Grid Integration of EVs for V2G Applications:

Wired & Wireless ?

Professor Udaya K Madawala

Email : u.madawala@auckland.ac.nz

Power Electronics Research Group
Department of Electrical & Computer Engineering

THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

Electric Vehicles (EVs)

EVs can be regarded as the means of ***'future transport'***

- ✓ *Reduce pollution*
- ✓ *Enable efficient and clean transport*
- ✓ *Ideal for sustainable living*
- ✓ *An alternative energy storage to offer grid services etc*

https://en.wikipedia.org/wiki/Nissan_Leaf

Global EV Sales

EV Type	2017	2018
BYD/BAIC	114,870/96,670	215,800/160,790
Tesla	91,360	233,760
BMW	70,790	86,940
Nissan	43,550	81,140
Mitsubishi	21,920	37,570
General Motors	50,980	49,660
VW	57,750	53,720
Total	1,279,430	2,242,720

THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

(1) https://www.zsw-bw.de/en/media-center/data-service.html#c6700
(2) https://insideevs.com/hyundai-ioniq-electric-sales-catches-up-with-ioniq-hybrid

Challenges!

Challenges

- Charging rate (power level)
  - *EV, grid, charging systems, standards etc*
  - *Latest chargers offering < 30 minute charging*

- Distance per charge (range anxiety!)
  - *EV and battery capacity*
  - *New Chevrolet Bolt, Kia Niro, Hyundai Kona Electric & Tesla Model S offer nearly 250-370 miles on a single charge*
  - *More stations for easy access to charging*

****http://newsroom.nissan-europe.com/uk/en-gb/media/pressreleases/145248/nissan-and-enel-launch-groundbreaking-vehicle-to-grid-project-in-the-uk***

Challenges

- Battery (size, weight, cost, life, disposal)
  - *Lithium-ion batteries with high energy density (100-265 Wh/kg), but are still significantly heavy, bulky & expensive*
    - *Weight : Nissan Leaf's (24-kWh) 200 kg, Tesla Model-S (85-kWh) 540 kg.*
    - *Cost : approximately $130 -145/kWh (2016) and $100 in 2021 by GM*
  - *Life span : generally 3-8 years, 100,000 km*
    - *A Chinese car battery-maker says it is ready to manufacture a product capable of powering a vehicle for 1.2 million miles (~2 million km) across the course of a 16-year lifespan*

***https://en.wikipedia.org/wiki/Electric_vehicle_battery,** https://www.bbc.com/news/technology-52966178

Means of Charging

➢ Wired ?

- ✓ *Relatively simple*
- ✓ *Less infrastructure change*
- ✓ *Standards (SAE J1772)*
- ✓ *In use at present*

➢ Wireless ?

- ✓ *Robust, safe & convenient*
- ✓ *Huge infrastructure change*
- ✓ *Standards (SAE J2954 ?)*
- ✓ *Cannot be used everywhere*
- ✓ *Development stage*

Wired Charging Standards (AC & DC)

Supply	Charger Location	Application Area	Interface	Input level
SAE (J1772_201710)				
AC Level 1 Single phase	On-board	Residential	Standard mains outlet (SMO)	120 V ac, 12 A 120 V ac, 20 A
AC Level 2 Single phase	On-board	Residential and commercial	Electric vehicle supply equipment (EVSE)	208-240 V ac, < 80 A
DC Level 1	Off-board	Commercial	EVSE	50-1000 Vdc, 80 A cont.
DC Level 2	Off-board	Commercial	EVSE	50-1000 Vdc, 400 A cont.
IEC (BS EN 61851-1 ED3 draft, BS EN 61851-23 ED2 draft)				
Mode 1 Single-phase Three-phase	On-board	Residential	SMO	< 250 Vac, < 16 A < 480 Vac, < 16 A
Mode 2 Single-phase Three-phase	On-board	Residential and commercial	SMO	< 250 Vac, < 32 A < 480 Vac, < 32 A
Mode 3 Three-phase	Off-board	Commercial	EVSE	
Mode 4 DC rapid	Off-board	Commercial	EVSE	

Wired Charging Systems

Sources : http://www.greencarreports.com/news/1099635_portland-airport-adds-42-electric-car-chargers-at-120-volts-heres-why, http://www.chademo.com/wp/ ; http://www.tesla.com

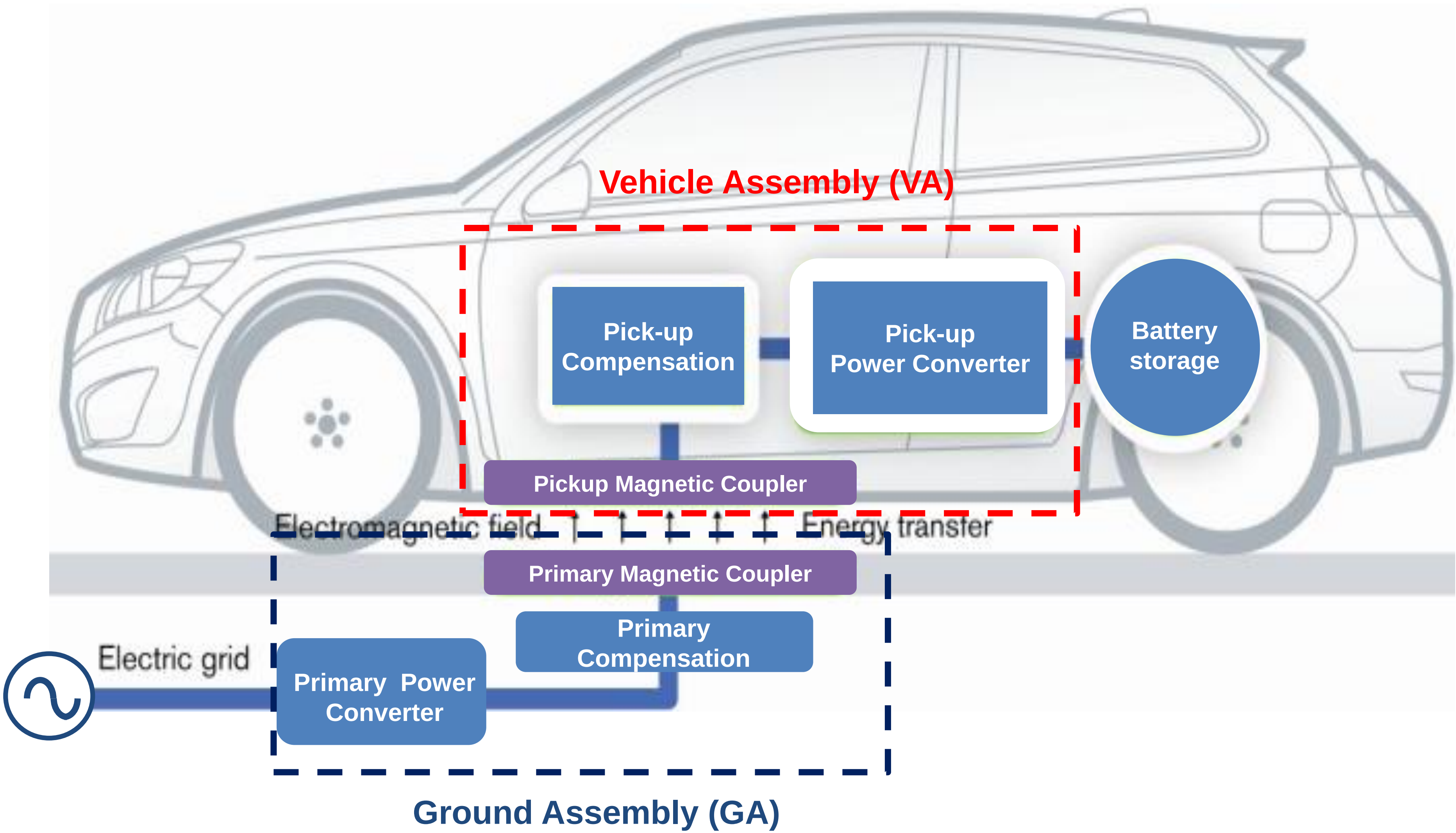
Wireless EV Charging

Wireless EV Charging

Based on:

- *Inductive Power Transfer (IPT) technology*

Wireless EV Charging



THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

Challenges *(Wireless EV Charging)*

- Charging
  - *stationary, or both stationary & dynamic (~ 25 kW !)*
- Uni- or bi-directional power flow at high frequency operation
- Controlling power converters
  - *High order resonant (SS/SP/PP etc) circuits with active & passive control*
- Magnetic pad (coupler) design, interoperability & alignment
  - *circular, solenoidal, DD, DDQ and bi-polar*
- Communication between VA & GA
  - *Tariff, synchronization, demand side management, etc.*
- Compliance with standards (ICNIRP) related to
  - *Safety, EMFs, FoD & LoD, radiated and conducted emissions, etc*
- Physical construction, cost, robustness etc

Standards *(Wireless EV Charging)*

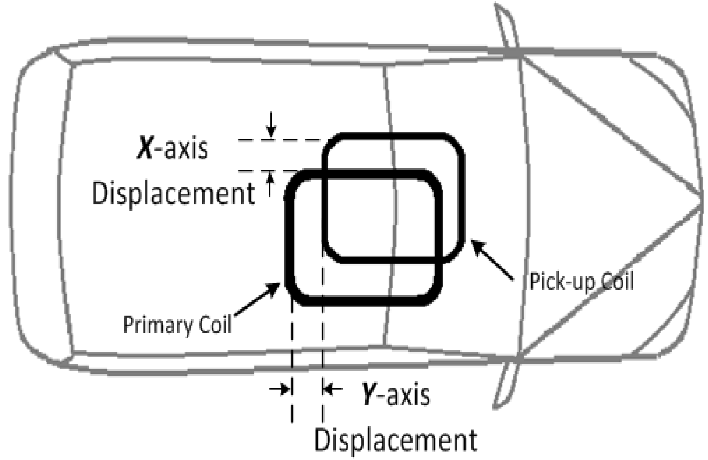
- Being implemented by SAE : TIR J2954(LDEVs), J2954/2 (HDEVs)
  - *Safety, performance, interoperability, communication, control, FoD & LoD, radiated and conducted emissions, etc.*
- Nominal frequency of operation is set as 85 kHz (79 kHz to 90.00 kHz)
- Minimum target efficiency is 85% (80% off set) for WPT1-3

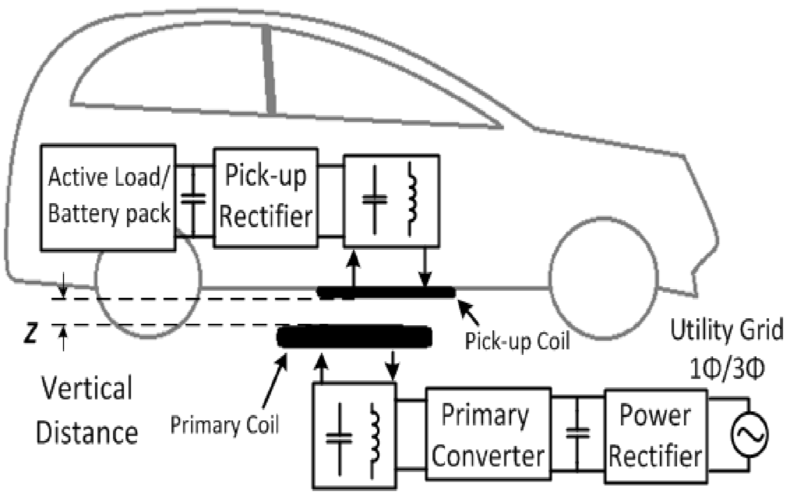
Classification: Light duty EVs	WPT1	WPT2	WPT3	WPT4
Maximum VA rating	3.7 kVA	7.7 kVA	11 kVA	22 kVA

http://www.standardsuniversity.org/e-magazine/june-2016/sae-publishes-tir-j2954-wireless-power-transfer-evphev/

Charging Pads *(Wireless EV Charging)*

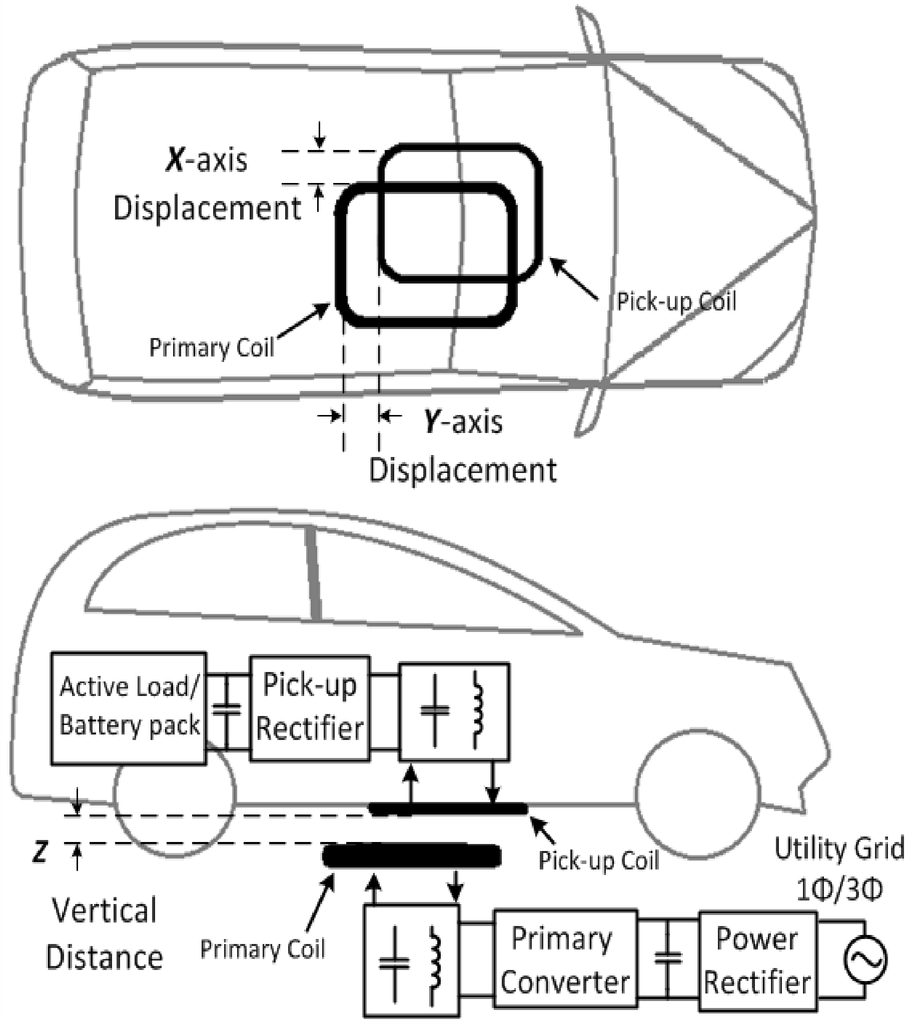
- Sizes depend on
  - *Power class & interoperability*
- Shapes include
  - *circular, solenoidal, DD, DDQ & bi-polar designs*
- GA (primary) Location
  - *above ground surface*
  - *flush mounted with ground surface*
  - *below ground surface*





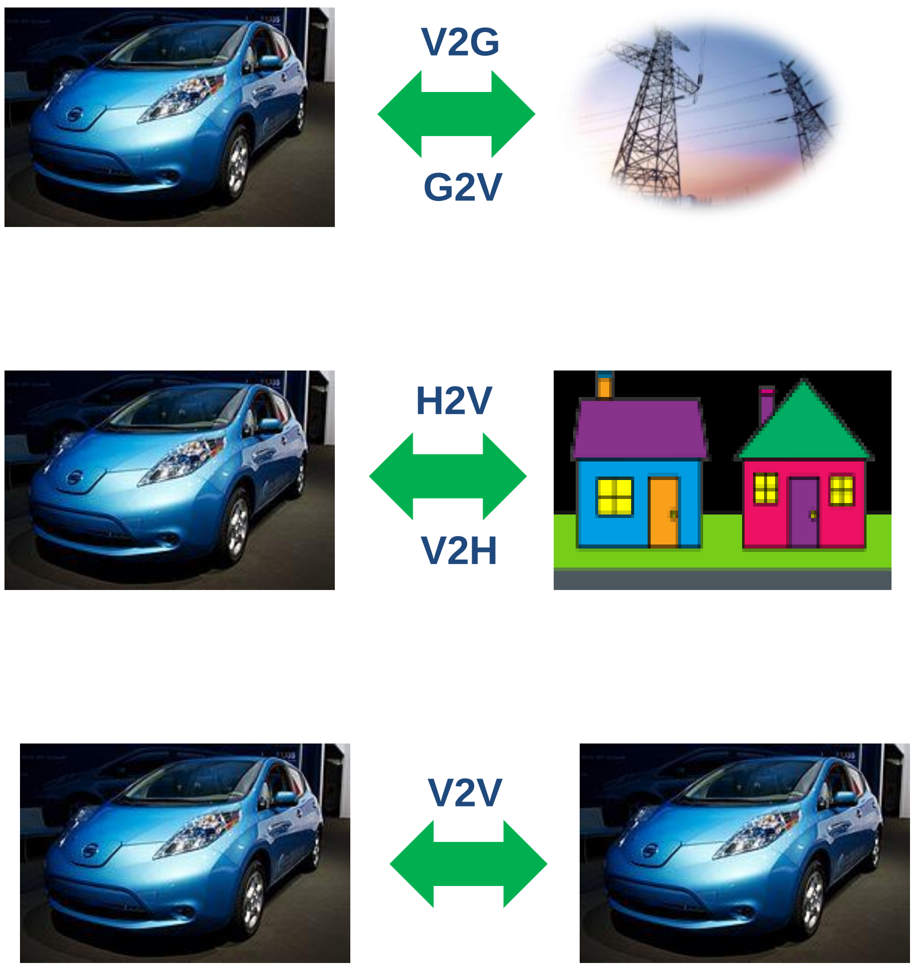
Charging Pads *(Wireless EV Charging)*

- Vertical distance (Z class)
  - *Z1 : 100 - 150 mm*
  - *Z2 : 140 - 210 mm*
  - *Z3 : 170 - 250 mm*



V2G to V2X Concept

Are EVs used only for commuting ?



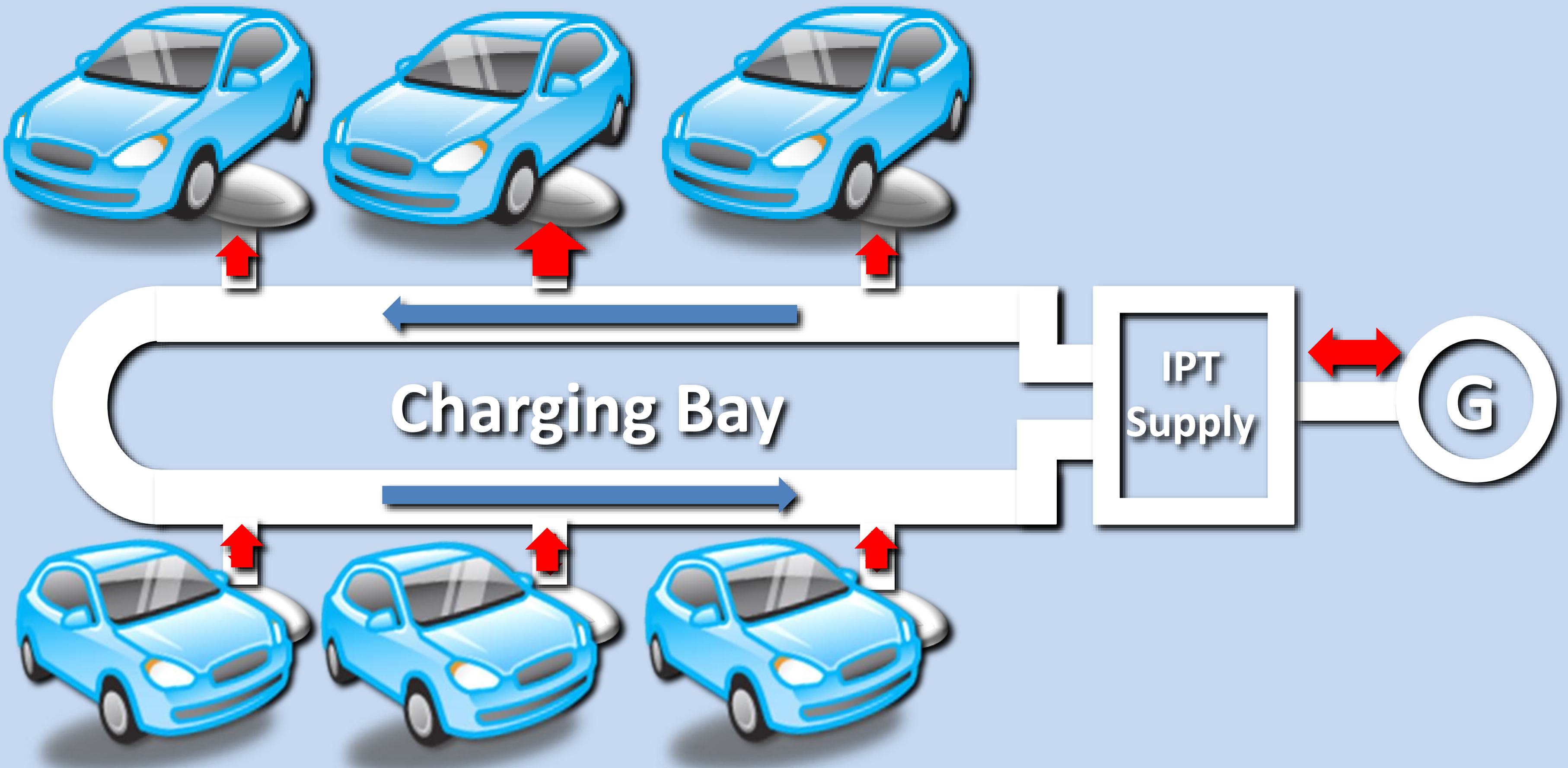
Legend :

Vehicle-to-Grid (V2G)

Vehicle-to-Vehicle (V2V)

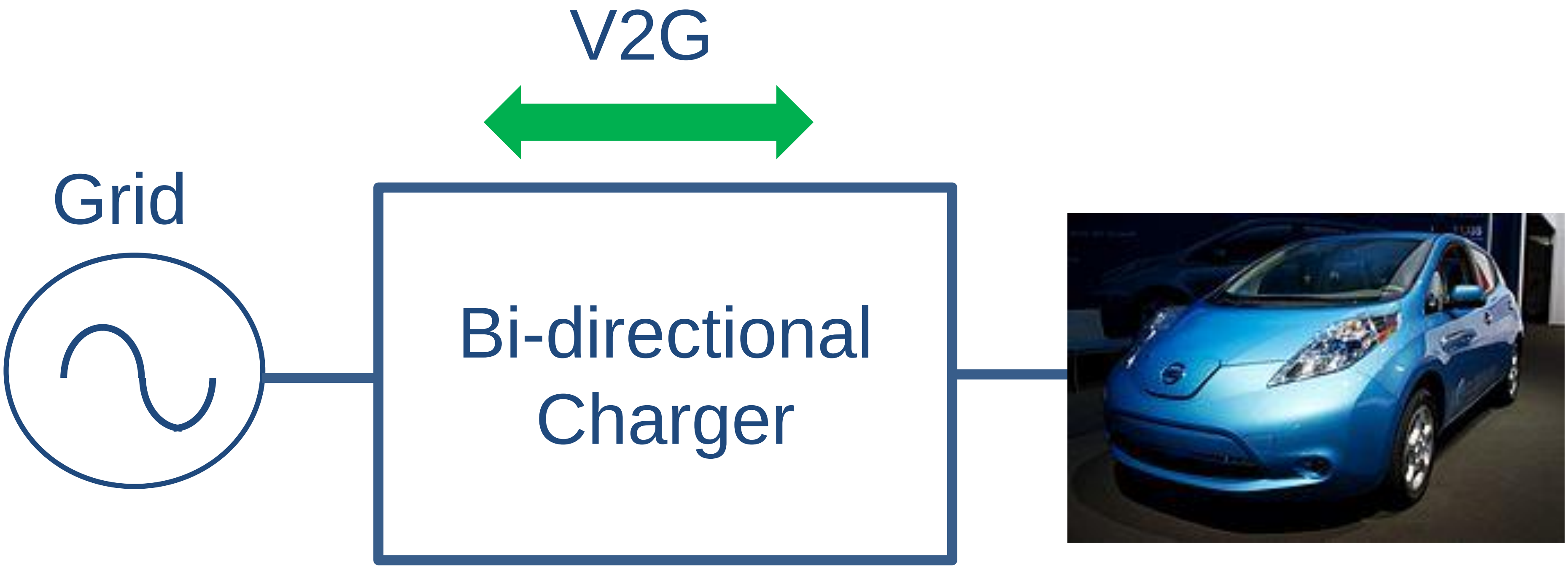
Home-to-Vehicle (H2V)

Charging a Fleet of EVs



V2G Compatible EVs

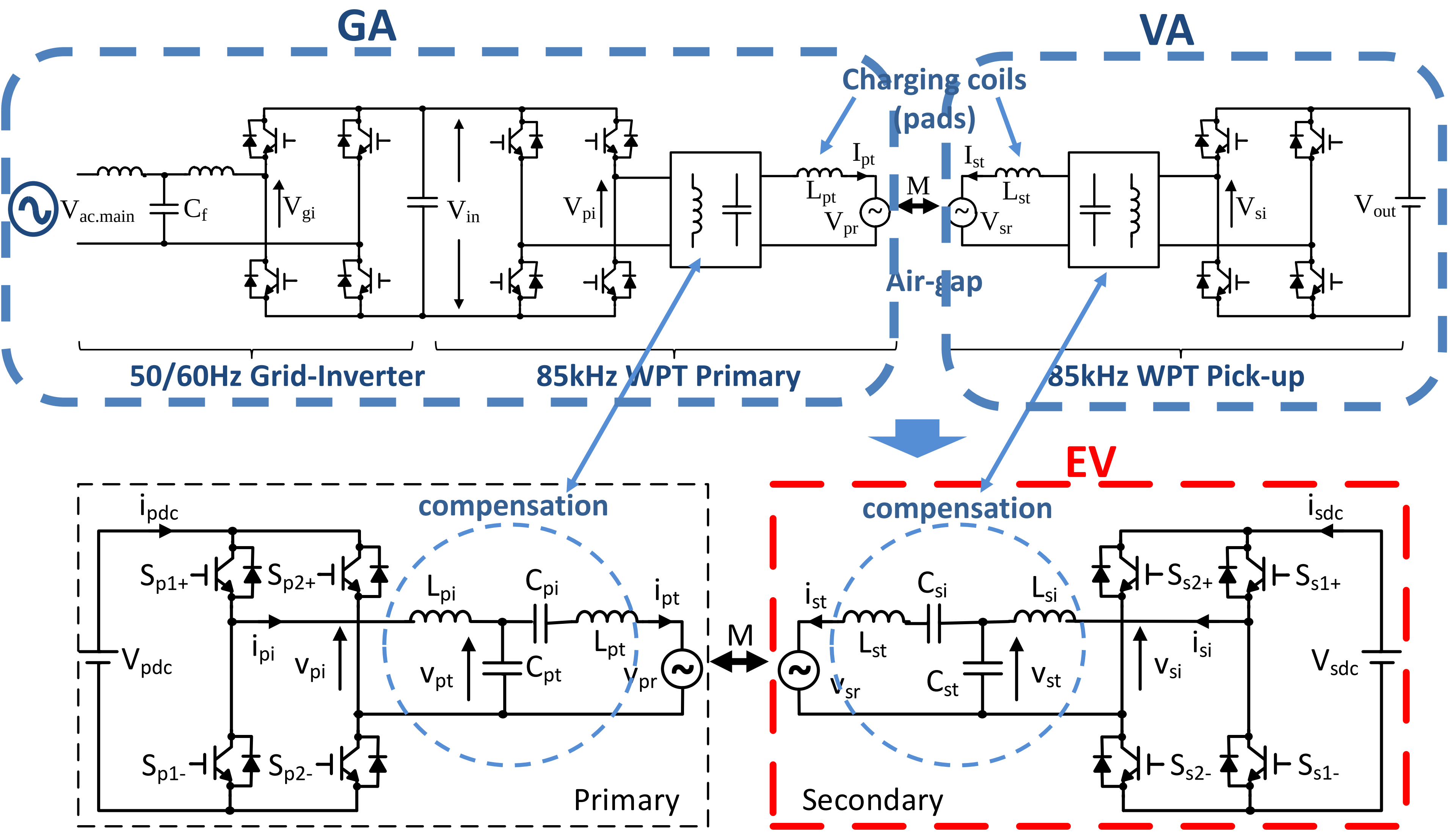
- Main requirement is the ‘bi-directional’ charger with communication



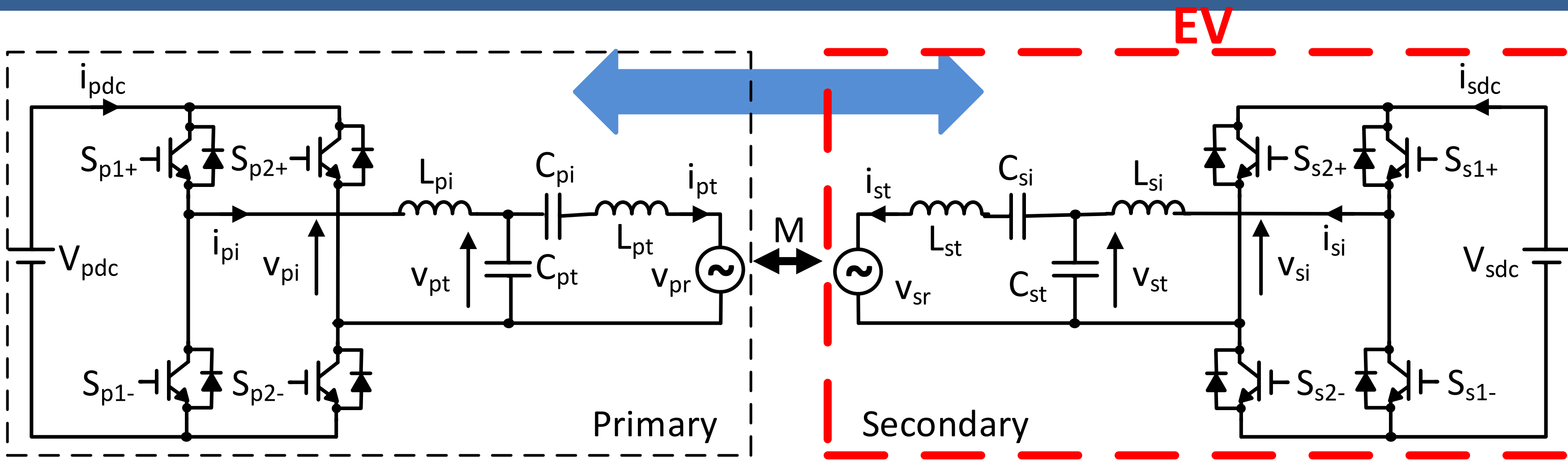
Bi-directional Wireless Power Transfer (BD-WPT) Systems

for V2G Applications

A typical Bi-directional WPT System



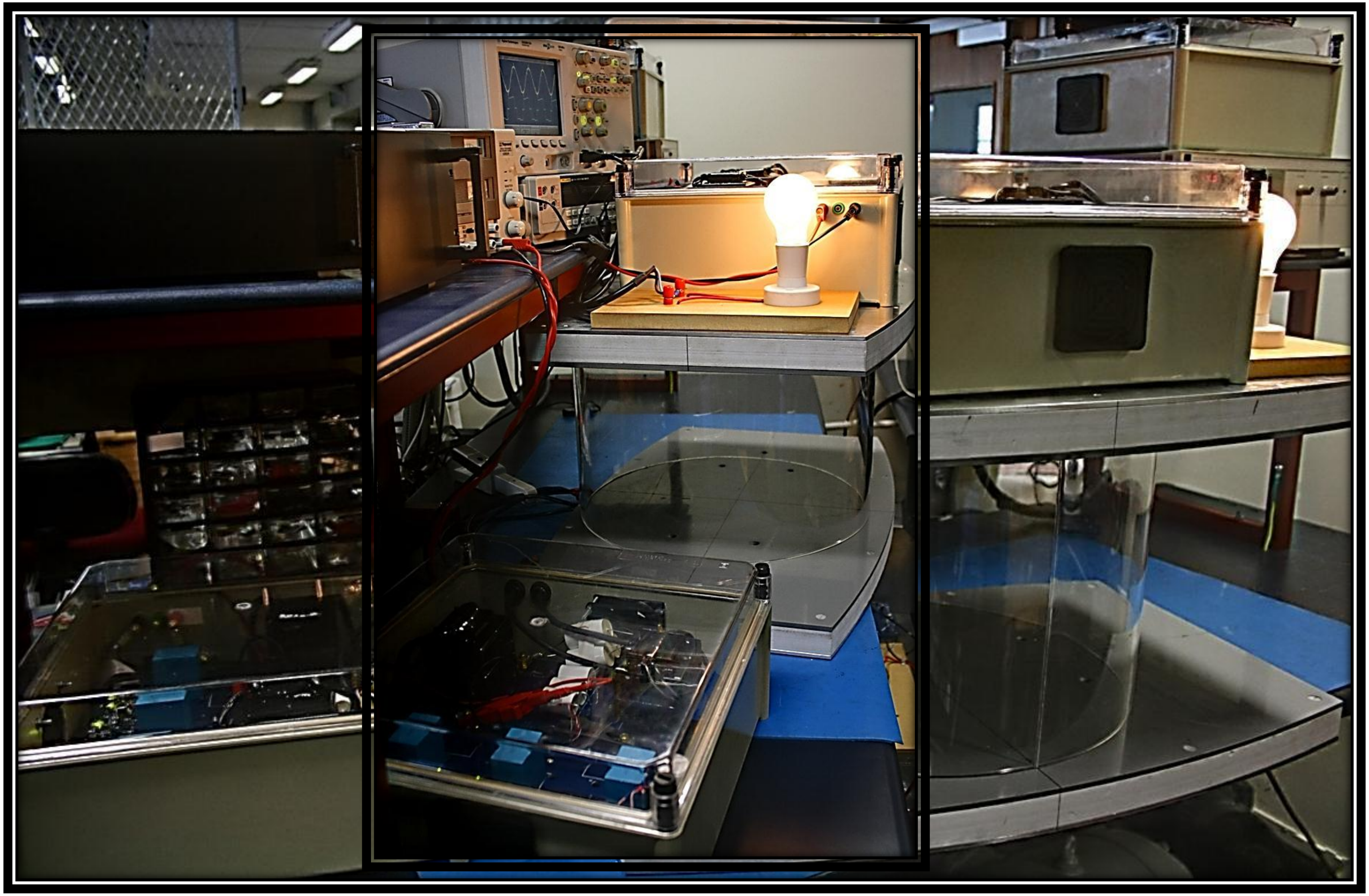
Control of Bi-directional WPT Systems



$$P_o = \frac{-M}{\omega_s L_{pt} L_{st}} \frac{8}{\pi^2} V_{pdc} V_{sdc} \sin(\theta) \sin\left(\frac{\phi_p}{2}\right) \sin\left(\frac{\phi_s}{2}\right)$$

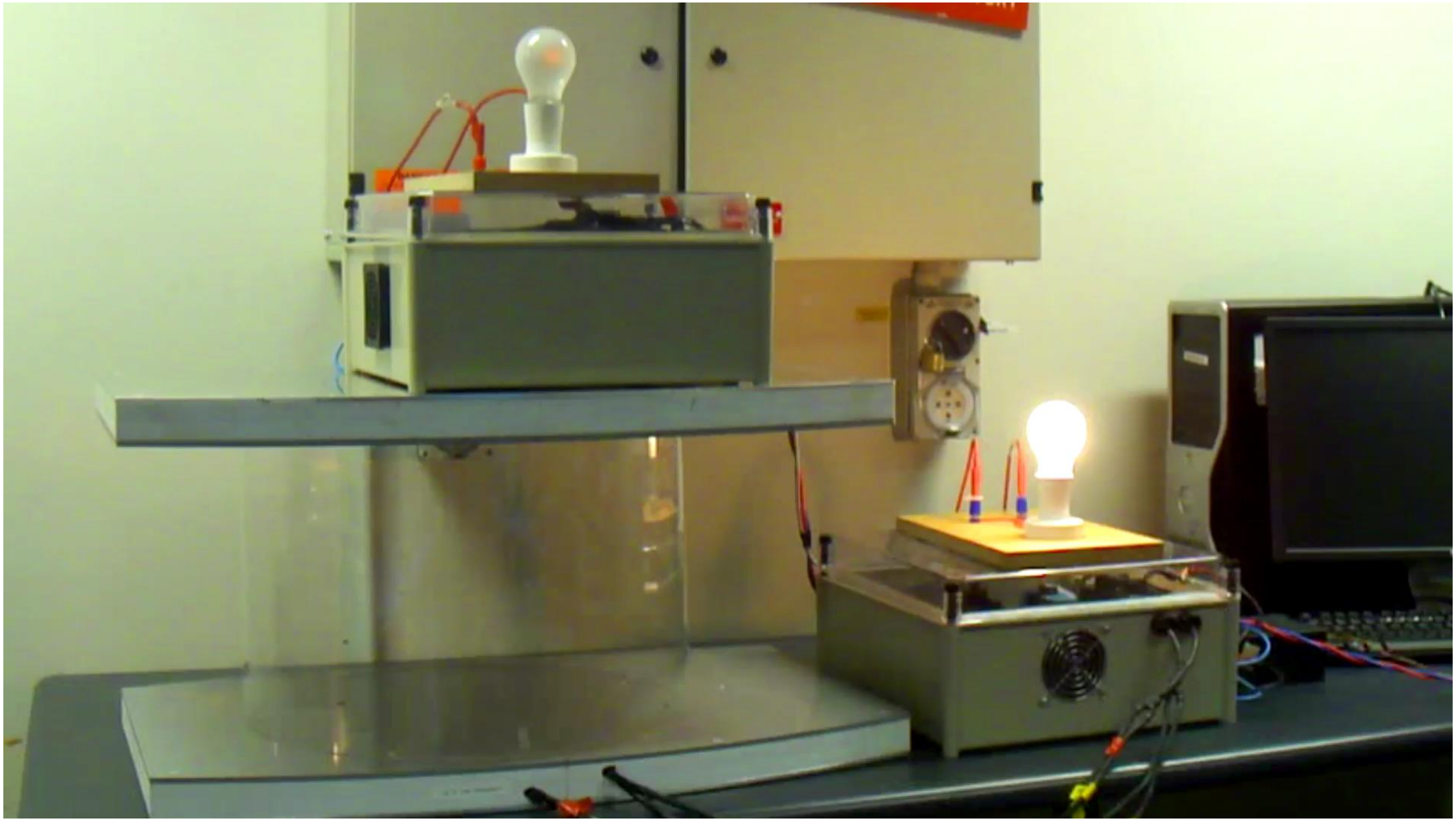
- *An 8th order resonant (tuned) system*
- *Controlled with **phase-modulation***
- *Proper control and synchronization are vital*

First Prototype 2009



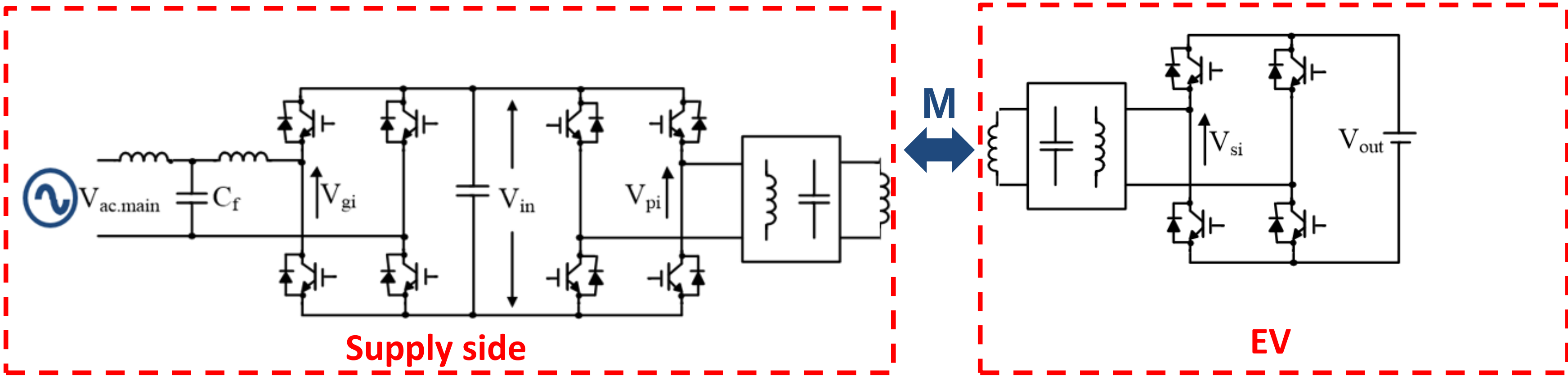
THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

First Prototype 2009

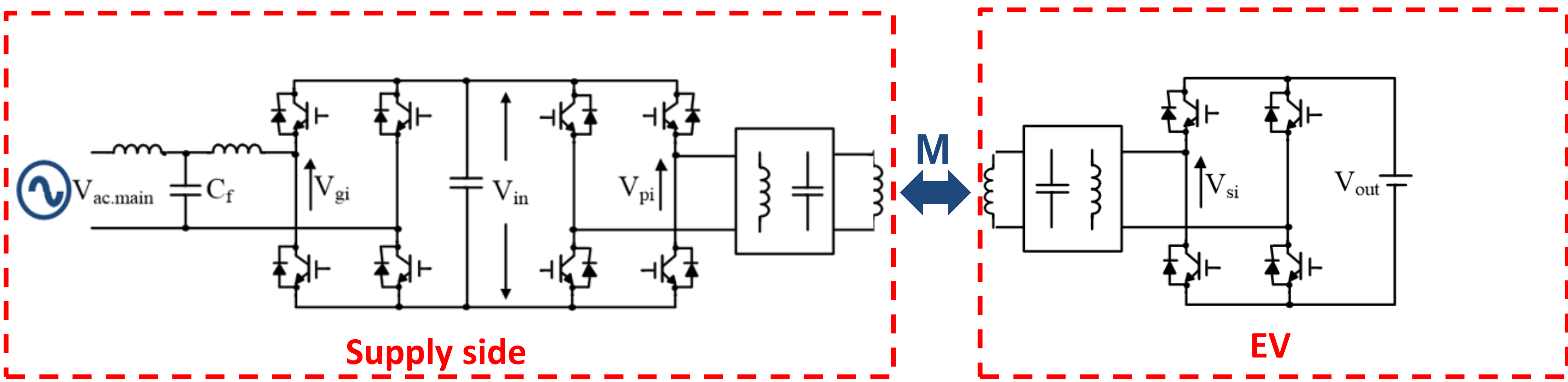


Pad (Coil) Misalignment

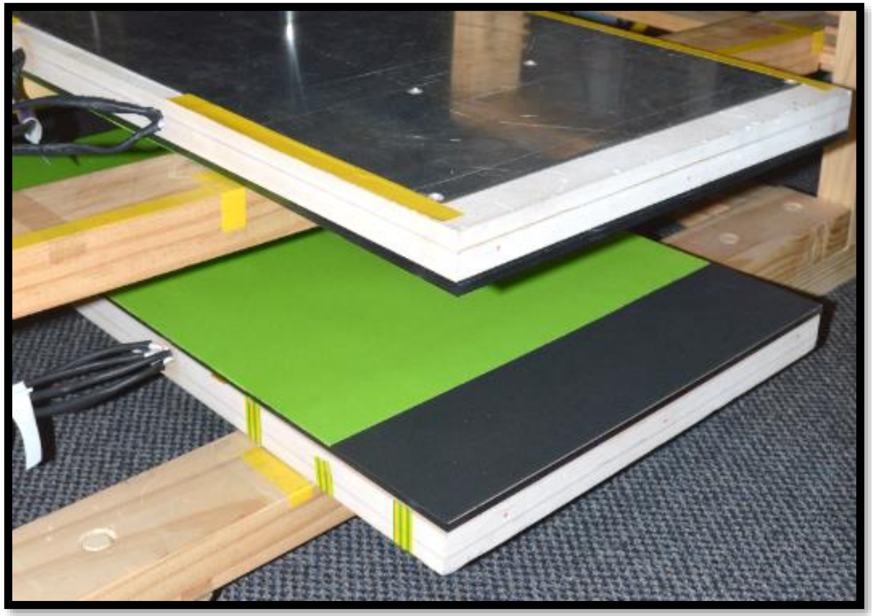
Pad Misalignment

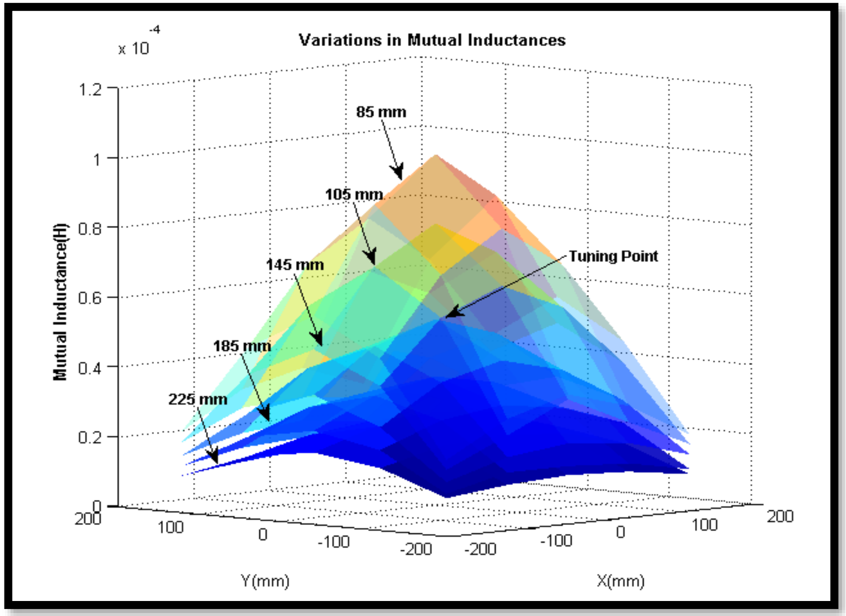


50/60Hz Grid-Inverter | 85kHz WPT Primary | 85kHz WPT Secondary



Impact of Pad Misalignment





$$P_o = \frac{-M}{\omega_s L_{pt} L_{st}} \frac{8}{\pi^2} V_{pdc} V_{sdc} \sin(\theta) \sin\left(\frac{\phi_p}{2}\right) \sin\left(\frac{\phi_s}{2}\right)$$

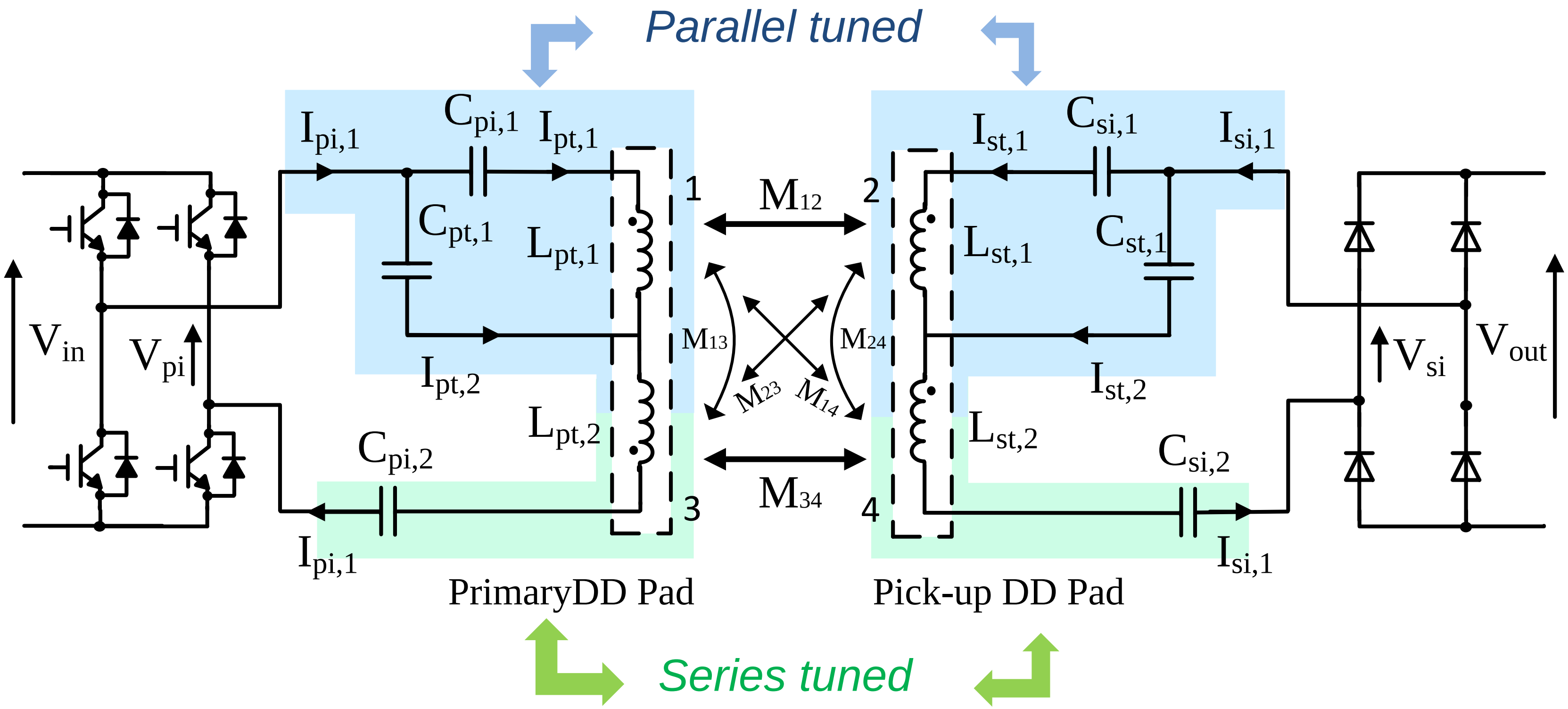
- Self & mutual inductances vary due to pad misalignments in 3-D
  - *Detunes the system increasing losses and reducing power delivery*
  - ***May adopt special and large pads, but at an increased cost!***

THE UNIVERSITY OF AUCKLAND Te Whare Wānanga o Tāmaki Makaurau NEW ZEALAND

Passive Control of WPT Systems (for Large Pad Misalignments)

A Hybrid BD-WPT System

for pad misalignment

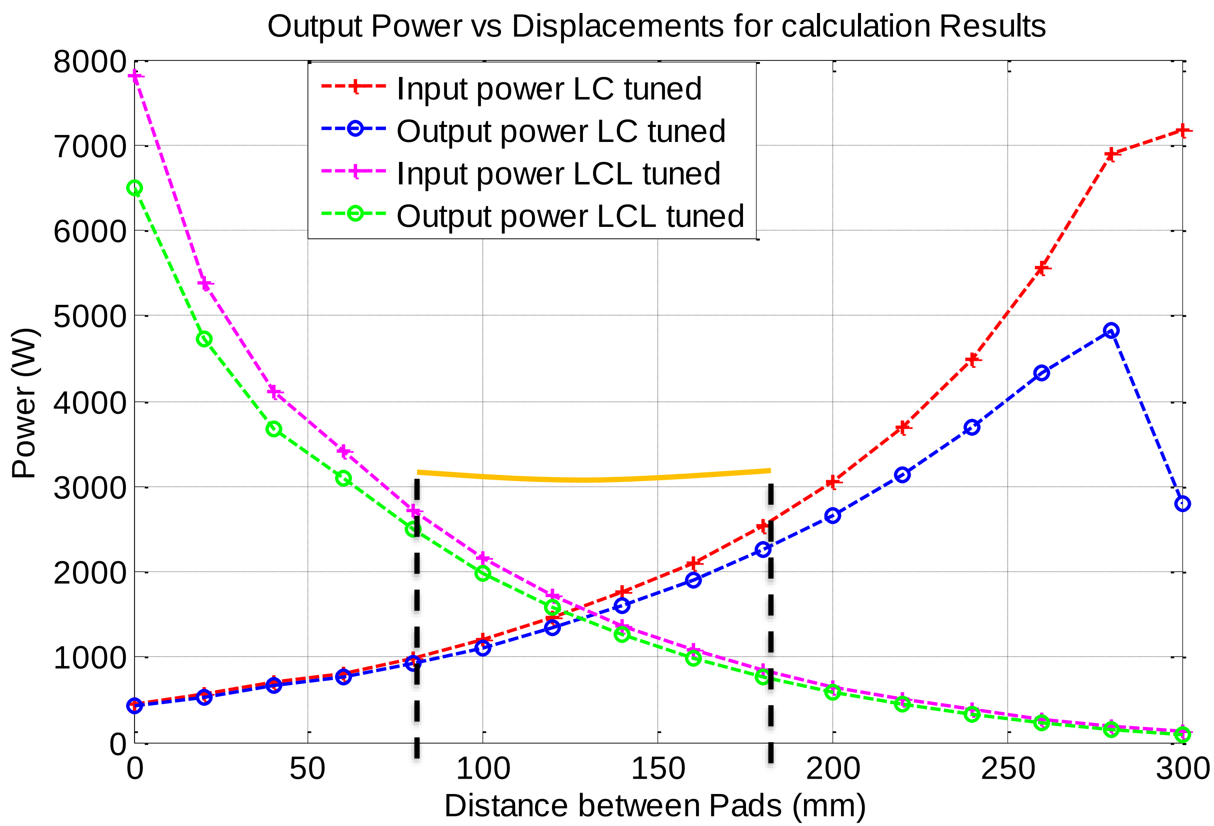


- ✓ *LCL and CL topologies are connected in series,*
- ✓ *Series inductors of the LCL networks are integrated into the polarized DD type or bi-polar type magnetic couplers*
- ✓ *Offers good tolerance to pad misalignments*

A Parallel Hybrid BD-WPT System

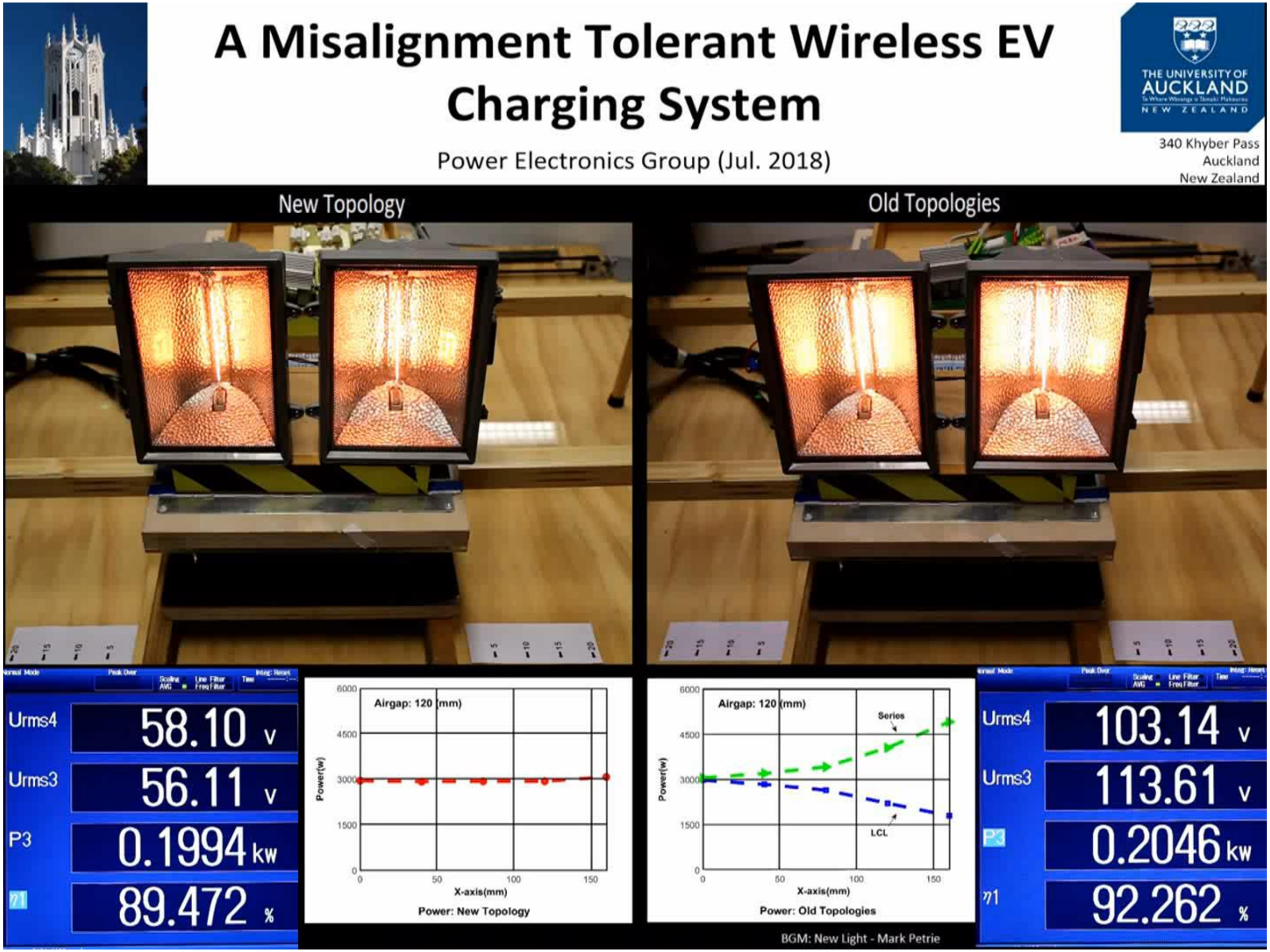
for pad misalignment

$$P_{hybrid} = \frac{8 \cdot V_{in} \sin(\varphi_p) \cdot V_{out} \sin(\varphi_s)}{\pi^2 \cdot \omega_T} \cdot \left(\frac{M_{11}}{L_{pi,1} \cdot L_{si,1}} + \frac{1}{M_{22}}\right)$$



Source : Lei Zhao, D. J. Thrimawithana & U. K. Madawala

A 3.3 kW Hybrid BD-WPT System



Active Control of BD-WPT Systems

(Optimal Efficiency under Large Pad Misalignments)

Control of Multiple Variables

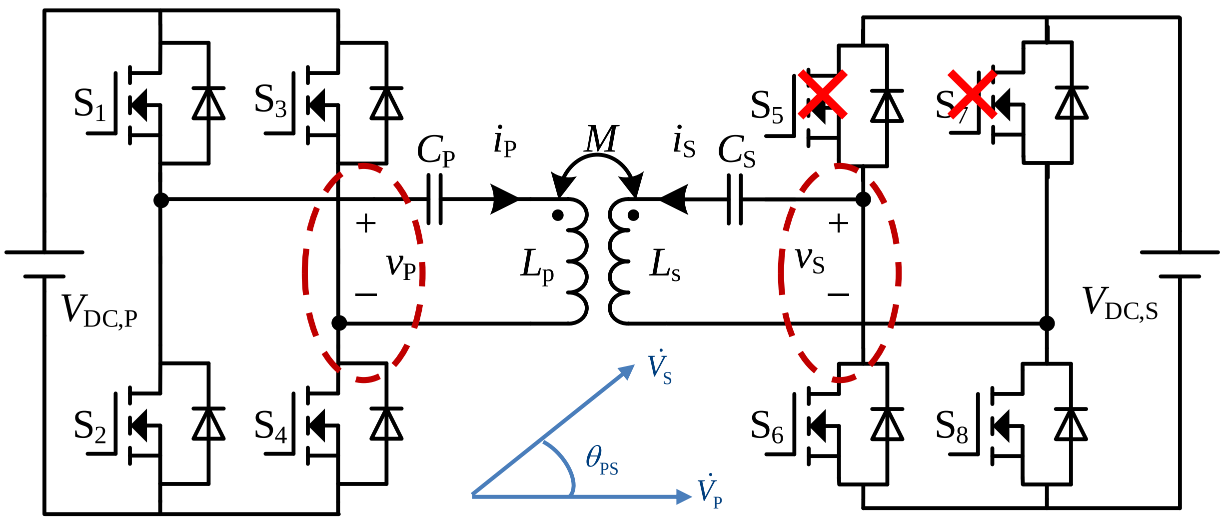
- Four control freedoms

- *Primary voltage: $v_P(\alpha)$*

$$V_P = \frac{2\sqrt{2}}{\pi}\sin\left(\frac{\alpha}{2}\right)V_{DC,P}$$

- *Secondary voltage: v_S (β)*

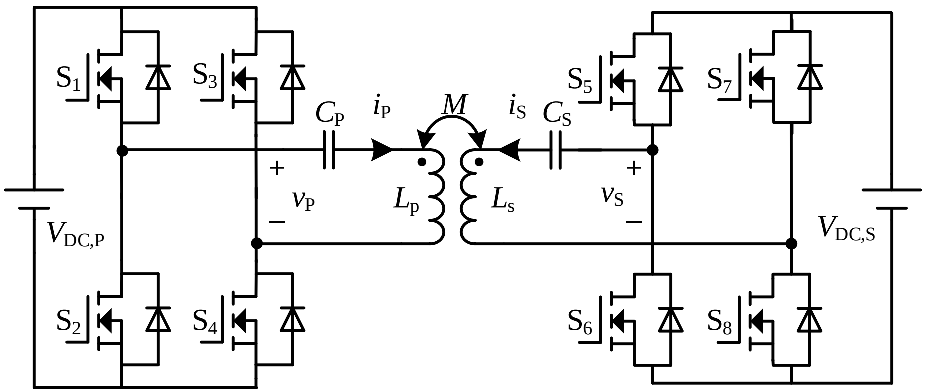
$$V_S = \frac{2\sqrt{2}}{\pi}\sin\left(\frac{\beta}{2}\right)V_{DC,S}$$

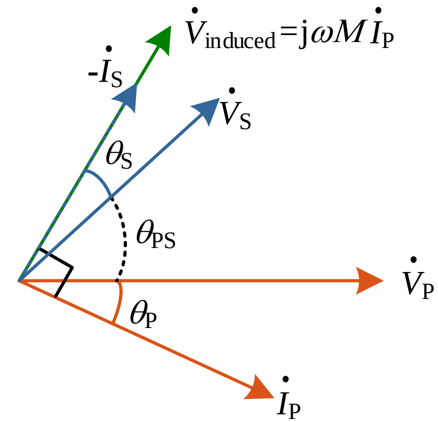


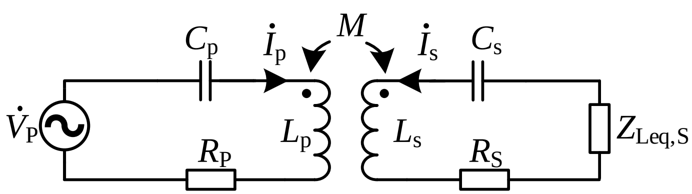
- *Operating frequency f*

- *Relative phase angle θ_{PS}*

Modelling BD-WPT Systems

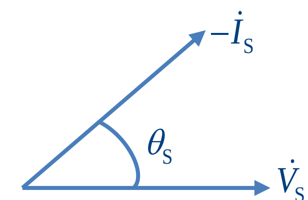


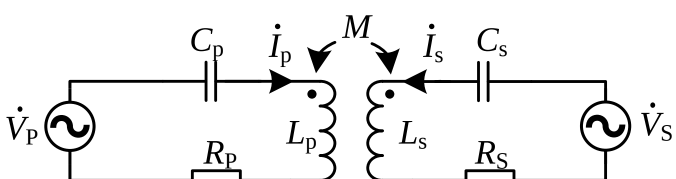




(a) Equivalent load impedance

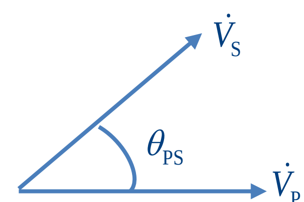
$$Z_{Leq,\,S} = \frac{\dot{V}_S}{\dot{I}_S} = R_{Leq,\,S}\left(\theta_S\right) + jX_{Leq,\,S}\left(\theta_S\right)$$





(b) Equivalent voltage source

$$\dot{V}_S = V_S \angle \theta_{PS}$$



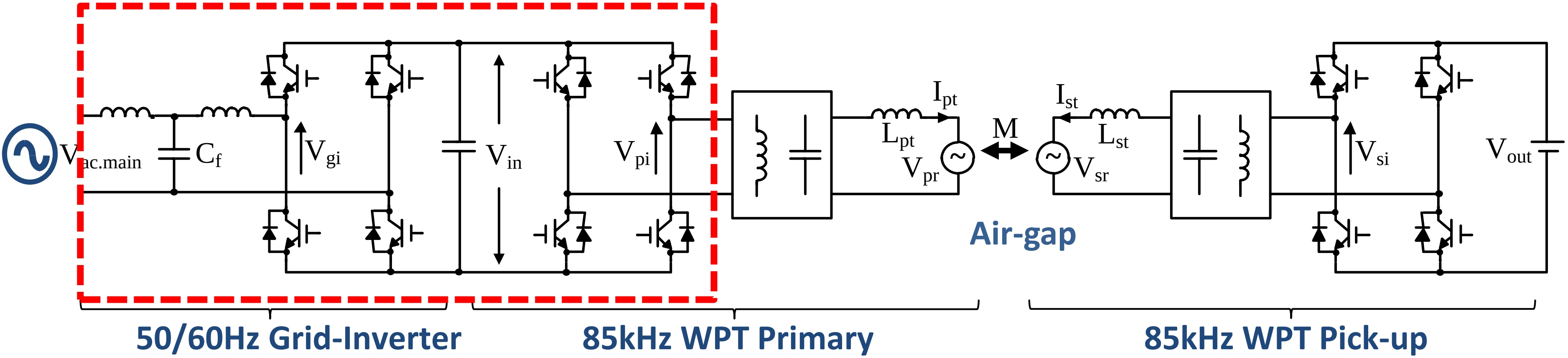
Source : Y. Liu & U. K. Madawala

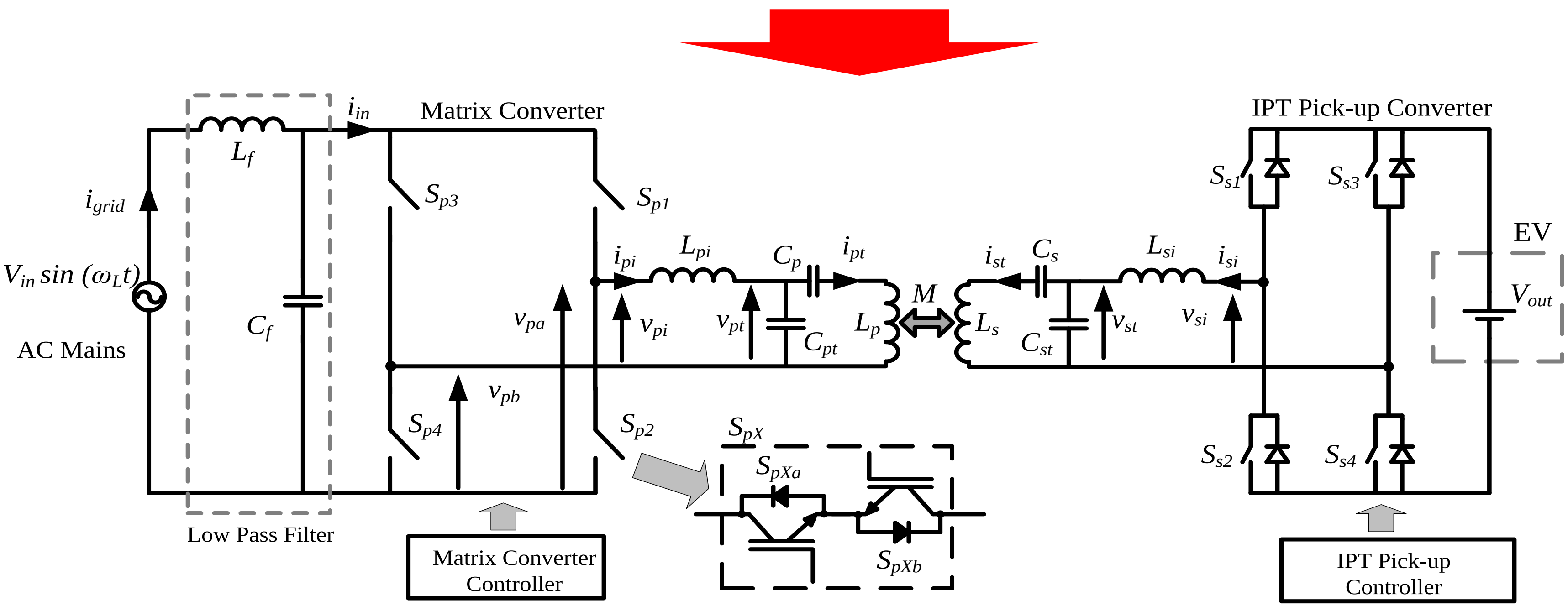
Grid Interfaces for BD-WPT systems

A BD-WPT System based on Matrix Converters

A BD-WPT System

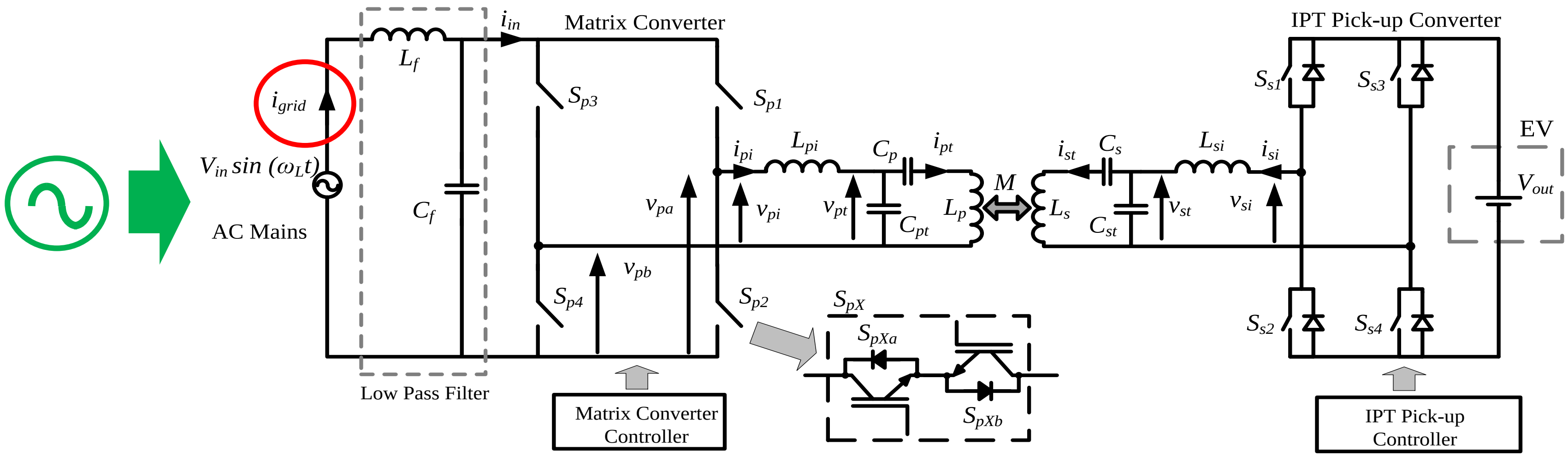
based on a matrix converter





A BD-WPT System

based on a matrix converter



- Direct 50/60 Hz to 85 kHz AC-AC conversion
  - *Does not require a large filter inductor or DC-link capacitors*
  - *Reduced number of conversion stages*
  - *Complex control strategies required to ensure reliable operation*

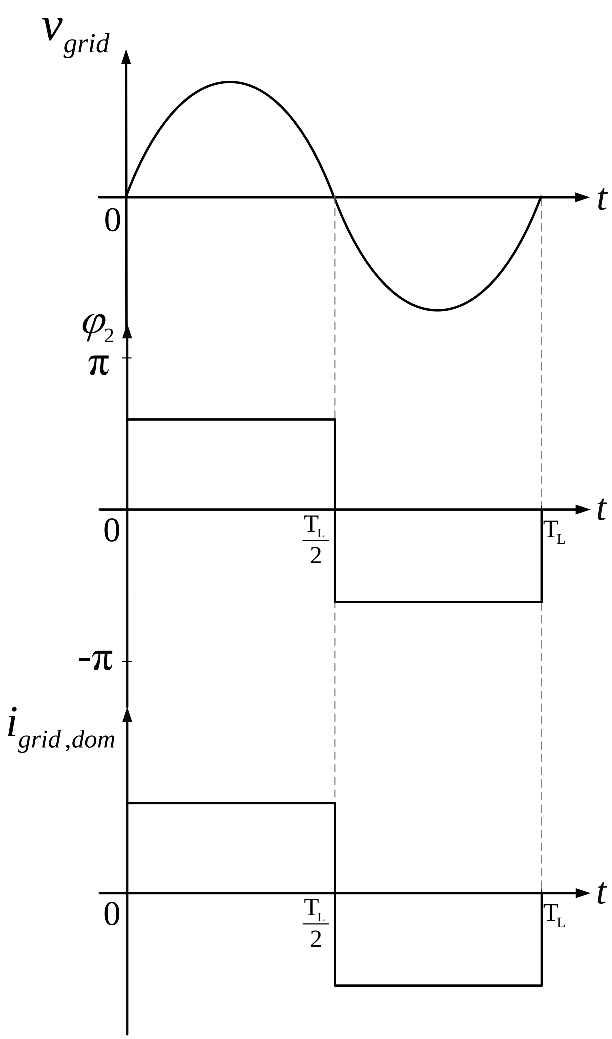
$$i_{grid}(t) = \frac{V_{in} L_f C_f \omega_L \sin\left(\omega_L t + \frac{\pi}{2}\right)}{1-\omega_L^2 L_f C_f} - \frac{\psi \sin(2\omega_T t + \theta)}{1-4\omega_T^2 L_f C_f} - \psi \sin\theta$$

$$P_{in+} = \frac{-16 M V_{in} V_{out}}{\pi^3 \omega_T L_{pt} L_{si}} \sin\left(\frac{\varphi_1}{2}\right) \sin\left(\frac{\varphi_2}{2}\right) \sin(\theta)$$

THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

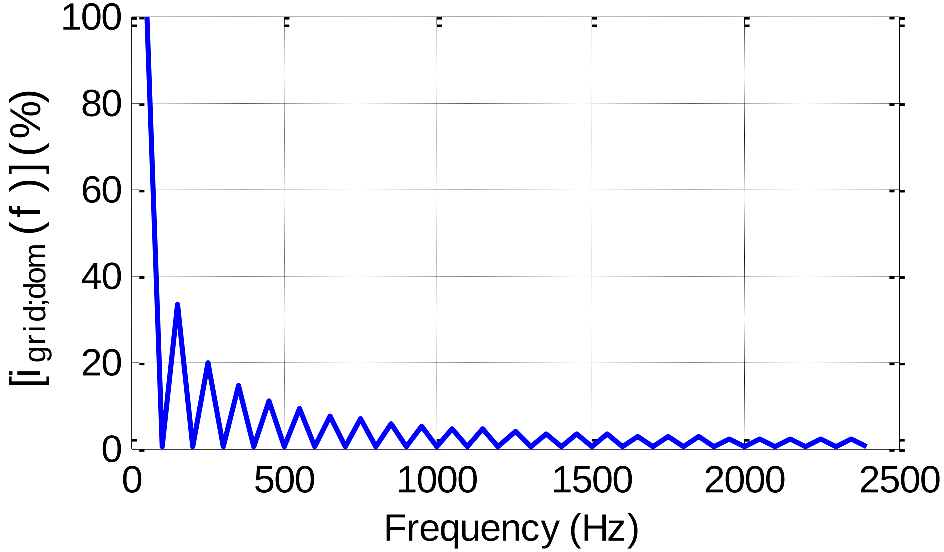
A BD-WPT System

based on a matrix converter



$$i_{grid,dom}(t) = \frac{8}{\pi^2}\frac{M}{\omega_T L_{pt} L_{si}} V_{out} \sin\left(\frac{\varphi_1}{2}\right)\sin\left(\frac{\varphi_2}{2}\right)\sin\theta$$

$THD \approx 48\%$



- *Attenuation of grid current harmonics is essential*
- *PWM based modulation techniques cannot be directly employed*

THE UNIVERSITY OF AUCKLAND Te Whare Wānanga o Tāmaki Makaurau NEW ZEALAND

A BD-WPT System

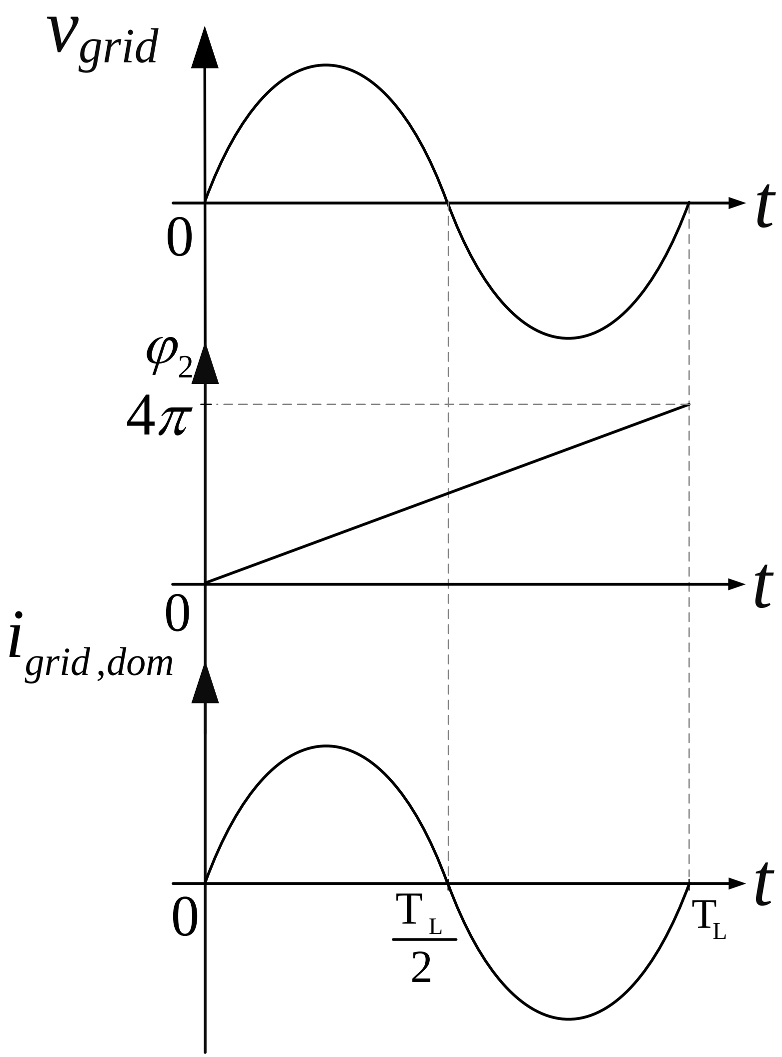
based on a matrix converter

$$i_{grid,dom}(t) = \hat{i}_{grid,dom} \sin\left(\frac{\varphi_2}{2}\right)$$

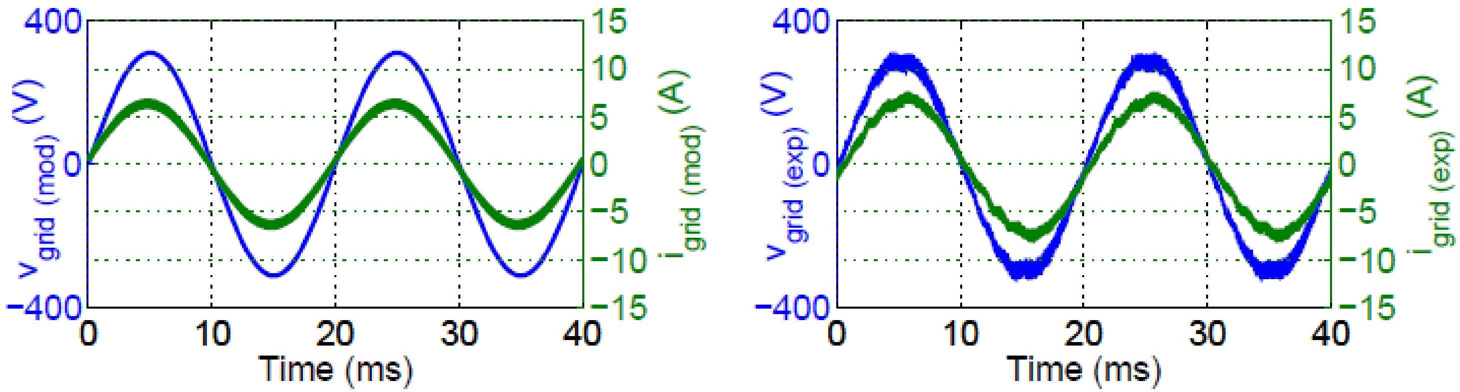
where

$$\hat{i}_{grid,dom} = \frac{8}{\pi^2} \frac{M}{\omega_T L_{pt} L_{si}} V_{out} \left| \sin\left(\frac{\varphi_1}{2}\right) \sin\theta \right|$$

$$\varphi_2 = \frac{4\pi}{T_L} t$$

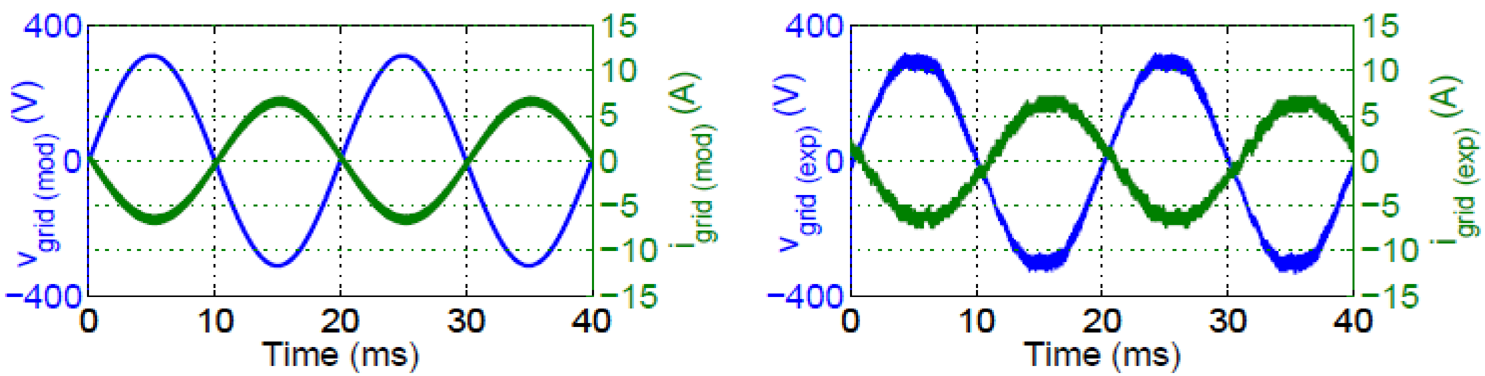


Forward & Reverse Power Flow



(a) (b)

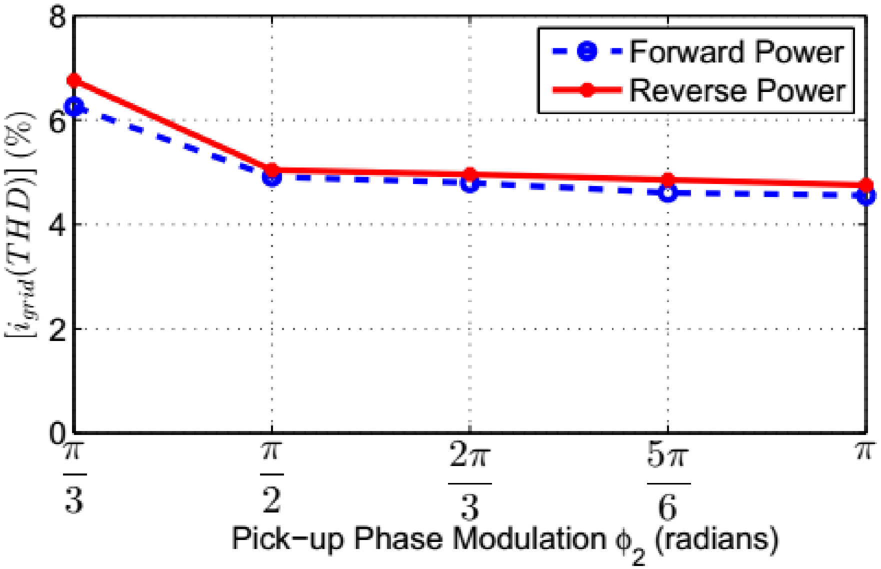
i_{grid} for maximum power in forward direction at $\varphi_1 = \pi$ and $\theta = -\pi/2$ (a) theoretical and (b) experimental

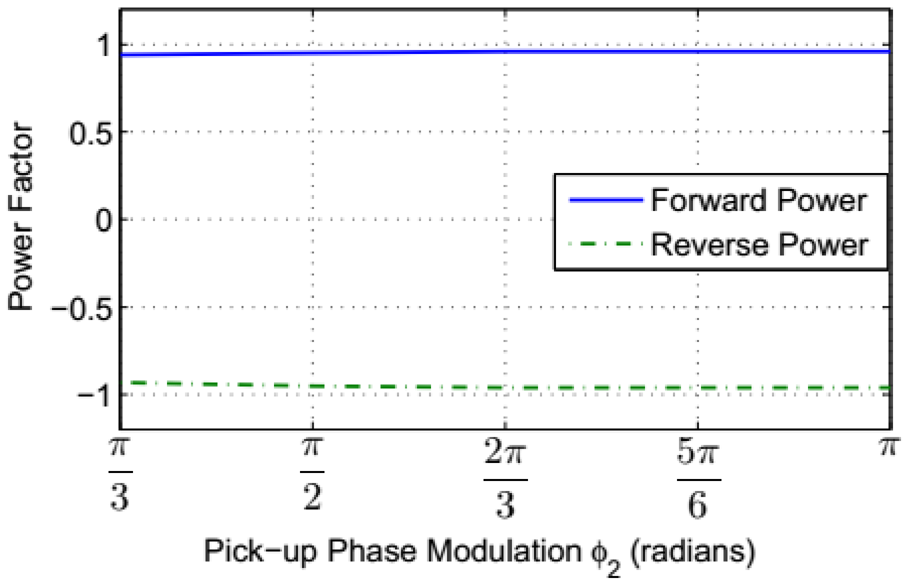


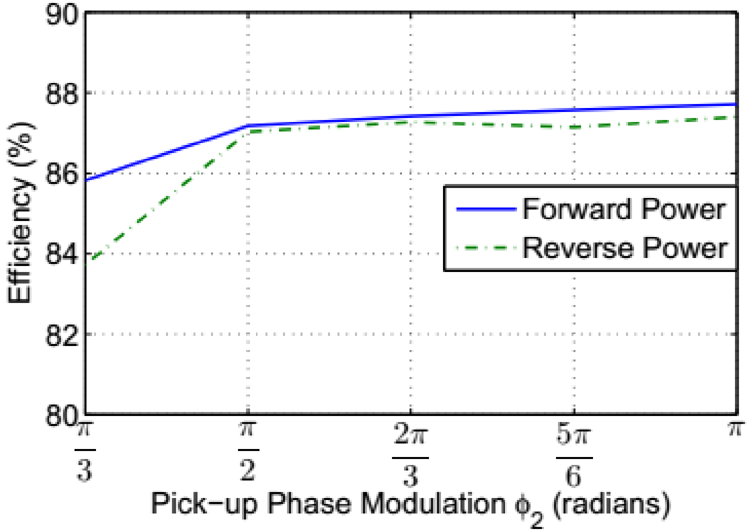
(a) (b)

i_{grid} for maximum power in reverse direction at $\varphi_1 = \pi$ and $\theta = \pi/2$ (a) theoretical and (b) experimental.

THD, Power Factor and Efficiency

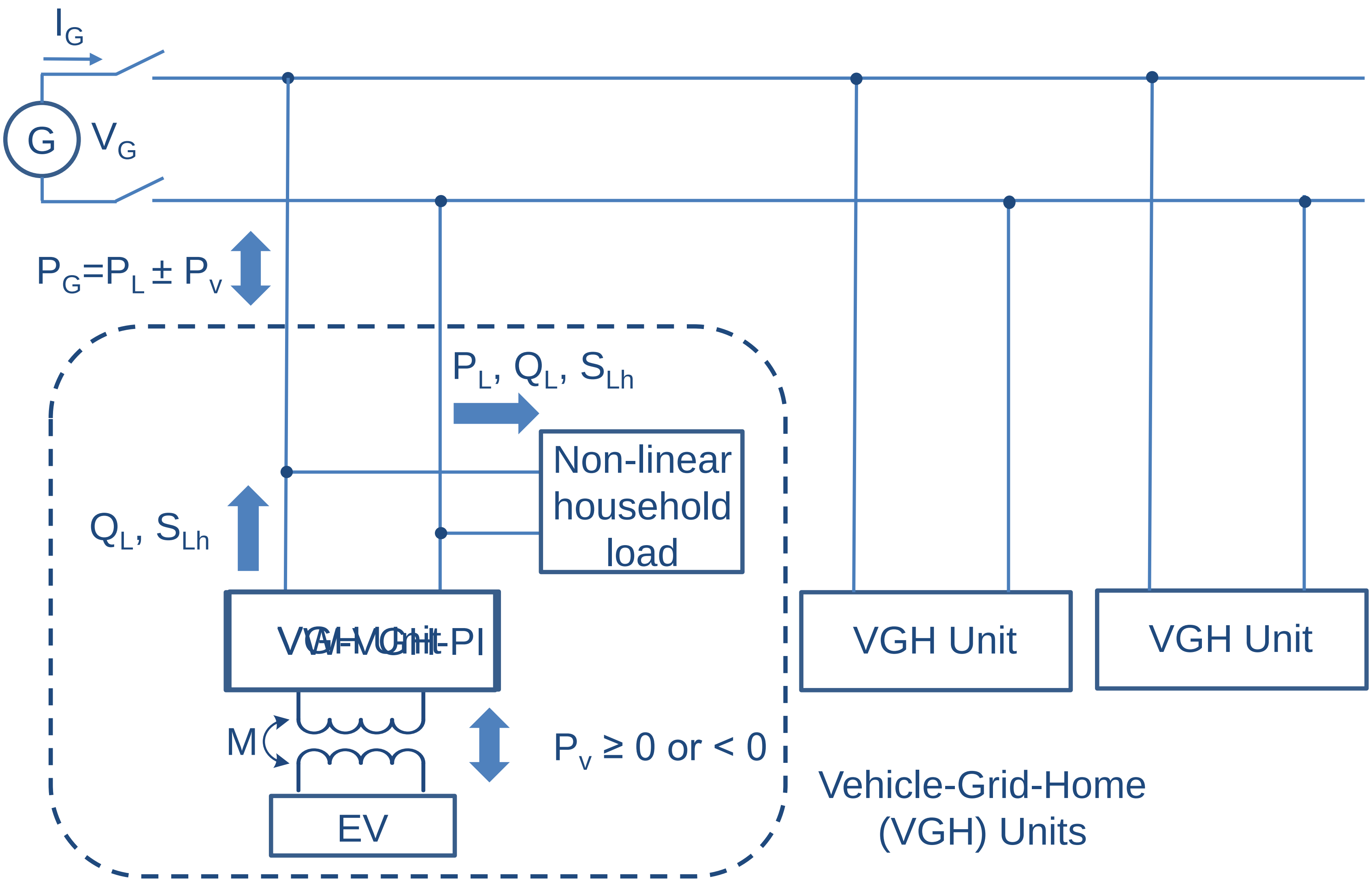






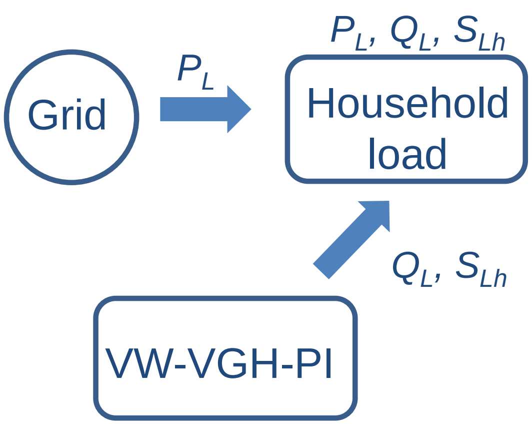
Versatile Wireless Vehicle-Grid-Home Power Interface (VW-VGH-PI)

VW-VGH-PI

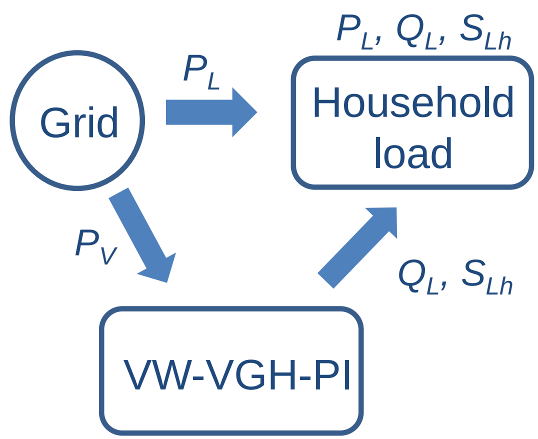


Vehicle-Grid-Home (VGH) Units

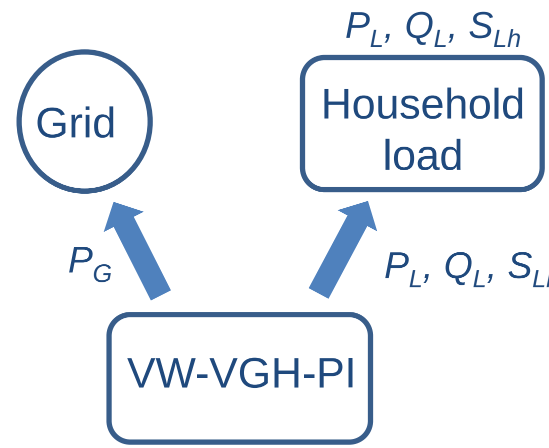
5 Modes of Operation



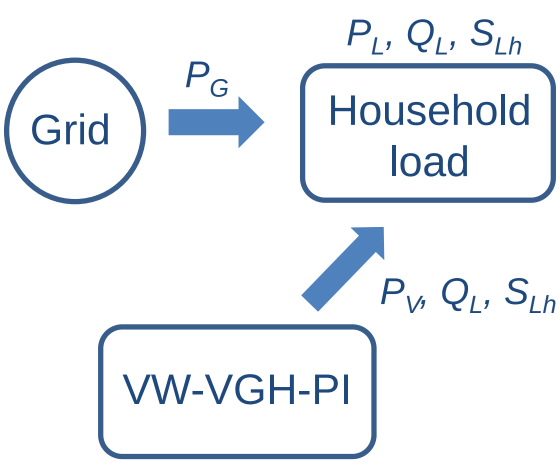
APF mode



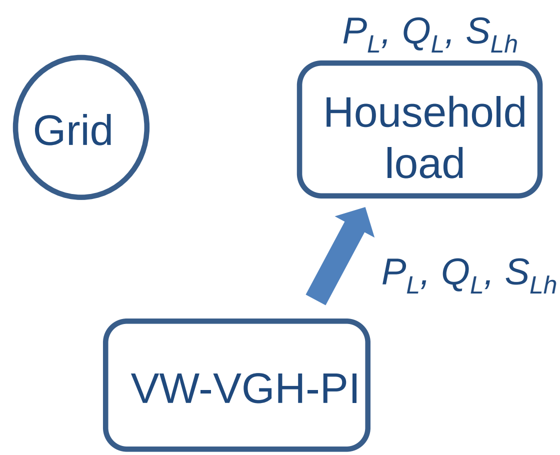
G2VH



V2HG



VG2H



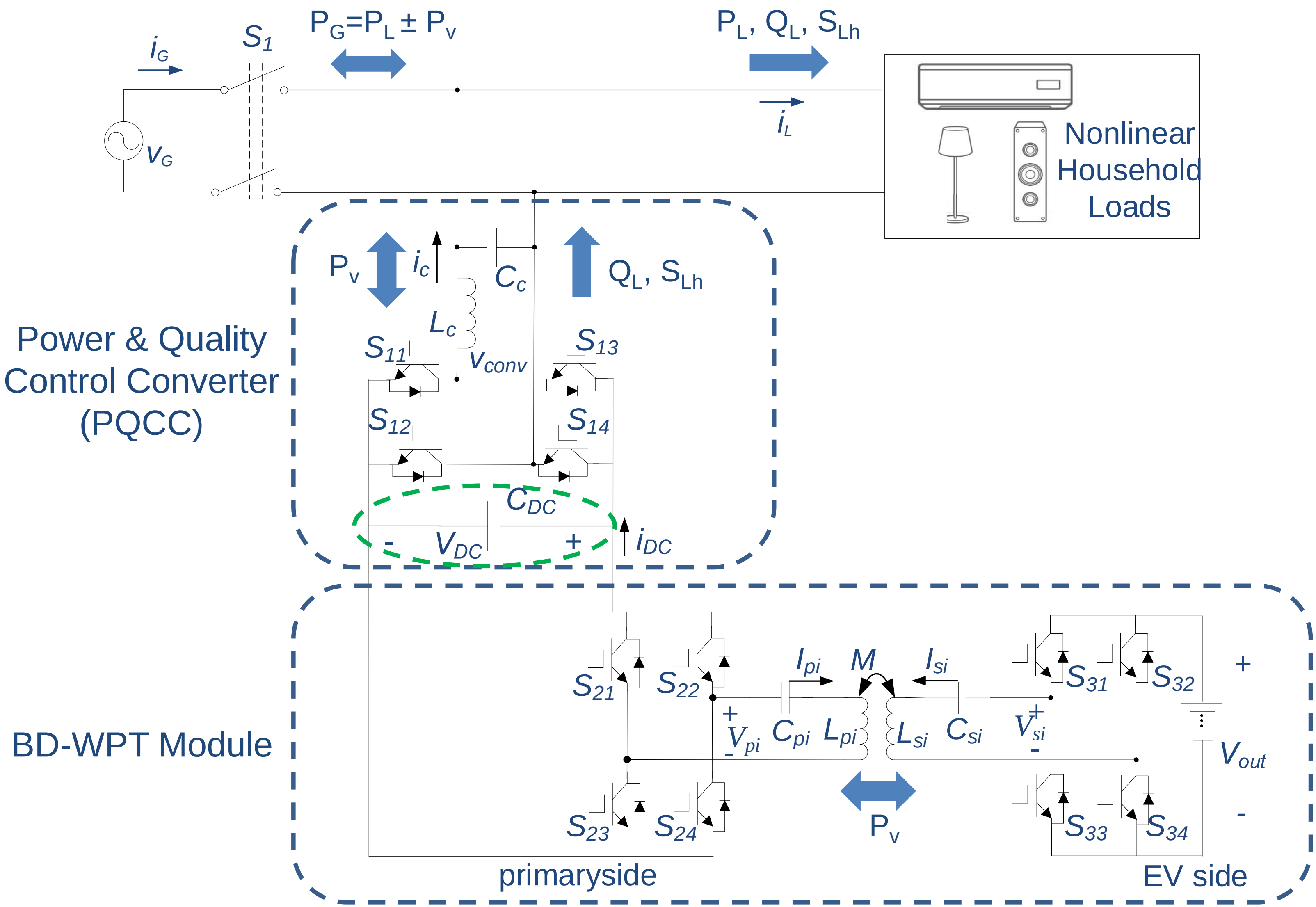
V2H (islanded)

THE UNIVERSITY OF AUCKLAND Te Whare Wānanga o Tāmaki Makaurau NEW ZEALAND

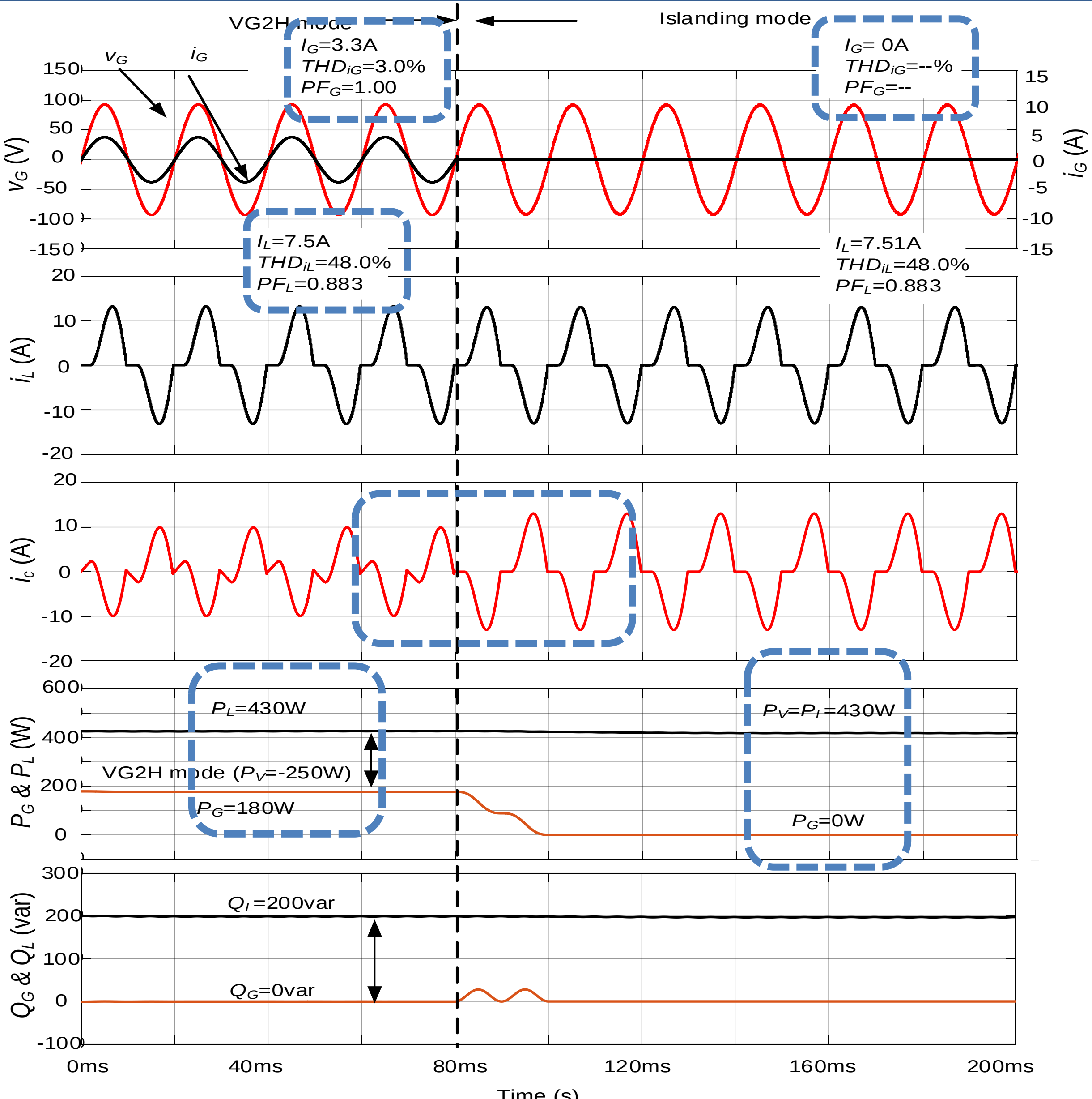
Source : L. Wang & U. K. Madawala

Adaptive DC link Voltage Control

with soft switching

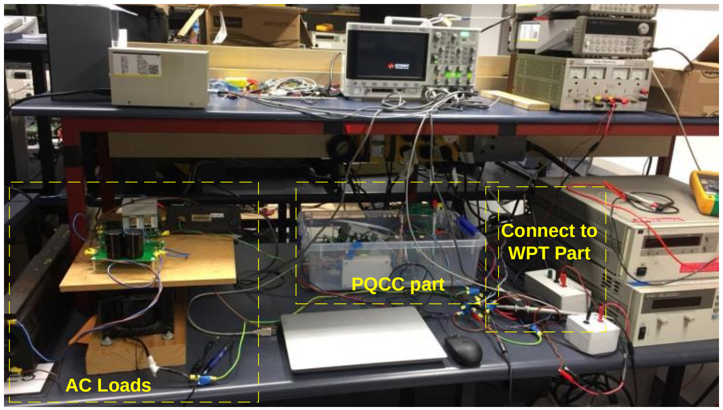


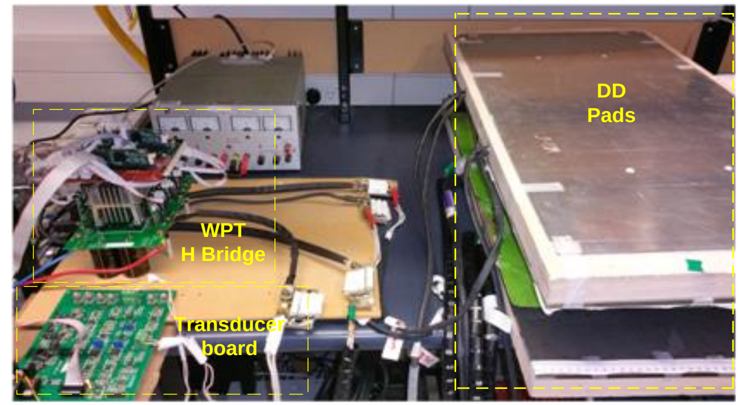
Results: VG2H to Islanded mode



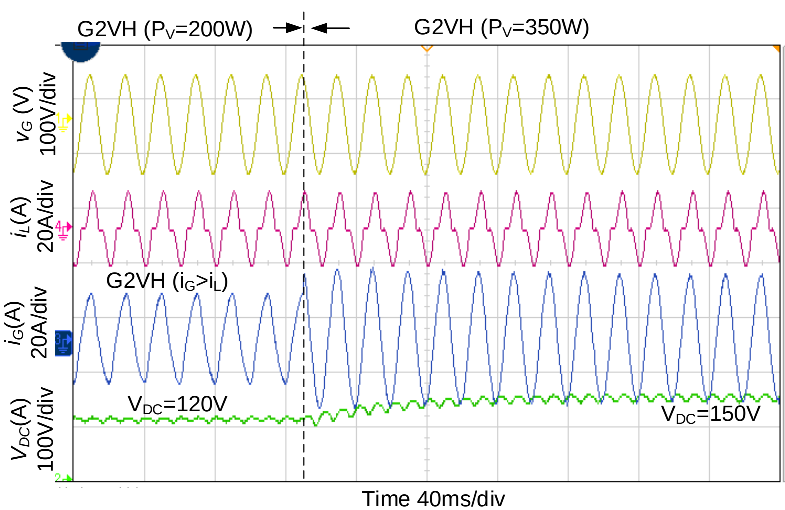
Source : L. Wang & U. K. Madawala

Experimental Results

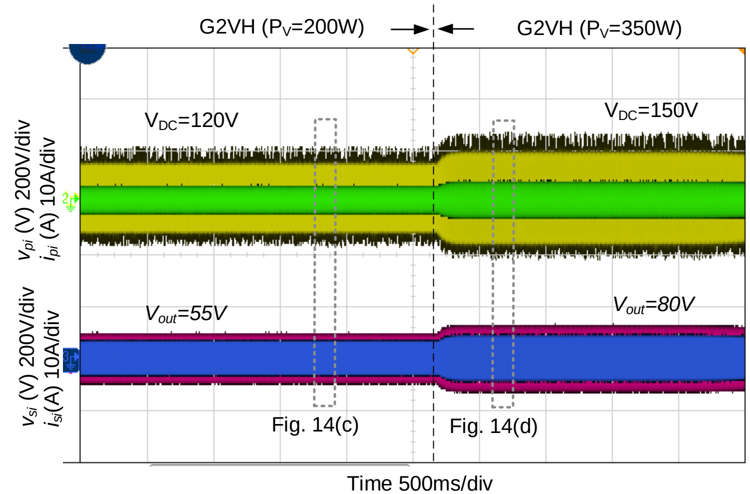




(a) Prototype



(b) Dynamic waveforms on grid side



(c) Dynamic waveforms BD-WPT side

THE UNIVERSITY OF AUCKLAND Te Whare Wānanga o Tāmaki Makaurau NEW ZEALAND

Source : L. Wang & U. K. Madawala

Vehicle-2-Grid (V2G) systems

Is this or will this be a reality?

Source : https://www.qualcomm.com/

Nissan : LEAF to HOME (V2H)

2 days of household electricity

Source : http://www.yougen.co.uk/blog-entry/2688/How+much+will+V2G+cost+and+when'2C+where+and+who+will+make+it+happen'3F/

Nissan & Enel V2G System

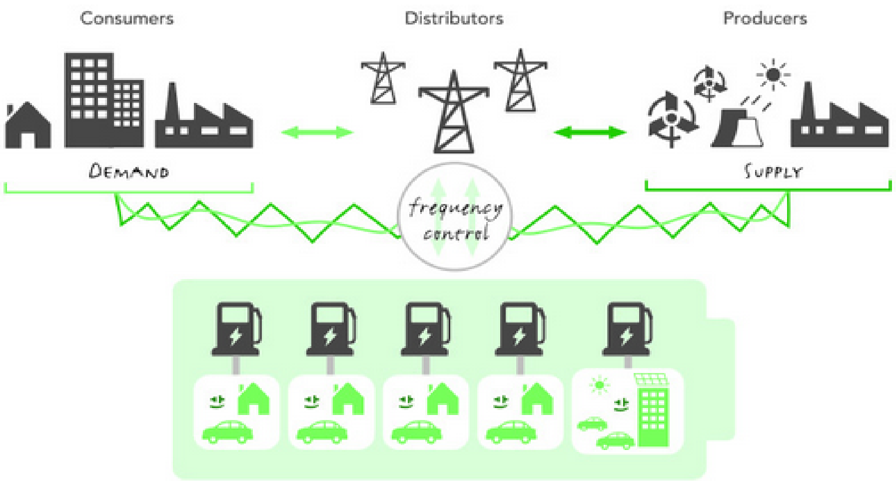
http://newsroom.nissan-europe.com/uk/en-gb/media/pressreleases/145248/nissan-and-enel-launch-groundbreaking-vehicle-to-grid-project-in-the-uk

V2X : Already a Reality at CHAdeMO

CHAdeMO protocol detailing V2X extension is available to Members. Certification of V2H/ V2L chargers is already available in Japan and in Europe.

"By 2025 V2G could provide additional revenues and cost savings of US$2 billion to global energy suppliers and offer consumers 15% savings on household energy bill"

ABI Research



A crucial element for a switch to renewables, V2X technology enables using EVs as both vehicles and portable batteries. With V2H devices, EVs can financial benefits to the EV owner:

- Save costs by optimizing the energy usage (e.g. charge from PV and use later).
- Make money by providing services to the Grid. CHAdeMO's EVs are the only mass-produced cars readily capable of V2X.

CHAdeMO-based V2X demo projects

Projects using V2X capacities of CHAdeMO protocol have been going on around the world since 2012. Recently, their scale and numbers have been growing, with more and more initiatives in Europe and the US. These demonstration projects provide valuable findings and data for large scale market deployment of V2H/ V2G technology.

Standards & V2G Compatible EVs

- IEC 63110 [1] : standard defining a protocol for the management of electric vehicles charging/discharging infrastructures, which is currently under development
- CHAdeMO is currently the only system that complies to standards (IEC 61851-23, EN50118), relevant to bi-directional energy flow
- Globally, except China, CHAdeMO is the most widely used charging system offering V2X chargers
- There are three EVs currently have V2G compatibility,
    - ✓ *Nissan Leaf, Nissan e-NV200, Mitsubishi Outlander*

Source [1]: (https://v2g-clarity.com/blog/the-road-to-iec-63110-and-how-you-can-impact-the-international-standard/)

Honda V2G System

HONDA

Honda R&D Americas

WiTricity Wireless Charging Featured in Honda's Vehicle-to-Grid Energy Management System

Honda V2G will create value for Honda owners and electric utilities, and will debut at the 2019 Consumer Electronics Show

Watertown, Mass., U.S.A. – December 12, 2018 –WiTricity, the industry pioneer in wireless power transfer over distance, has collaborated with Honda for its bi-directional, wireless Vehicle-to-Grid (V2G) energy management system. The solution, which will debut at the 2019 Consumer Electronics Show (CES), has the potential to reduce carbon dioxide emissions, balance the energy grid and save money for EV owners and electric utilities.

> read full press release

Witricity is now collaborating with University of Auckland

http://newsroom.nissan-europe.com/uk/en-gb/media/pressreleases/145248/nissan-and-enel-launch-groundbreaking-vehicle-to-grid-project-in-the-uk

Dynamic Charging

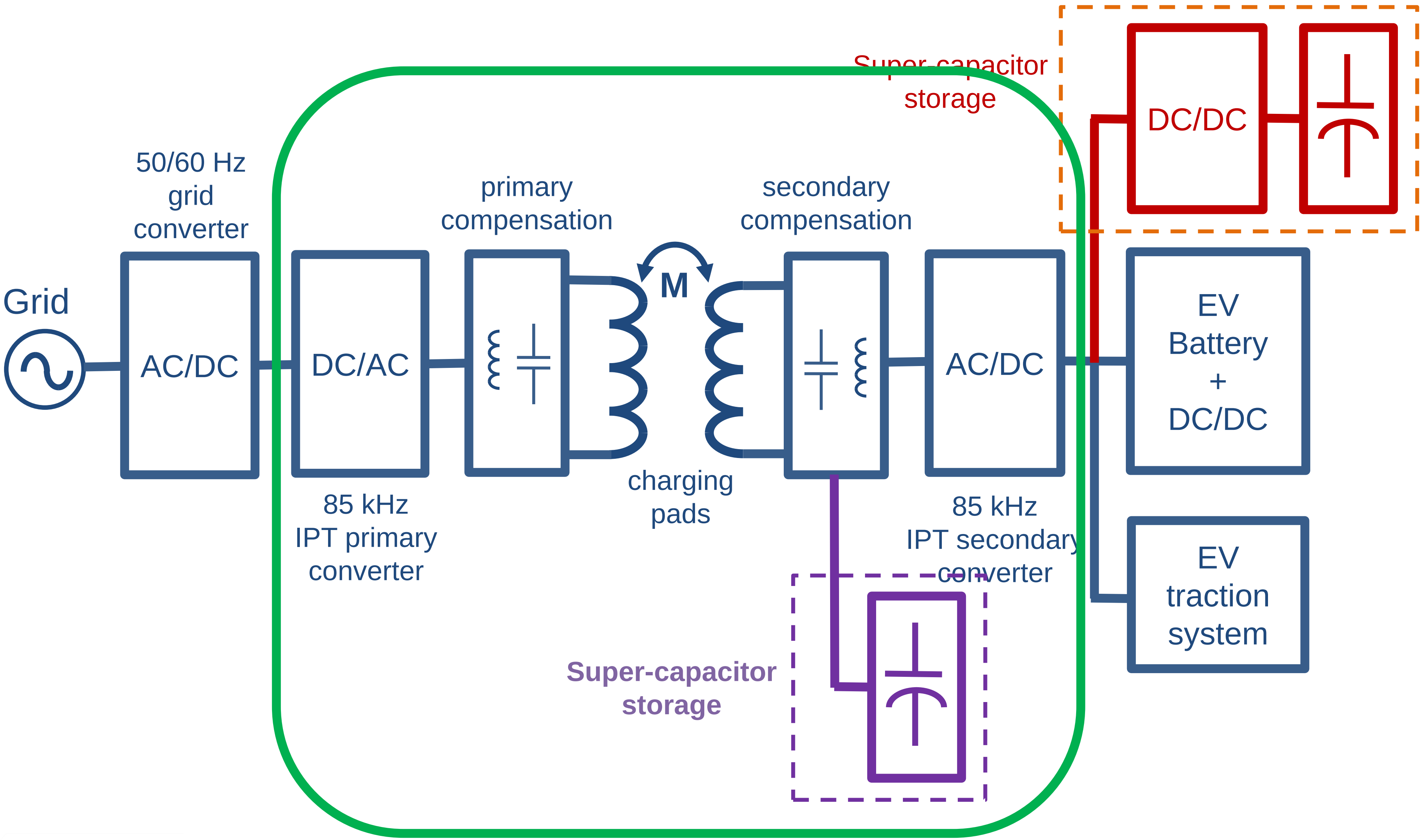
Charging moving EV(s) with pulsed power

Dynamic EV Charging

https://www.google.co.nz/search?q=wireless+ev+charging&source=lnms&tbm=isch&sa=X&ved=0ahUKEwiP9_nkvcvMAhXGUZQKHd9CArQQ_AUIBygB&biw=1366&bih=644

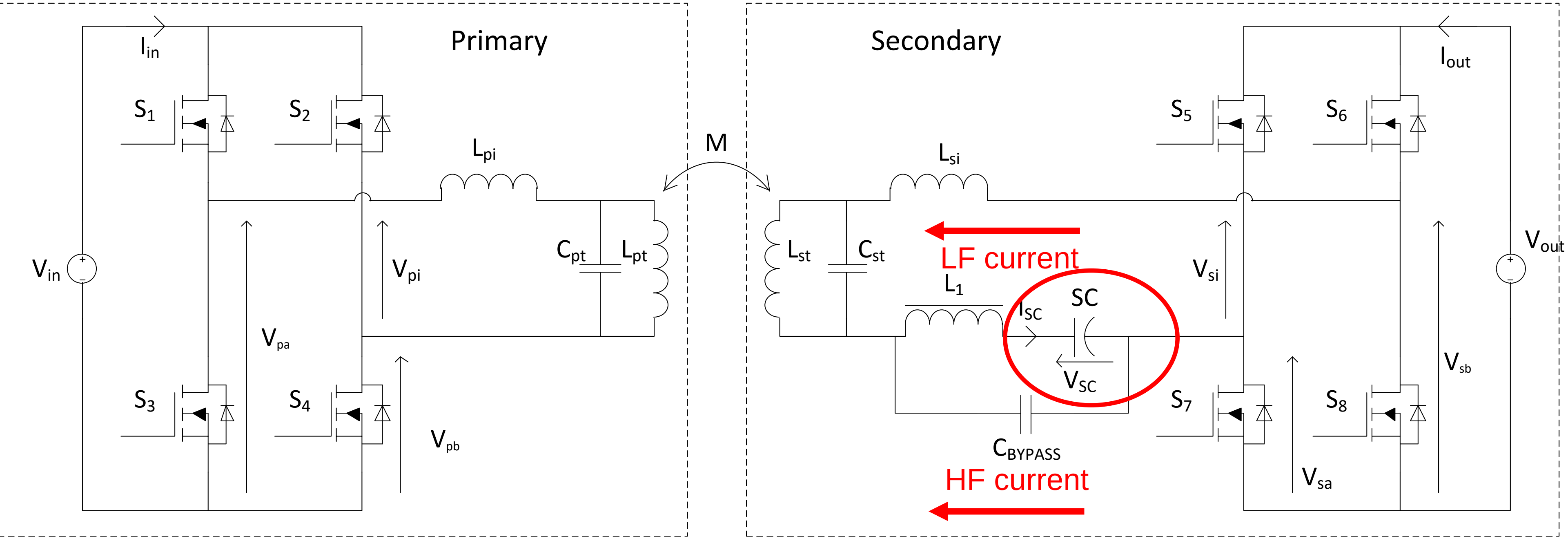
A Hybrid BD-WPT system

for dynamic charging



A Hybrid BD-WPT system

for dynamic charging

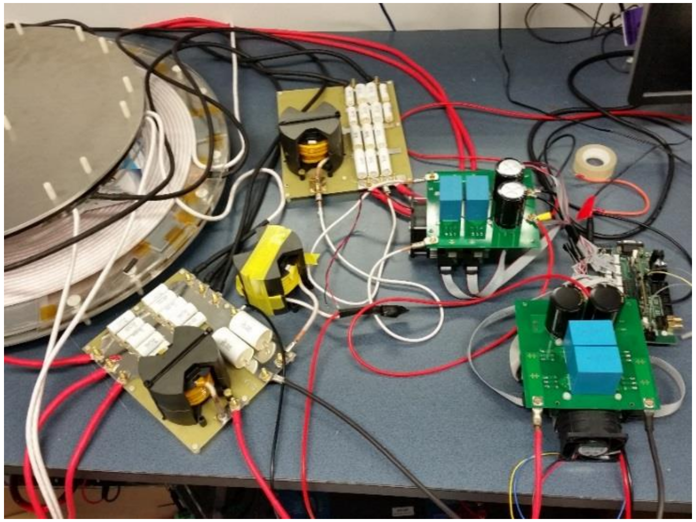


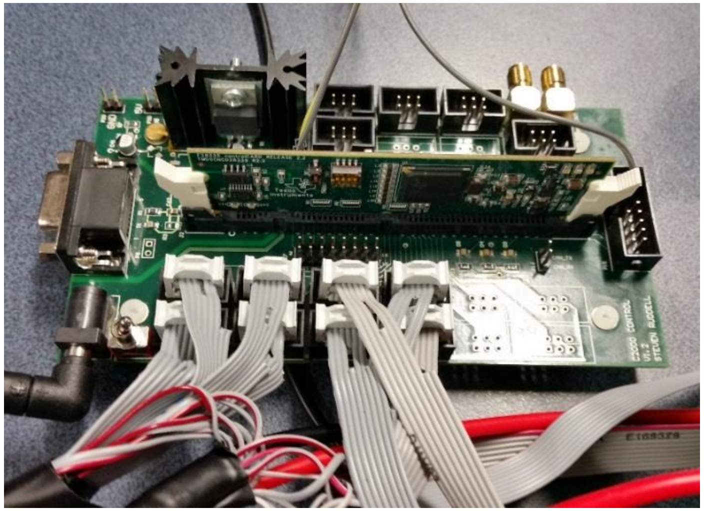
- An integrated (in primary or secondary) super-capacitor (SC) bank
- Eliminates the extra converter stage
- Allows for both storage and retrieval of energy in 9 modes of operations

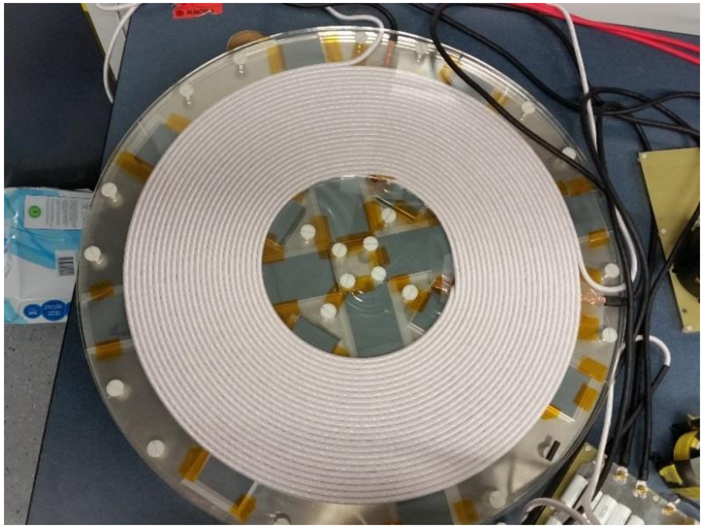
Source : S. Ruddell, D. J. Thrimawithana & U. K. Madawala.

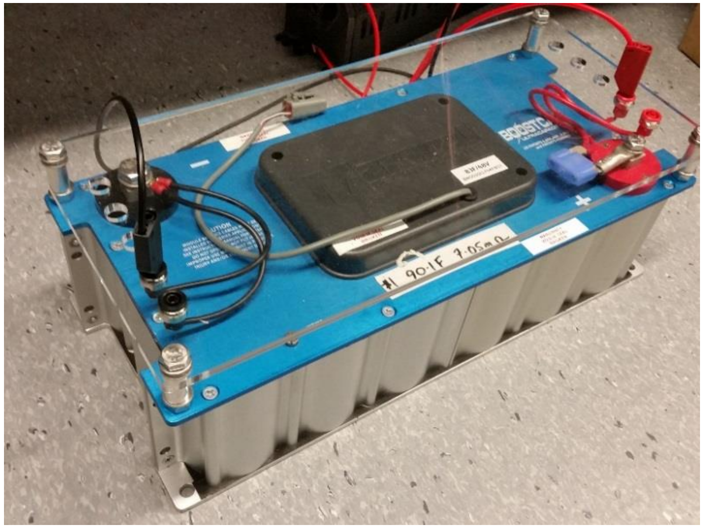
Experimental Results

- 3.7 kW nominal rating, LCL tuning, 90 F super capacitor



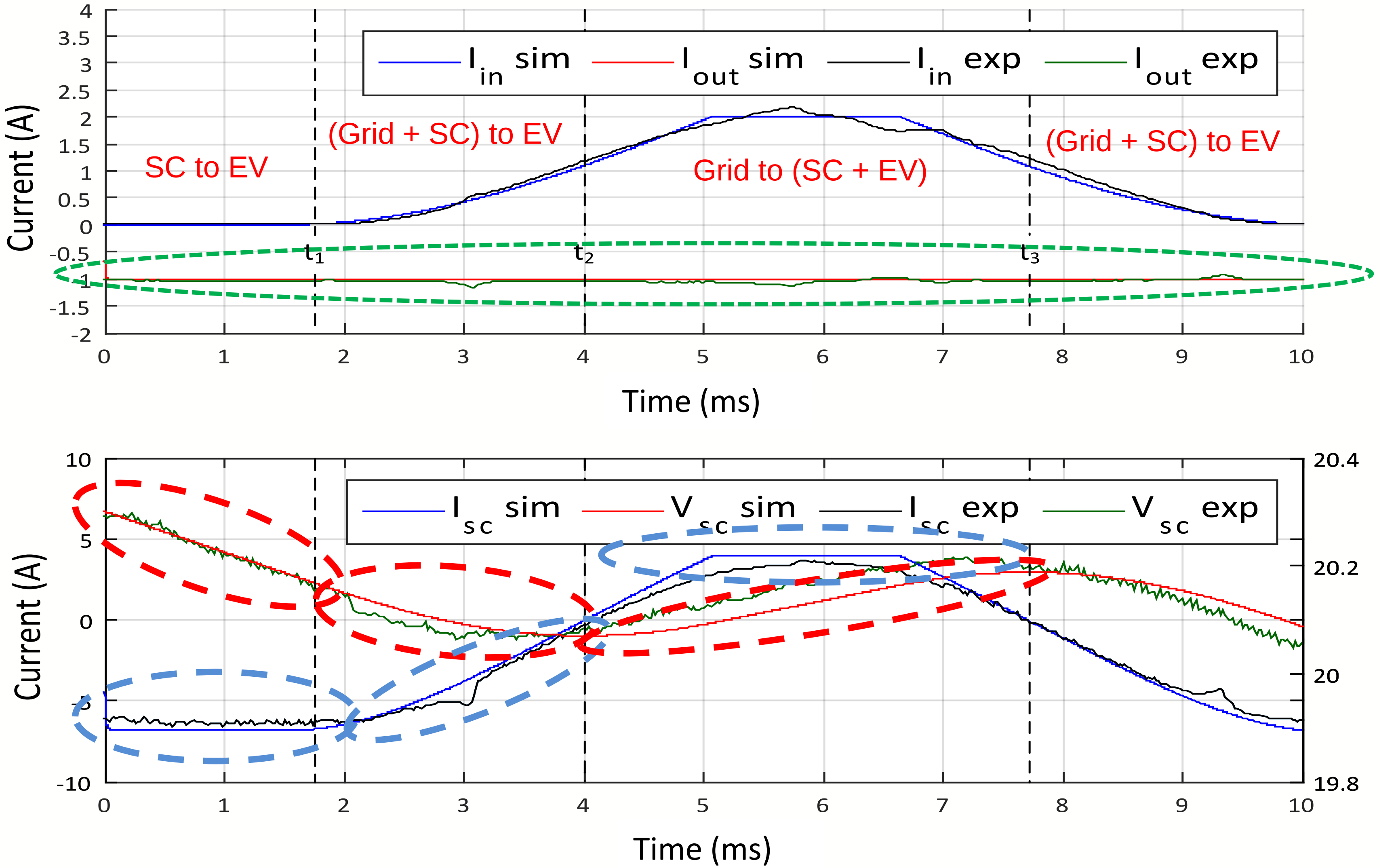






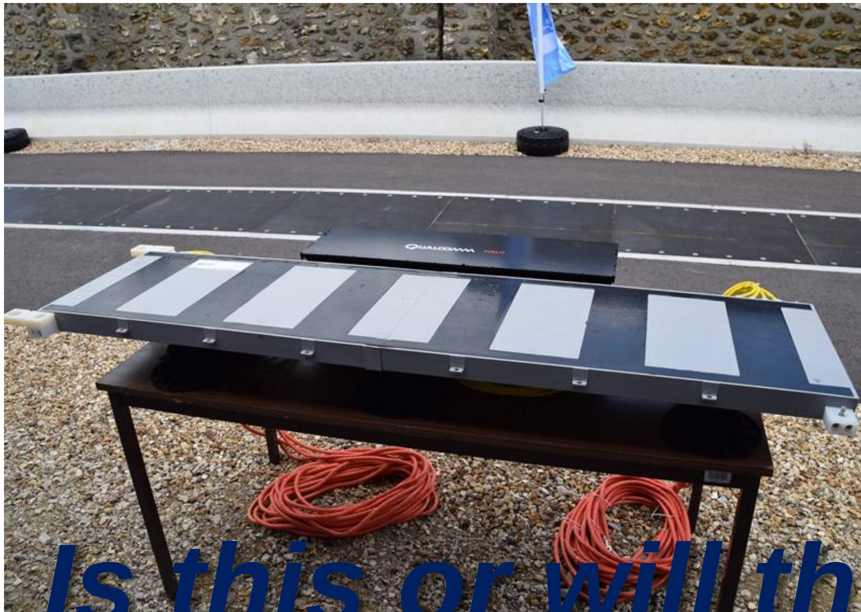
Source : S. Ruddell, D. J. Thrimawithana & U. K. Madawala.

Experimental Results



Source : S. Ruddell, D. J. Thrimawithana & U. K. Madawala.

Dynamic EV Charging



Is this or will this be a reality?

100 m long FABRIC dynamic test track near Versailles, France.

- *FABRIC is a €9 million project, mostly funded by the European Commission,*
- *Dedicated for technological feasibility & economic viability of wireless DEVC*
- ***Tested for providing 50 ms pulses of 20 kW at 85 kHz by QUALCOMM HALO!***

Kaist, Bombardier, ORNL, UoA and others are also actively involved in R & D

References

1. U. K. Madawala and D. J. Thrimawithana, "A Bidirectional Inductive Power Interface for Electric Vehicles in V2G Systems," in IEEE Transactions on Industrial Electronics, vol. 58, no. 10, pp. 4789-4796, Oct. 2011.
2. Y. Liu, U. K. Madawala, R. Mai and Z. He, "An Optimal Multi-Variable Control Strategy for Inductive Power Transfer Systems to Improve Efficiency," in IEEE Transactions on Power Electronics, doi: 10.1109/TPEL.2020.2970780.
3. Y. Liu, U. K. Madawala, R. Mai and Z. He, "Zero-Phase-Angle Controlled Bi-directional Wireless EV Charging Systems for Large Coil Misalignments," in IEEE Transactions on Power Electronics, doi: 10.1109/TPEL.2019.2941709
4. S. I. Ruddell, U. K. Madawala and D. J. Thrimawithana, "A Wireless EV Charging Topology with Integrated Energy Storage," in IEEE Transactions on Power Electronics, doi: 10.1109/TPEL.2020.2969027
5. S. Weerasinghe, U. K. Madawala and D. J. Thrimawithana, "A Matrix Converter-Based Bidirectional Contactless Grid Interface," in IEEE Transactions on Power Electronics, vol. 32, no. 3, pp. 1755-1766, March 2017.
6. S. Weerasinghe, D. J. Thrimawithana, and U. K. Madawala, "Modeling Bidirectional Contactless Grid Interfaces With a Soft DC-Link," IEEE Transactions on Power Electronics, vol. 30, no. 7, pp. 3528–3541, Jul. 2015.
7. S. Ruddell, U. K. Madawala and D. J. Thrimawithana, "Dynamic WPT system for EV charging with integrated energy storage," in IET Power Electronics, vol. 12, no. 10, pp. 2660-2668, 28 8 2019.
8. Y. Song, U. K. Madawala, D. J. Thrimawithana and M. Vilathgamuwa, "Three-phase bi-directional wireless EV charging system with high tolerance to pad misalignment," in IET Power Electronics, vol. 12, no. 10, pp. 2697-2705, 28 8 2019
9. L. Zhao, D. J. Thrimawithana and U. K. Madawala, "Hybrid Bidirectional Wireless EV Charging System Tolerant to Pad Misalignment," in IEEE Transactions on Industrial Electronics, vol. 64, no. 9, pp. 7079-7086, Sept. 2017.
10. B. X. Nguyen et al., "An Efficiency Optimization Scheme for Bidirectional Inductive Power Transfer Systems," in IEEE Transactions on Power Electronics, vol. 30, no. 11, pp. 6310-6319, Nov. 2015.
11. D. J. Thrimawithana and U. K. Madawala, "Generalised mathematical model for high-voltage pulse propagation along electric fence structures," in IET Science, Measurement & Technology, vol. 5, no. 3, pp. 109-116, May 2011
12. M. J. Neath, A. K. Swain, U. K. Madawala and D. J. Thrimawithana, "An Optimal PID Controller for a Bidirectional Inductive Power Transfer System Using Multiobjective Genetic Algorithm," in IEEE Transactions on Power Electronics, vol. 29, no. 3, pp. 1523-1531, March 2014.
13. F. Faradjizadeh, M. Vilathgamuwa, D. Jovanovic, P. Jayathurathnage, G. Ledwich and U. Madawala, "Expandable N-Legged Converter to Drive Closely Spaced Multi Transmitter Wireless Power Transfer Systems for Dynamic Charging," in IEEE Transactions on Power Electronics., doi: 10.1109/TPEL.2019.2939848
14. L. Zhao, D. J. Thrimawithana, U. K. Madawala, A. P. Hu and C. C. Mi, "A Misalignment-Tolerant Series-Hybrid Wireless EV Charging System With Integrated Magnetics," in IEEE Transactions on Power Electronics, vol. 34, no. 2, pp. 1276-1285, Feb. 2019.
15. Y. Tang, Y. Chen, U. K. Madawala, D. J. Thrimawithana and H. Ma, "A New Controller for Bidirectional Wireless Power Transfer Systems," in IEEE Transactions on Power Electronics, vol. 33, no. 10, pp. 9076-9087, Oct. 2018.

Thank You!