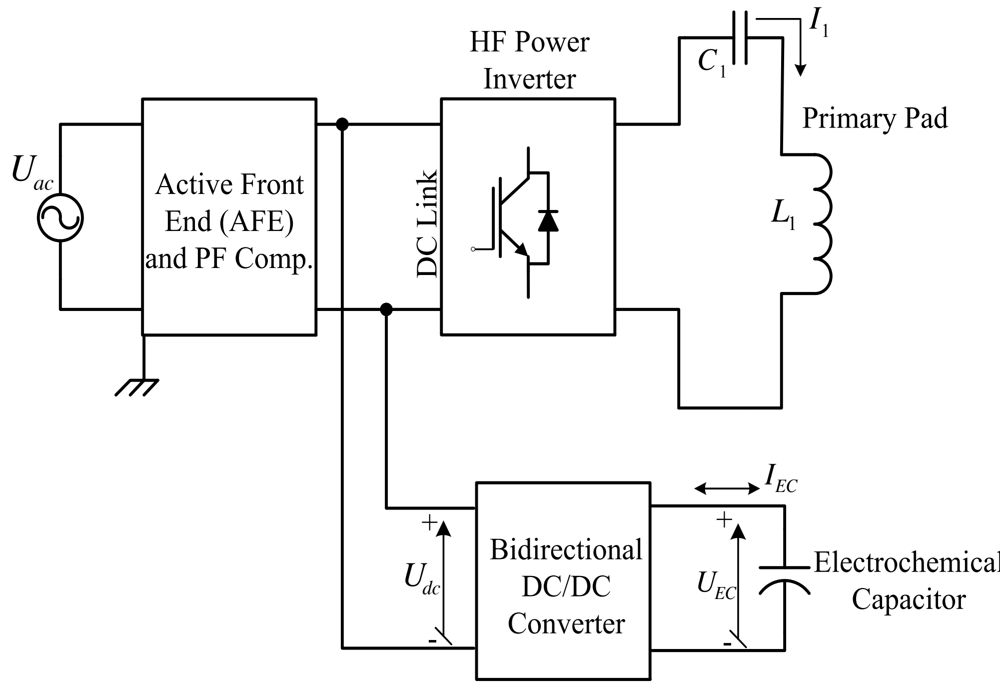
- Architecture 1: EC energy storage system is connected to the AC grid through a bi-directional rectifier/inverter:

- In this scheme, EC bidirectional converter is first controlled in rectifier mode to smoothly charge the EC in normal conditions.
- This rectifier operation is stopped when the EC voltage reaches to its maximum value.
- Then, as soon as a vehicle starts passing through the primary coil, EC converter is operated in inverter mode.
- In this mode, EC is discharged with a high pulse power so that the charging power required for the car is not supplied from the grid.
- Once the vehicle moves away from the primary pads, EC converter is again operated in rectifier mode to relatively more slowly recharge the EC.



Grid-side energy buffering/peak current reduction

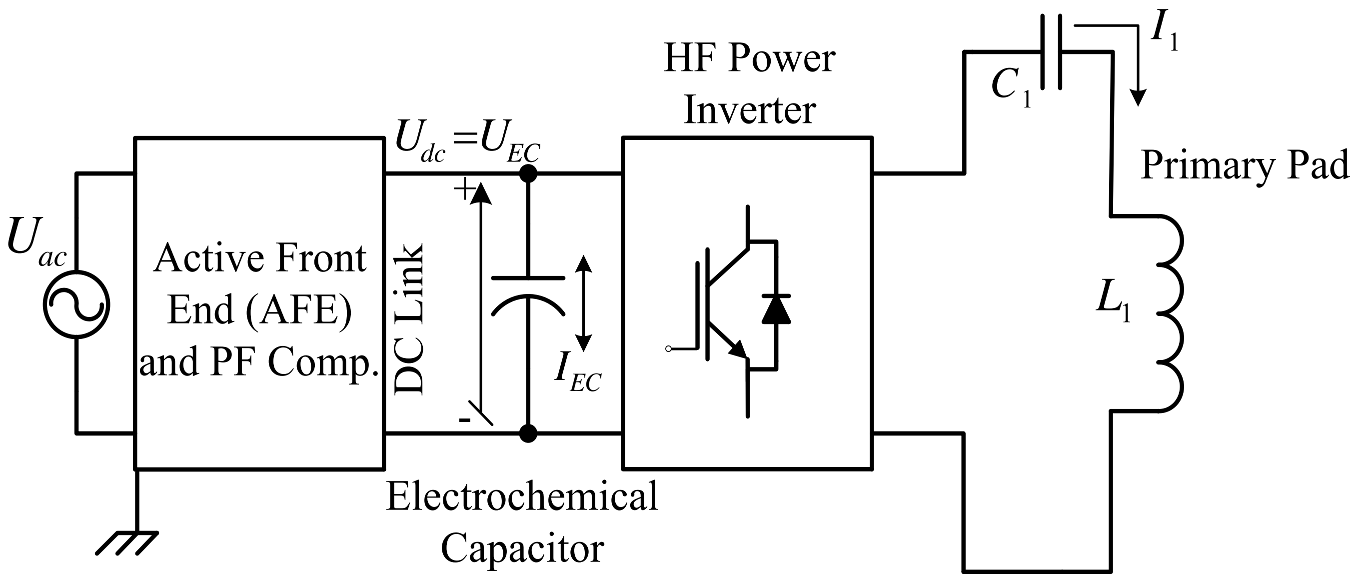
- **Architecture 2: EC energy storage system is connected to DC link through a DC/DC converter:**



- **In this configuration, instead of using a bi-directional rectifier/inverter, a bi-directional DC/DC converter is utilized by moving the EC to the DC side of the circuit.**
- **In this case, the EC is recharged from the DC link through a DC/DC converter under normal conditions. As soon as a vehicle starts passing through the primary pads, the EC is discharged to the DC link through the bi-directional DC/DC converter. After vehicle completes the WPT charging track, DC/DC converter is operated to relatively more slowly recharge the EC. In this configuration, the EC charging power is commanded by a controller with relatively slower dynamics.**

Grid-side energy buffering/peak current reduction

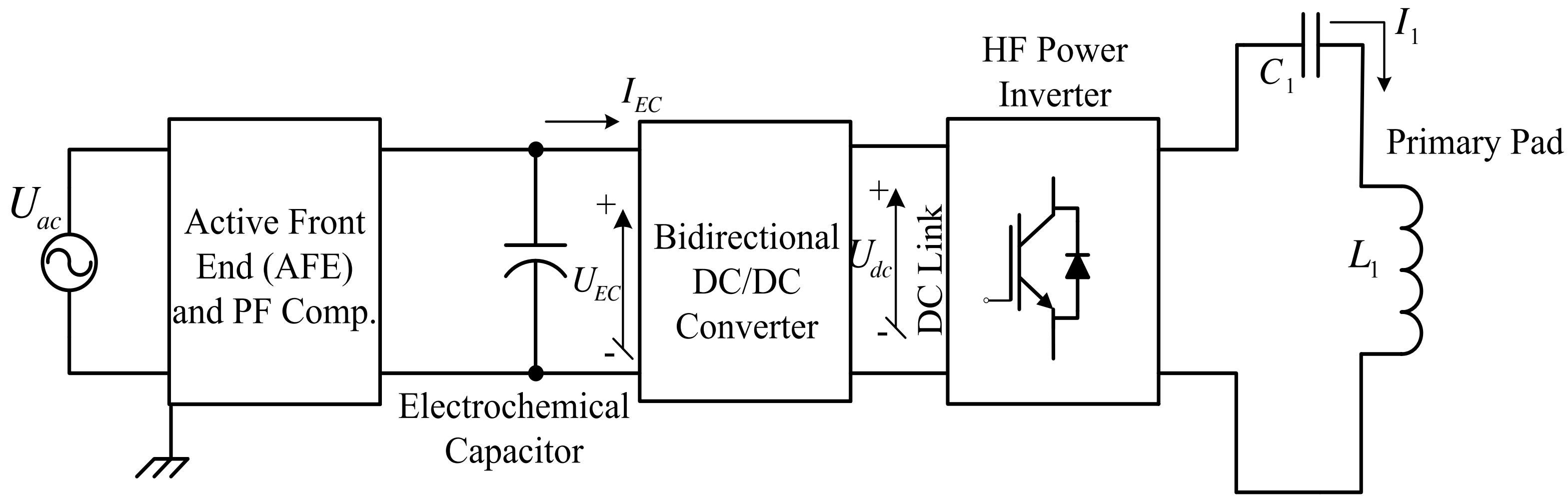
- **Architecture 3: EC energy storage system is passive parallel (directly) connected to the DC link:**



- **In this case, EC supplies a large burst of power to the HF inverter as a vehicle passes through the primary pad. Although this configuration does not provide an active energy management on the EC, the AFE rectifier's DC link voltage dynamics can be slowed down so the high charging power does not reflect back to the grid.**

Grid-side energy buffering/peak current reduction

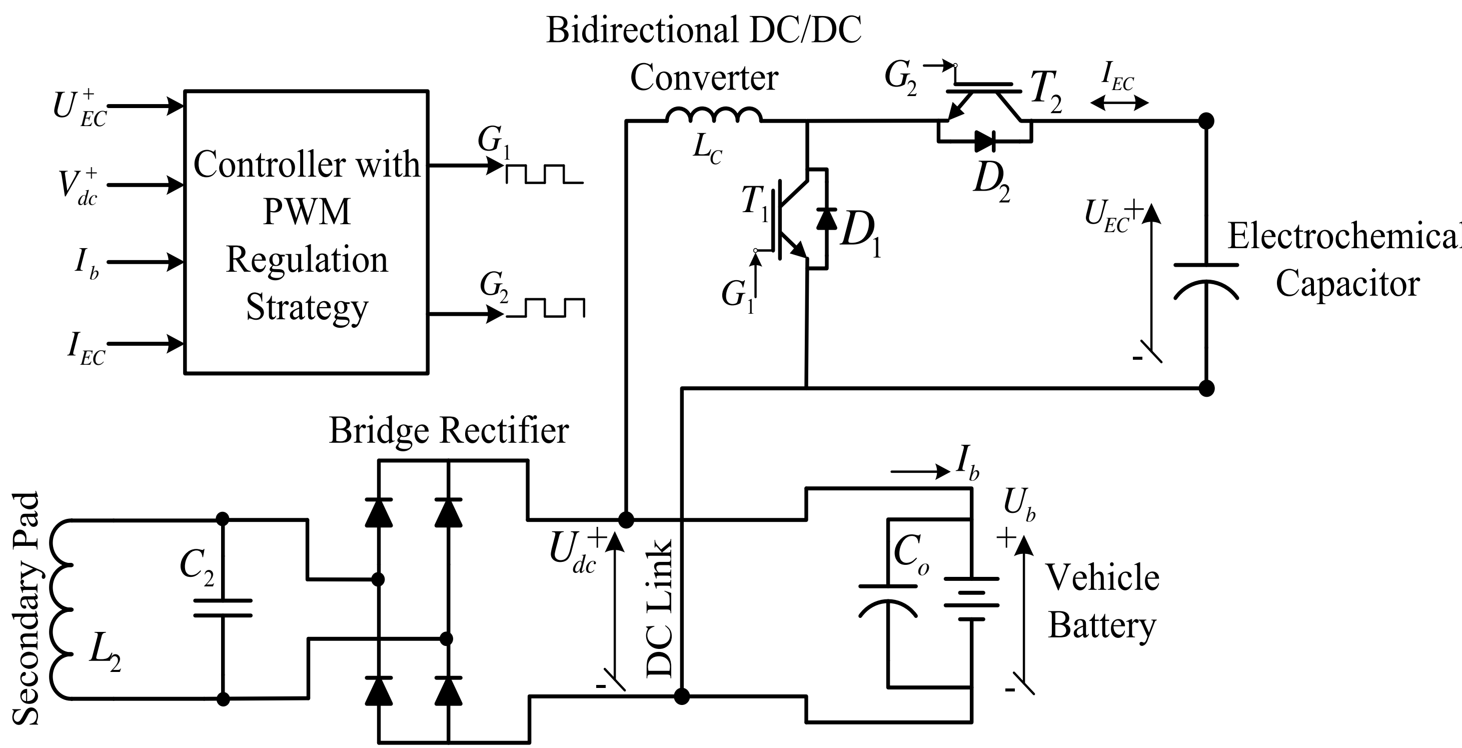
- **Architecture 4: EC energy storage system is connected to the DC link with a cascaded DC/DC converter:**



- **In this case, the EC and its DC/DC converter are in a cascaded form with the AFE converter and the HP power inverter. In this scheme, the DC/DC converter does not have to be bidirectional as compared to the Architecture 2 shown earlier; therefore, cost and size savings are possible.**

Vehicle-side energy buffering/peak current reduction

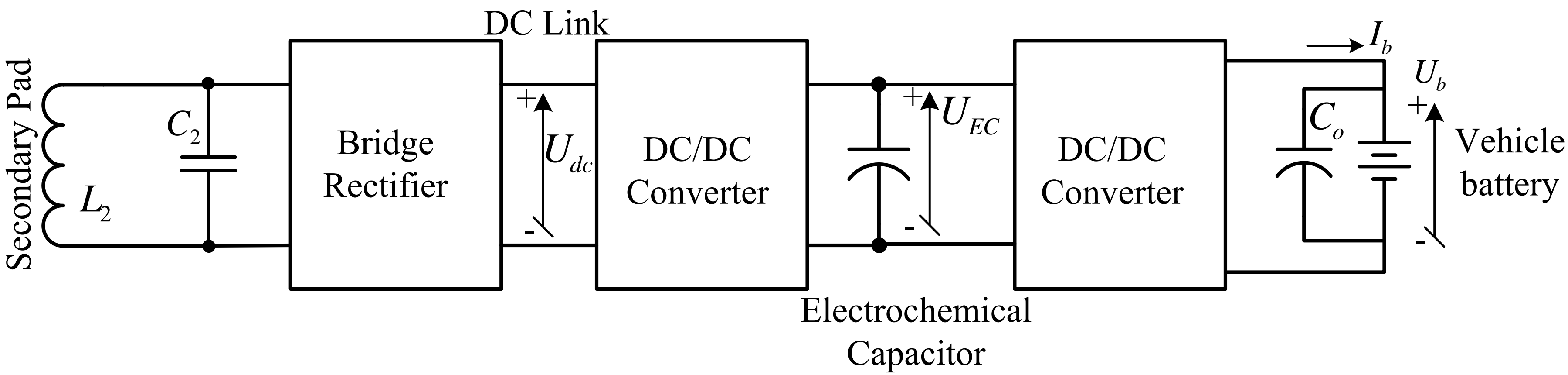
- **Architecture 1: EC energy storage system is connected to the battery terminals via a cascaded DC/DC converter:**



- **In this case, the high power pulse received by the secondary coils is rectified and dumped onto the DC link.**
- **Due its relatively faster dynamics, EC receives this high charging pulse.**
- **When the vehicle completes the WPT pad tracks, EC is controlled in a way that it relatively more slowly recharges the battery over a period of time.**

Vehicle-side energy buffering/peak current reduction

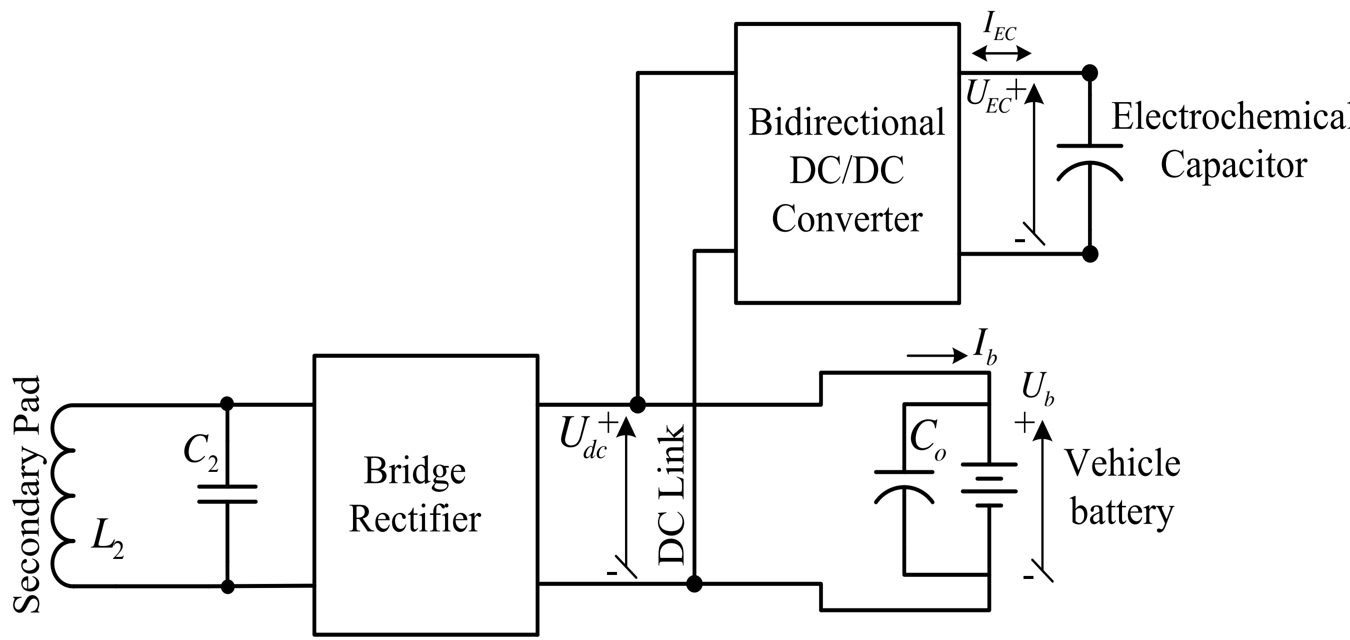
- **Architecture 2: EC energy storage system is connected to the DC link through a cascaded DC/DC converter and it is connected to the battery terminals via another cascaded DC/DC converter:**



- **This architecture provides a more flexible control of the EC power and in this case the EC voltage is decoupled from the EC link voltage.**

Vehicle-side energy buffering/peak current reduction

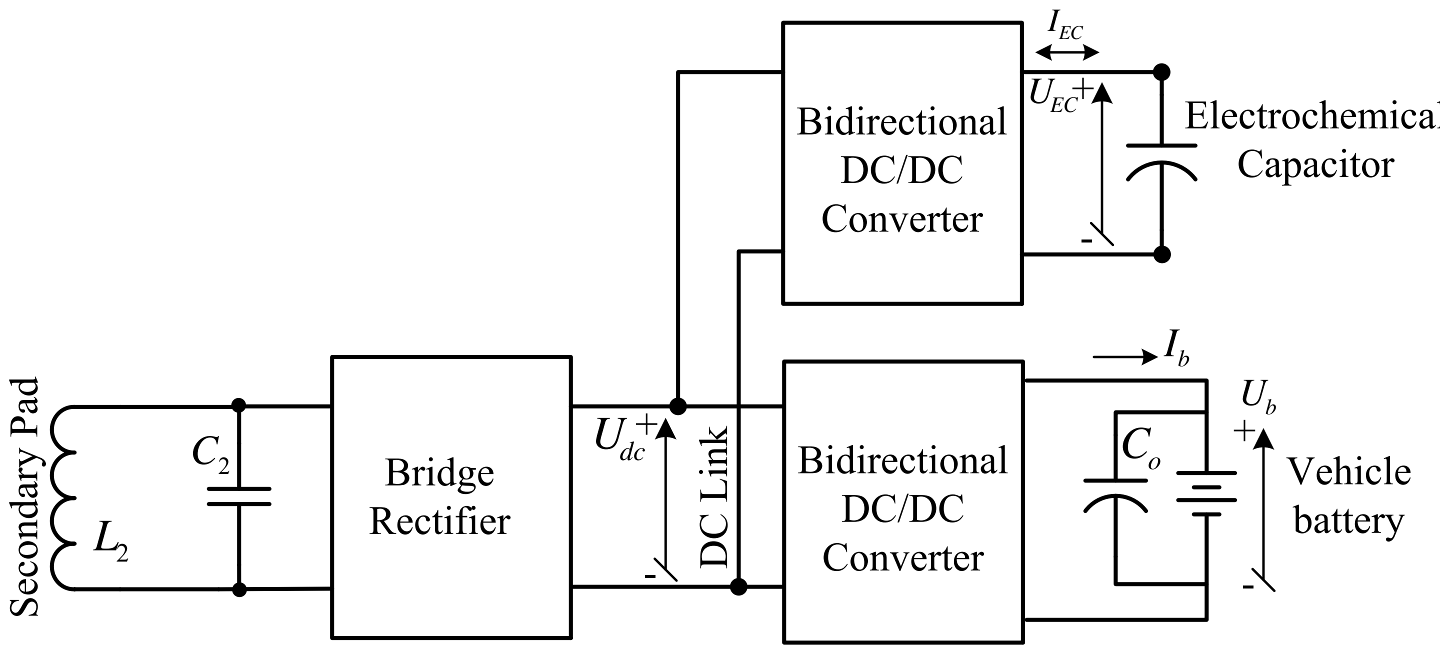
- **Architecture 3: EC energy storage system is connected to the DC link through a parallel bi-directional buck-boost DC/DC converter:**



- **EC is recharged with a high power pulse when the vehicle is moving on the WPT pads.**
- **Once the charge is received and vehicle moves away, EC is controlled to slowly recharge the vehicle battery over a period of time.**
- **This configuration provides that the EC voltage is decoupled from that of the battery voltage and DC link voltage and enables actively controlling the charge and discharge power of the EC.**

Vehicle-side energy buffering/peak current reduction

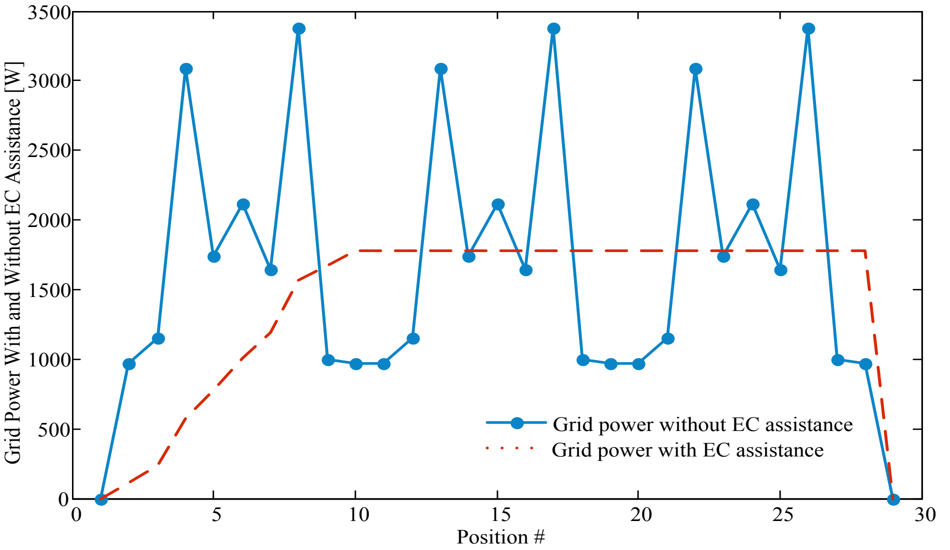
- **Architecture 4: Two parallel individual DC/DC converters are utilized for vehicle battery and the EC:**

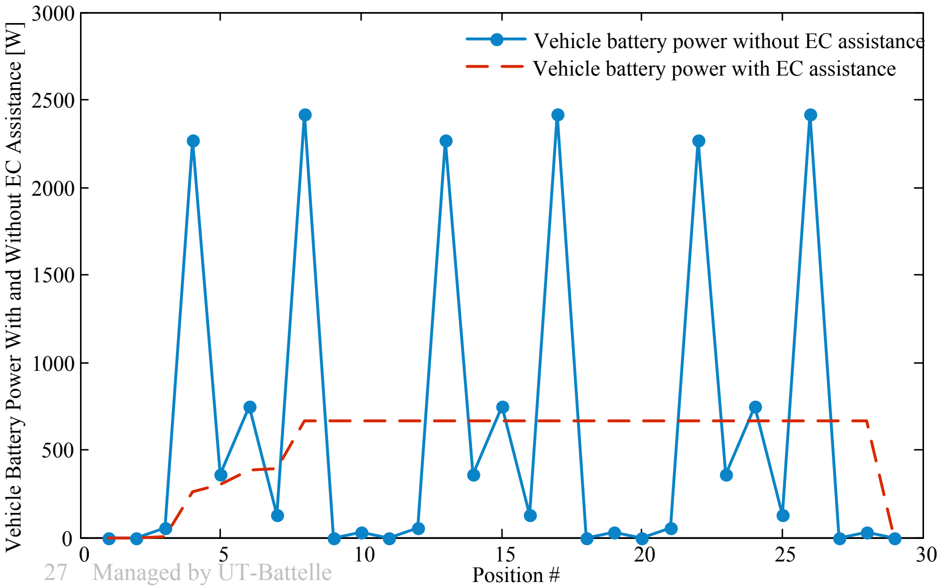


- **This configuration involves two separate bi-directional DC/DC converters; one for the vehicle battery and other one for the EC for maximized flexibility in controls and active energy management among the storage devices.**

Simulations for a 6-coil track – ideal case

- The power delivered from the grid with and without the EC assistance with respect to the positions as the vehicle is passing through the transmit pads.
- Without the EC assistance on the primary side, the grid is more stressed and grid power has large dips and current ripples. However, under the EC assistance, only the average and much smoother power variations are reflected to the grid. All the grid power ripples and transients are eliminated since the EC is utilized as an energy buffer on the grid side

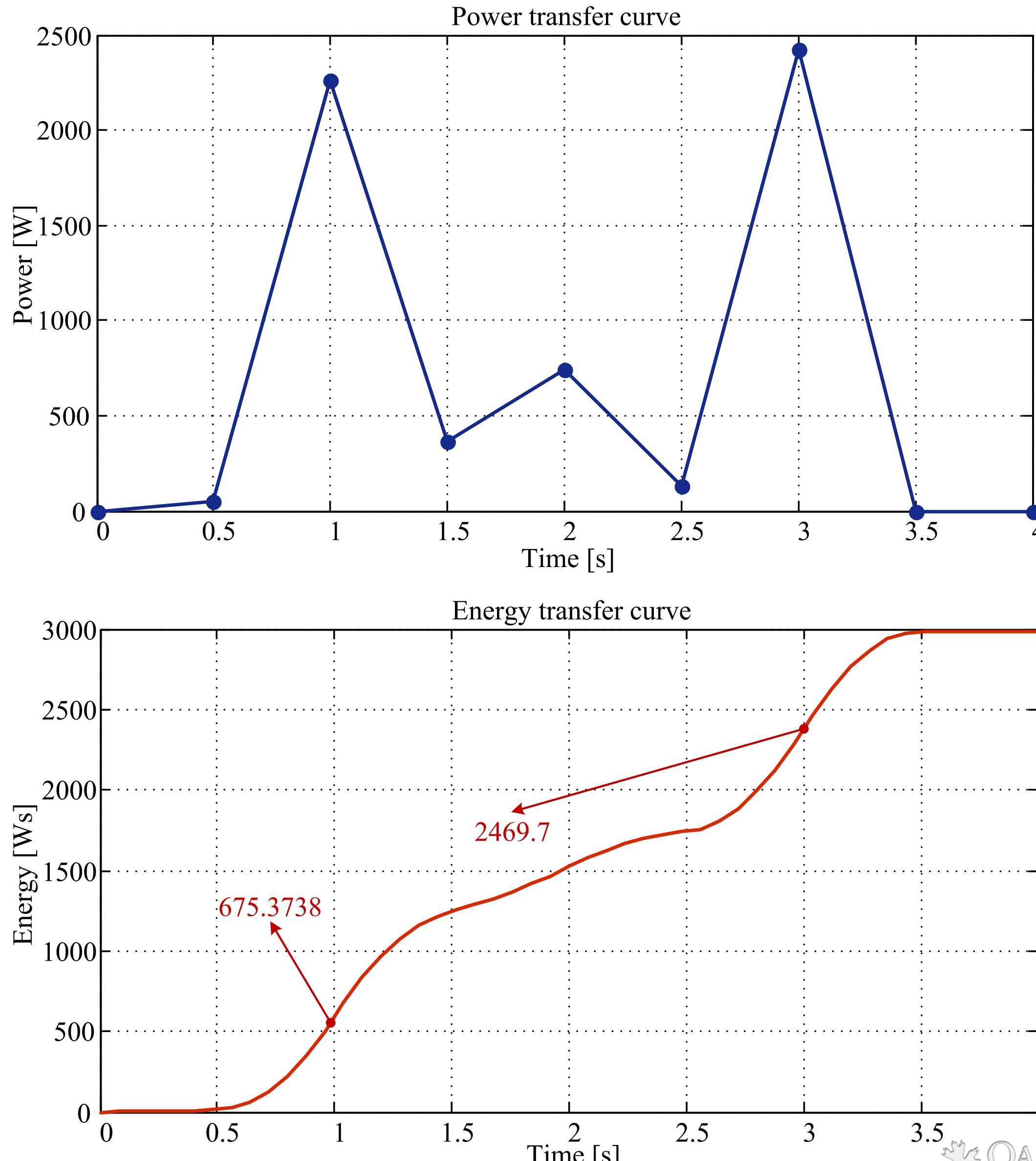




- Positive effect on the battery power variations.
- Similar to the grid power variations, ripples and dips in vehicle battery power can also be eliminated with the EC assistance.
- With the proper utilization of the EC, vehicle battery is only subject to the much smoother average power variations whereas EC energy storage system handles the ripples and high power variations.

Example design case: Ultra-capacitor sizing

- **Let's take the case moving from one coil to the other.**
- **There are 2 peak power transfer points on the track.**
- **The integral of the power transfer curve indicates that the energy transferred between two peak power points is 1794.3 Watt-seconds.**
- **Therefore:**
- **2469.7-675.3738 = 1794.3 Watt-seconds of energy should be captured by the ultra-capacitor so that the battery receives only the average of the overall energy transfer between these points.**



Example design case: Ultra-capacitor sizing

- Maxwell K2 series ultra-capacitors have ideal maximum current rating. Particularly, maximum current rating of BCAP0650 can carry 88 A_{rms} maximum which is sufficient for our application.
- GEM vehicle on-board battery pack is a lead-acid battery with 72V nominal voltage with 82V max during charging.
- Rated voltage of BCAP0650 is 2.70 V. In order to get a string of ultra-capacitors with ~82 V of rated voltage, 30 ultra-capacitor cells are required in series:

$$30 \times 2.70 = 81V$$

- The rated capacitance of the string becomes 36.11 Farads:

$$650 \div 30 = 21.67F$$

- The voltage variation can be calculated by:

$$E = \frac{1}{2} C \left[V_{final}^{\ 2} - V_{initial}^{\ 2} \right]$$

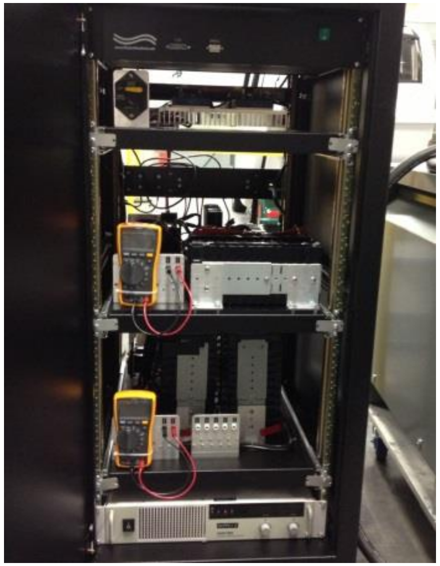
- Therefore:

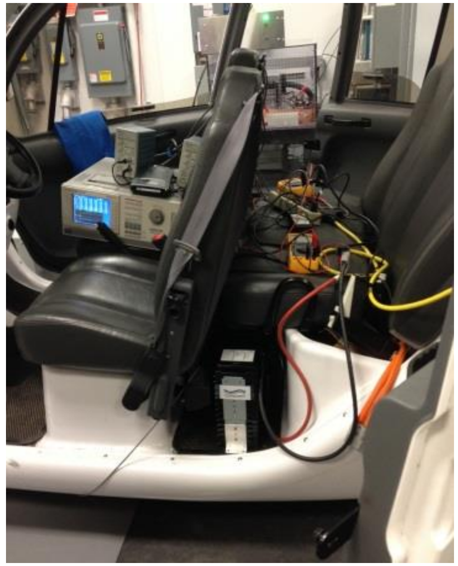
$$V_{final}^{\ 2} = \sqrt{V_{initial}^{\ 2} - \frac{2E}{C}} = \sqrt{72^2 - \frac{2 \times 1794.3}{21.67}} = 70.84V$$

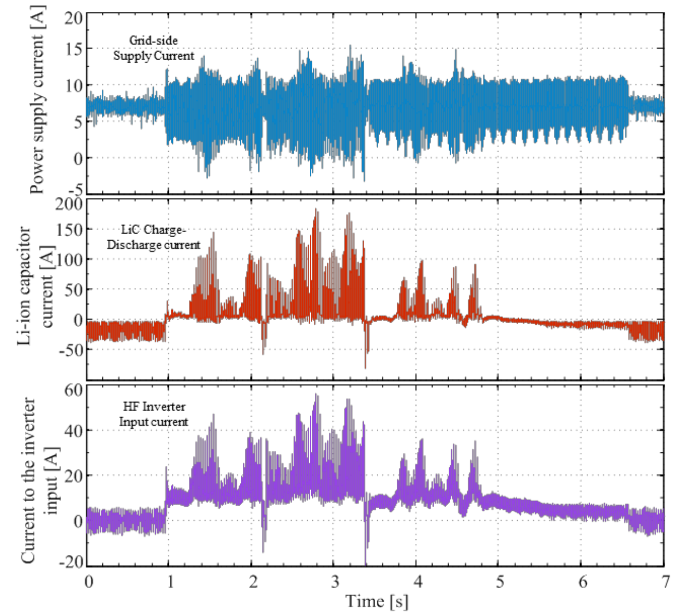
- Hence, with 1.16 V of variation (discharge or discharge) in the ultra-capacitor string's voltage, 1794.3 Watt-seconds of energy can be captured or delivered by the ultra-capacitor.

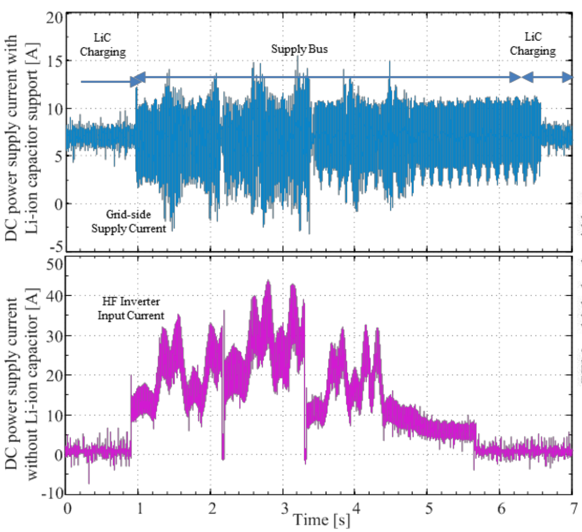
Experimental test results

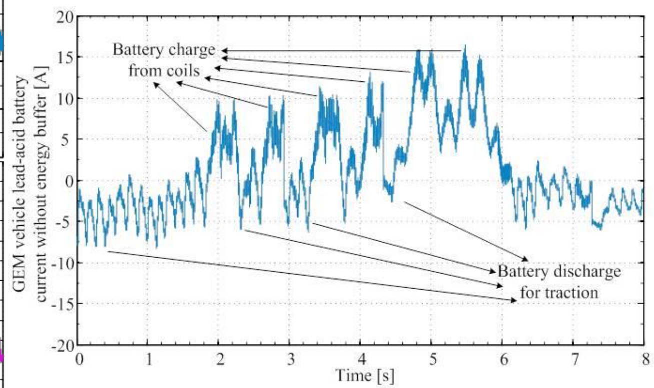
- Current ripple smoothing with Li-ion capacitors on the grid side unit and carbon electrochemical ultra-capacitors on the vehicle side.

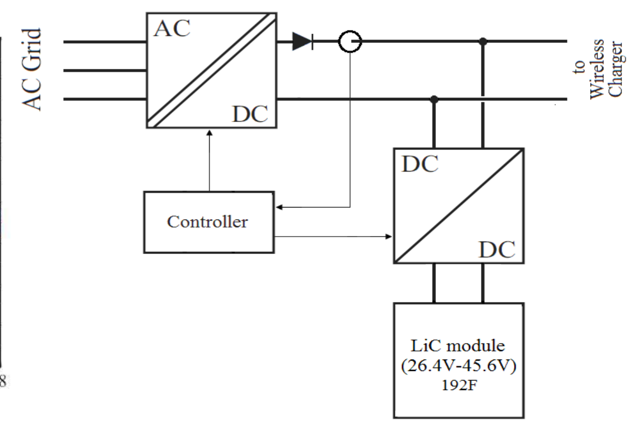












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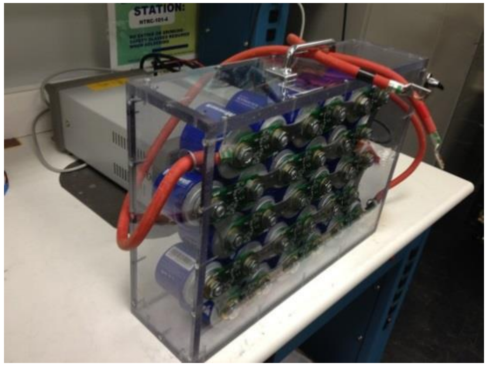
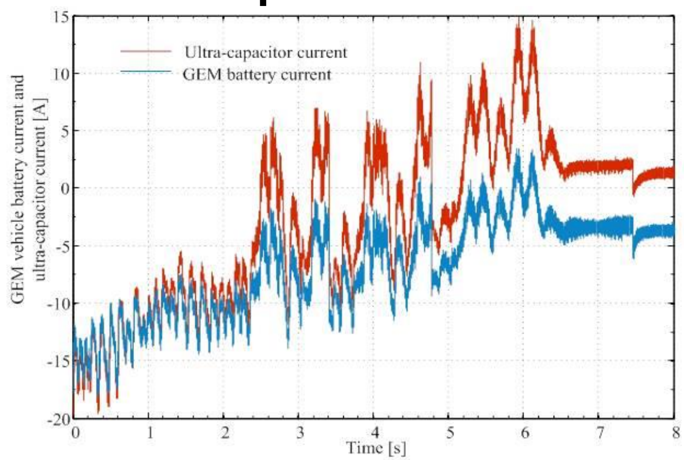
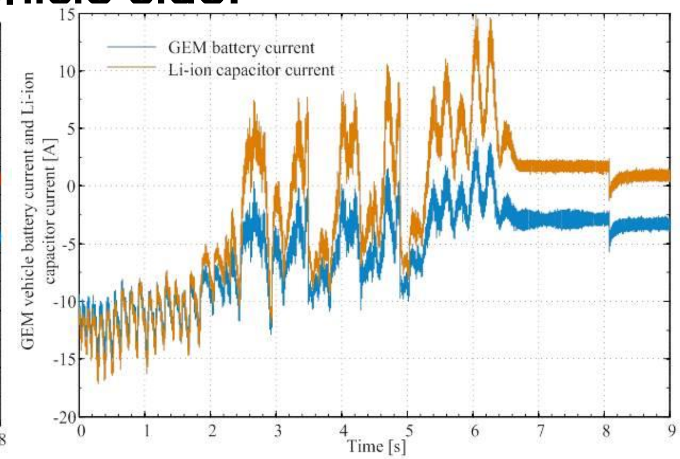
OAK RIDGE National Laboratory

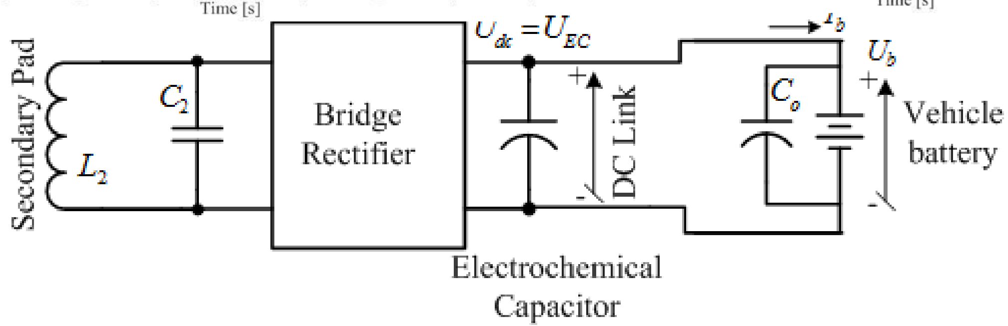
Summary

- Current ripple smoothing with Li-ion capacitors on the grid side unit and carbon electrochemical ultra-capacitors on the vehicle side.









Current ratio (I_{pk}/I_{avg})	Grid-side WPT base station	In-vehicle
III. No smoothing	53A	16A
IV. Grid-side only with LiC	10A	16A
VA.Vehicle side with UC	10A	2.6
VB.Vehicle side with LiC	10A	2.6
Pulse reduction	81%	84% for UC 84% for LiC

Questions & Discussions

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