EV Chargers

Current Status and Future Directions

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

The University of Auckland

- Highest ranked New Zealand university and 85th in the QS World University Ranking
- Over 5,000 staff members and 40,000 students
- Nine faculties including Medical & Health Sciences, Engineering, Business & Economics and Science

Dept. of Electrical, Computer & Software Eng.

- One of the 5 deparments in the Faculty of Engineering
- Offers 3 undergraduate degree programs
  - Electrical & Electronics, Computer Systems and Software
  - Project based teaching
- 35+ full-time academic staff members and 15+ post-doctoral research fellows
- 150+ postgraduate students and 600+ undergraduate students
- Regular visiting research scholars and research students
- Research groups include Power Electronics, Power Systems, Signal Processing, Robotics, Embedded Systems, Parallel Computing, Telecommunications and Control Systems

Dept. of Electrical, Computer & Software Eng.

Power Electronics Research Group

Dist. Prof. Emeritus John Boys

Prof. Grant Covic

Prof. Udaya Madawala

Prof. Patrick Hu

Dr. Duleepa Thrimawithana

35+ Postgraduates

10+ Research Fellows

$100M+ Research Funding

3 Spin-Out Companies

Collaborations with Top US, UK, EU & Asia-Pacific Universities

Collaborations with Industry Partners Worldwide

Multidisciplinary Research

Cutting-Edge Laboratory Facilities

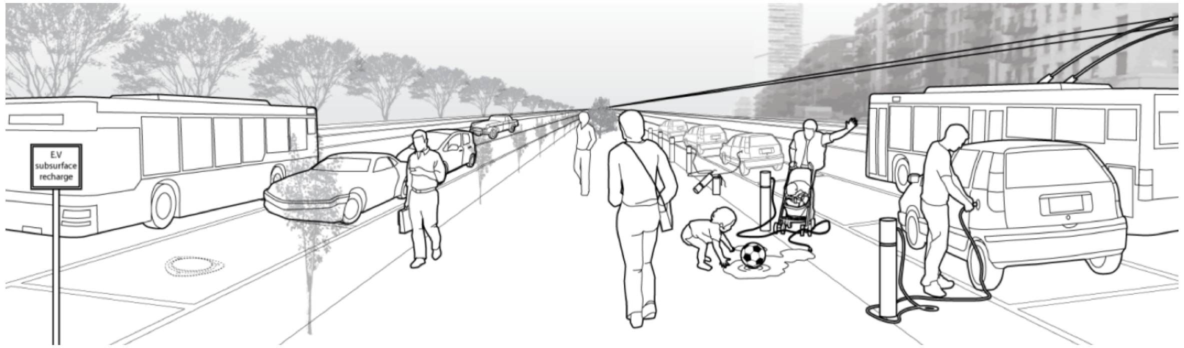
100+ Patent Families & 7 Licensees

Engineering Education

Introduction

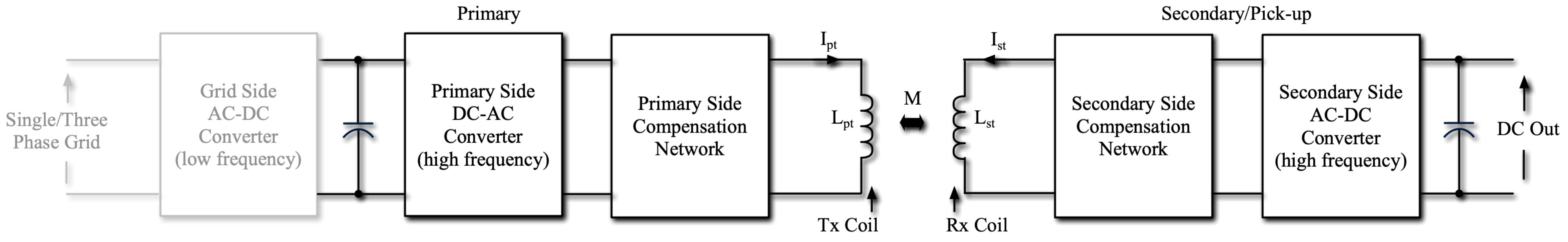
Plug-in vs Wireless Charging

Plug-in vs Wireless Charging



- Wireless chargers are convinient and provide a ubiquitous connection between EVs and the grid
  - Ideal for autonomous vehicles and V2G services
- Plug-in chargers are cheaper, have higher power density and employ mature technology
  - Provide an economical and reliable solution
- Wireless chargers are safer under harsh weather and usage
  - Can operate safely under rainy/snowy/dusty/etc conditions
- Wired chargers do not generate strong fields
  - Wireless chargers require FOD and LOP circuitry to ensure safety during operation

Components of a Wireless Charger

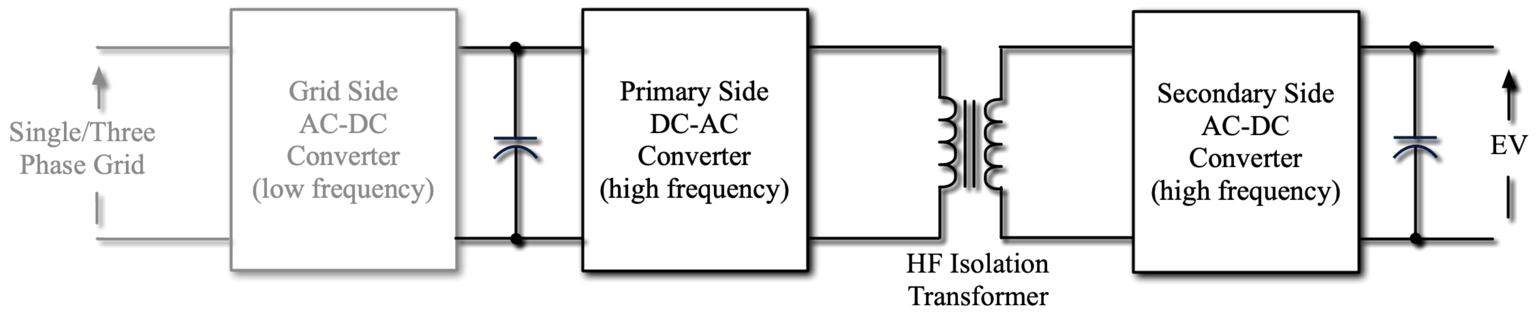


- Primary consists of a DC-AC switched-mode converter, a compensation network and a transmitter coil(s)
  - A lumped transmitter coil is often referred to as a primary pad/coil/coupler
  - An elongated coil is often called a primary track
  - Can be directly fed by a DC-bus or through a grid-connected AC-DC converter
- Secondary/pick-up consists of a receiver coil(s), a compensation network and an AC-DC converter
  - The reciever coil is is often referred to as a secondary/pick-up pad/coil/coupler
- Primary and pick-up coils are magnetically coupled but the coupling coefficient is typically less than 40%
- The compensation networks help improve efficiency by minimizing the VA requirements of converters

Current Status of Wireless Chargers

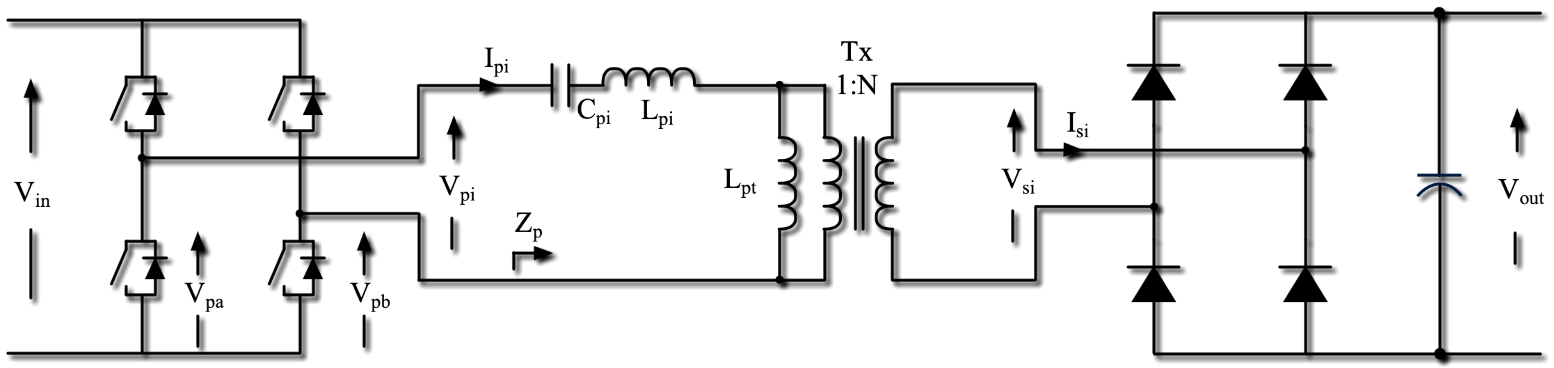
- Uni or bi-directional power flow
  - Primary may use a full-bridge, half-bridge, push-pull, multi-level or matrix based converter topology
  - Pick-up may use a boost, buck, full-bridge, half-bridge or push-pull topology
  - Control techniques that facilitate ZVS/ZCS over a wide range of conditions
  - Compensation for both sides is provided through series, parallel or a combination of series-parallel tuned networks
- Power ratings up to tens of kWs
  - Magnetic designs include circular coil, solenoidal coil, polarised coil, multi coil structures as well as track based systems
  - Ferrites and/or reflection coils are often used to shape the magnetic fields generated
  - Transmission range of over 400 mm with over ± 200 mm XY tolerance
  - Efficiency typically over 85% but can be as high as 97%
  - Operating frequency typically ranges from tens of kHz to tens of MHz

Components of a Plug-in Charger



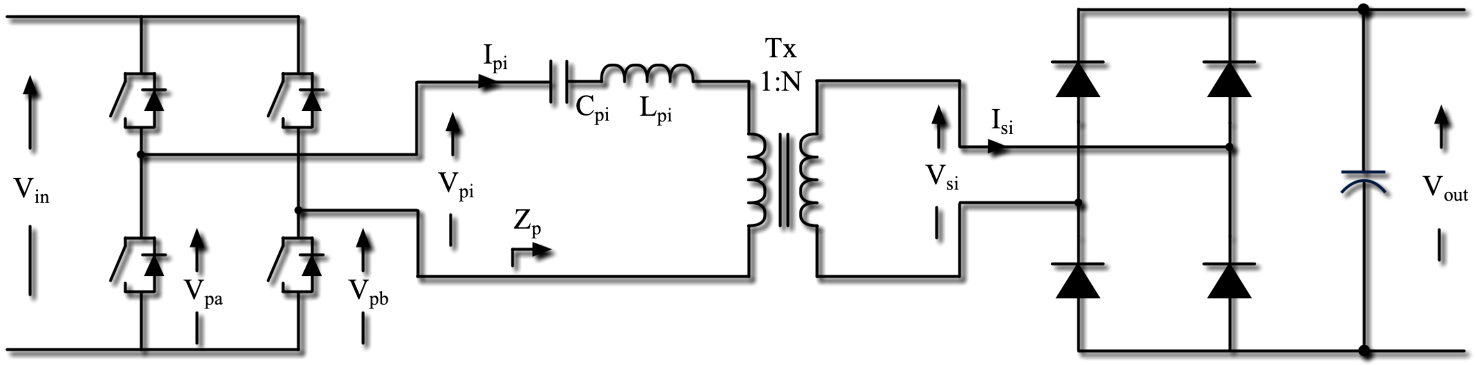
- A PFC stage, a grid-tie inverter or a DC-bus utilised to interface with the grid
- Safety isolation through high-frequency transformer preferred, specially in fast and extreme fast chargers
  - Hard-switched, soft-siwtched or resonant converter topologies are employed to implement the DC-DC converter
  - LLC and series resonant converters are common in uni-directional systems
  - DABs are common in bi-directional systems
- Integrated on-board charger designs, which reuse components of the traction system has been proposed

LLC Resonant Converter



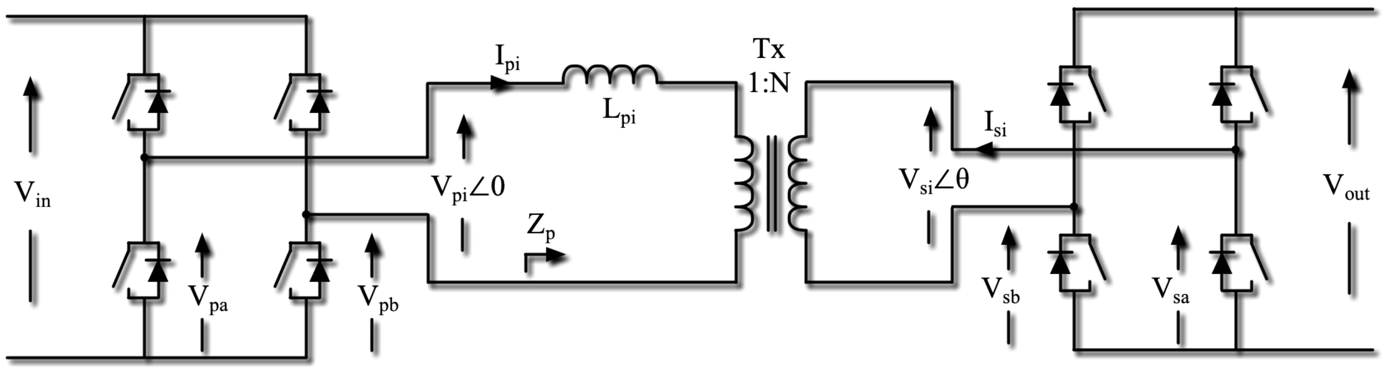
- One of the most popular topologies used in isolated DC-DC converters
  - Higher efficiency and power density
- The full-bridge converter generates a square-wave V_{pi} at a frequency close to the resonance between L_{pi} and C_{pi}
  - Output typically regulated through controlling the switching frequency
  - Designed to operate in the inductive region to ensure soft-switching

Series Resonant Converter



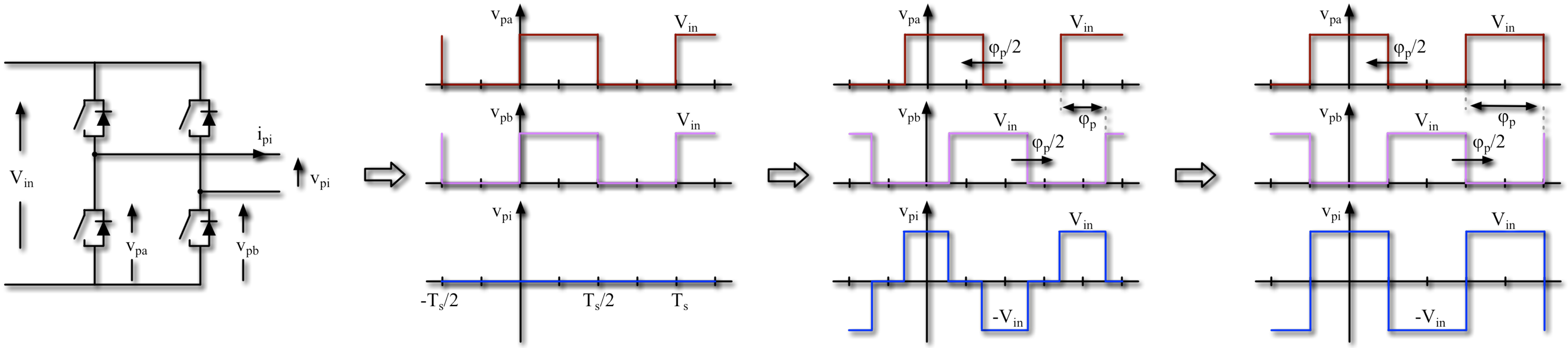
- A popular and simple topology used in isolated DC-DC converters
  - Good efficiency
- The full-bridge converter generates a V_{pi} at a frequency close to the resonance between L_{pi} and C_{pi}
  - Output typically regulated through controlling the switching frequency and/or phase-shift modulation
  - Designed to soft-switch under a range of loading conditions

Dual Active Bridge



- A popular topology used in isolated bi-directional DC-DC converters
  - L_{pi} can be the leakage indutance of the isolation transformer
- The full-bridge converters generate V_{pi} and V_{si} typically at a fixed frequency f_s
  - Designed to soft-switch under a range of loading conditions
  - VA requirements of the full-bridges must be minimised
- Typically the amplitudes of V_{pi} and V_{si} as well as the phase-angle, θ, between them are controlled to regulate the power flow

Control of DAB



- Each leg of a full-bridge operated at 50% duty-cycle, generating for example the square-waves v_{pa} and v_{pb}
  - The phase-shift modulation, ϕ_p, applied between v_{pa} and v_{pb}, regulates the magnitude of the fundamental component of v_{pi}, since $v_{pi} = v_{pa} - v_{pb}$
- Phase-shift modulation applied to each converter as well as phase-angle of V_{si} with respect to V_{pi} is used to regulate the power flow magnitude and direction while minimising losses

Modelling a DAB

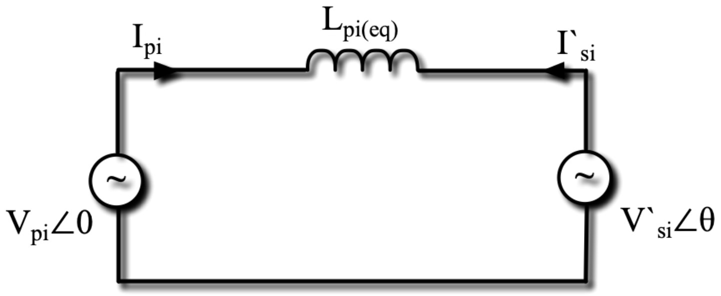
- Noting that $\omega_s = 2\pi f_s$, v_{pi} and v_{si} can be given by

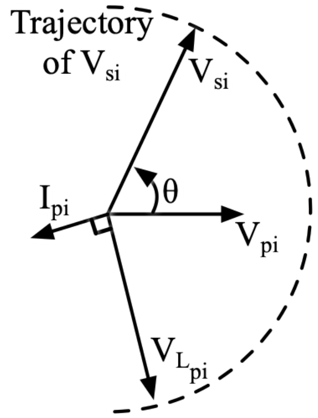
$$v_{pi} = V_{in}\frac{4}{\pi}\sum_{m=1,3,..}^{\infty}\frac{\sin\left(m\phi_p/2\right)}{m}\sin\left(m\omega_s t\right)$$

$$v_{si} = V_{out}\frac{4}{\pi}\sum_{m=1,3,..}^{\infty}\frac{\sin\left(m\phi_s/2\right)}{m}\sin\left(m\omega_s t + m\theta\right)$$

- Power transferred to the load is therefore

$$P_o = \frac{-8V_{in}V_{out}}{N\pi^2\omega_s L_{pi(eq)}}\sin\left(\theta\right)\sin\left(\phi_p/2\right)\sin\left(\phi_s/2\right)$$

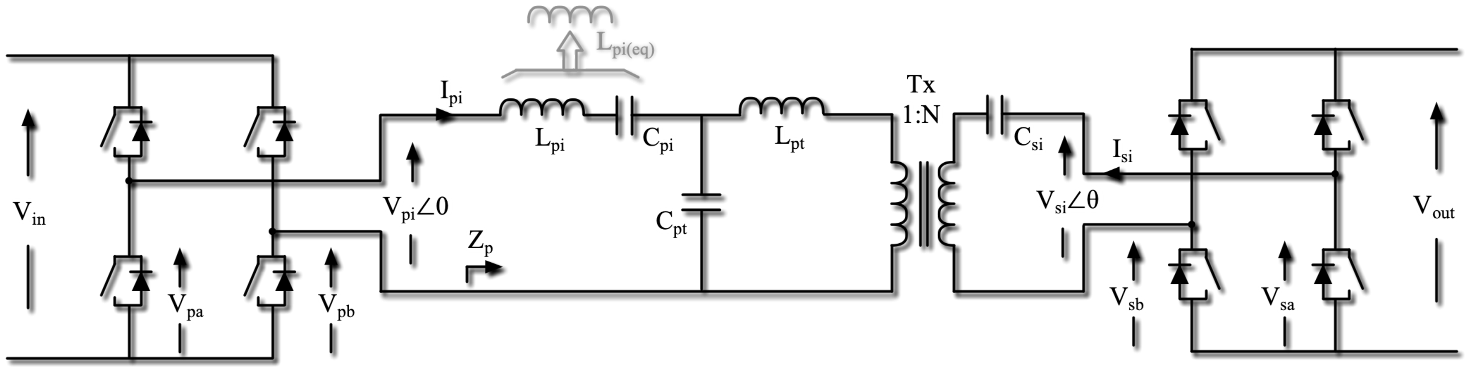




Research Advances

Highlights & Updates

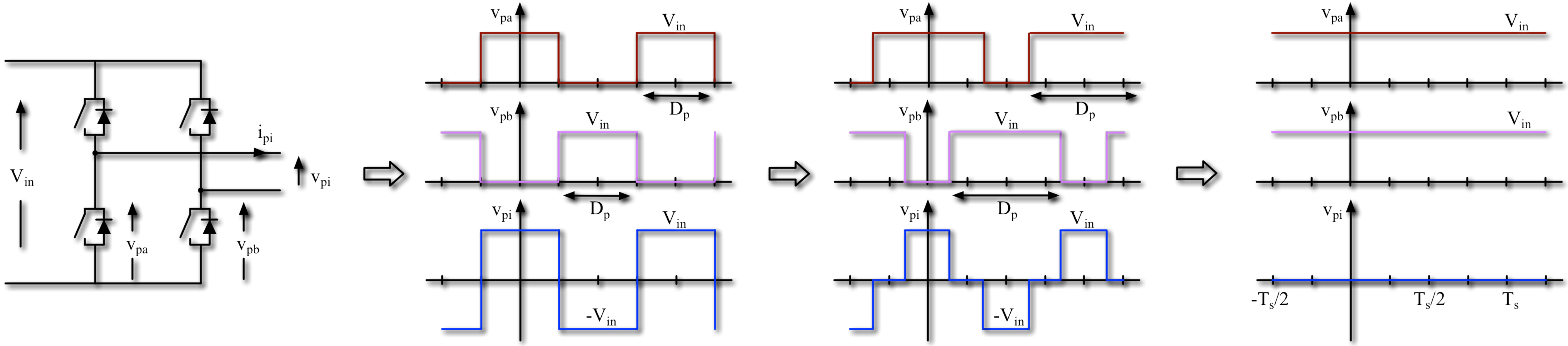
LCL Resonant Dual Active Bridge



- An LCL T-resonant network is used to minimise the VA requirements of the converters
  - L_{pt} can compose of the leakage indutance of the isolation transformer
  - Series blocking capacitors, C_{pi} and C_{si}, can be part of the resonant network
- The full-bridge converters generate V_{pi} and V_{si} typically at a fixed frequency f_s close to the resonant frequency of the LCL network
  - Designed to soft-switch under a range of loading conditions
- Typically the amplitudes of V_{pi} and V_{si} as well as the phase-angle, θ, between them are controlled to regulate the power flow

Control of LCL-RDAB

- Phase-shift modulation applied to each converter as well as phase-angle of V_{si} with respect to V_{pi} is used to regulate the power flow magnitude and direction while minimising losses
- Alternatively, the duty-cycle modulation applied, can be used to regulate the magnitude V_{pi} and V_{si}
  - For example, since $v_{pi} = v_{pa} - v_{pb}$, when v_{pa} and v_{pb} are 180^0 out of phase D_p controls magnitude of V_{pi}
  - When $D_p = 50\%$, V_{pi} is a maximum



Modelling a LCL-RDAB

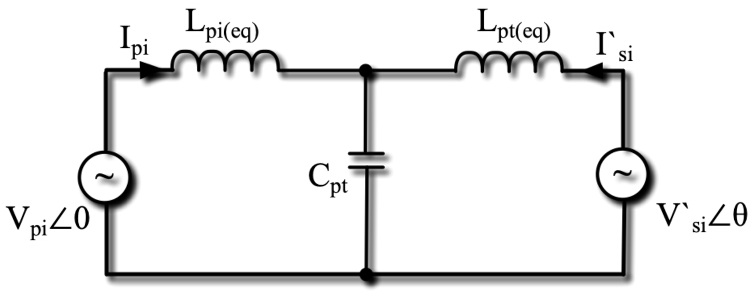
- The LCL T-Network is tuned such that $\omega_s L_{pt(eq)} = 1/\omega_s C_{pt} = \omega_s L_{pi(eq)}$, where $\omega_s = 2\pi f_s$
- Noting that $\phi_{p/s} \equiv 2\pi(1 - D_{p/s})$ or $2\pi D_{p/s}$, bridge currents are

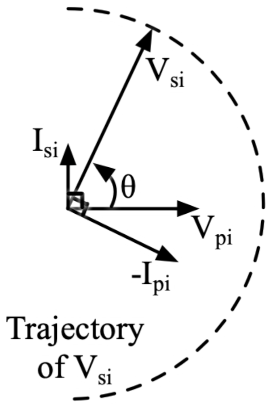
$$i_{pi} = \frac{4V_{out}}{N\pi\omega_s L_{pt(eq)}} \sin(\phi_s/2)\cos(\omega_s t + \theta)$$

$$i_{si} = \frac{4V_{in}}{N\pi\omega_s L_{pi(eq)}} \sin(\phi_p/2)\cos(\omega_s t)$$

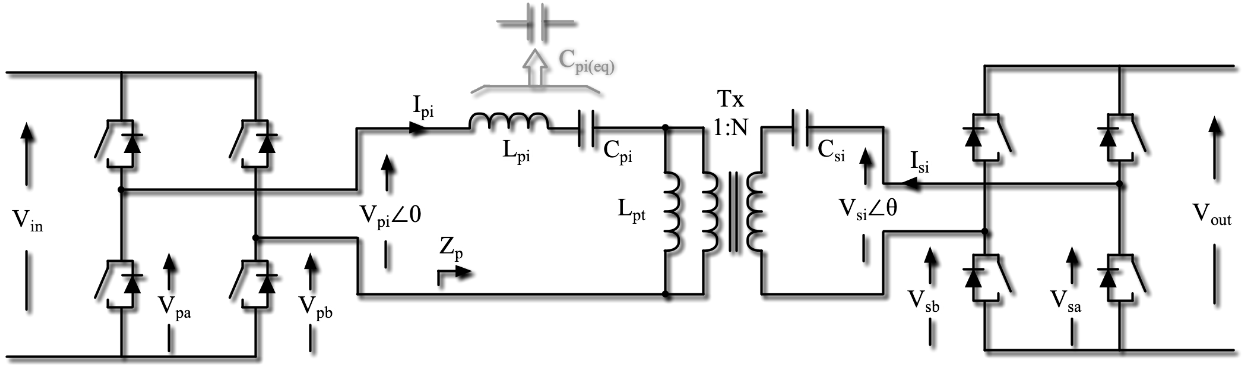
- Power transferred to the load is therefore

$$P_o = \frac{-8V_{in}V_{out}}{N\pi^2\omega_s L_{pi(eq)}} \sin(\theta)\sin(\phi_p/2)\sin(\phi_s/2)$$





CLC Resonant Dual Active Bridge



- A CLC T-resonant network is used to minimise the VA requirements of the converters
  - The magnitizing inductance, L_{pt}, is a part of the resonant network
  - L_{pi} can compose of the leakage indutance of the isolation transformer
- The full-bridge converters generate V_{pi} and V_{si} typically at a fixed frequency f_s close to the resonant frequency of the CLC network
  - Designed to soft-switch under a range of loading conditions
- Typically the amplitudes of V_{pi} and V_{si} as well as the phase-angle, θ, between them are controlled to regulate the power flow

Modelling a CLC-RDAB

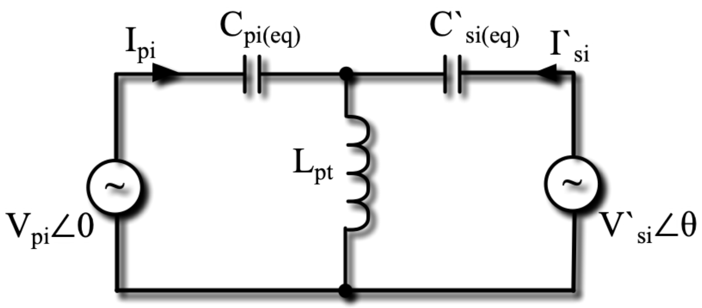
- The LCL T-Network is tuned such that $\omega_s L_{pt} = 1/\omega_s C_{pi(eq)} = 1/\omega_s C_{si(eq)}$, where $\omega_s = 2\pi f_s$
- Noting that $\phi_{p/s} \equiv 2\pi(1 - D_{p/s})$ or $2\pi D_{p/s}$, bridge currents are

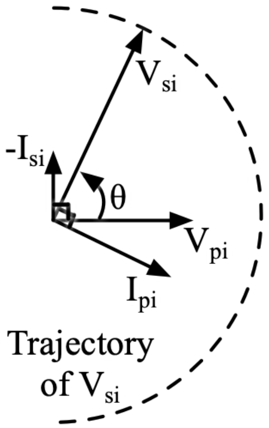
$$i_{pi} = \frac{-4V_{out}}{N\pi\omega_s L_{pt}} \sin(\phi_s/2)\cos(\omega_s t + \theta)$$

$$i_{si} = \frac{-4V_{in}}{N\pi\omega_s L_{pt}} \sin(\phi_p/2)\cos(\omega_s t)$$

- Power transferred to the load is therefore

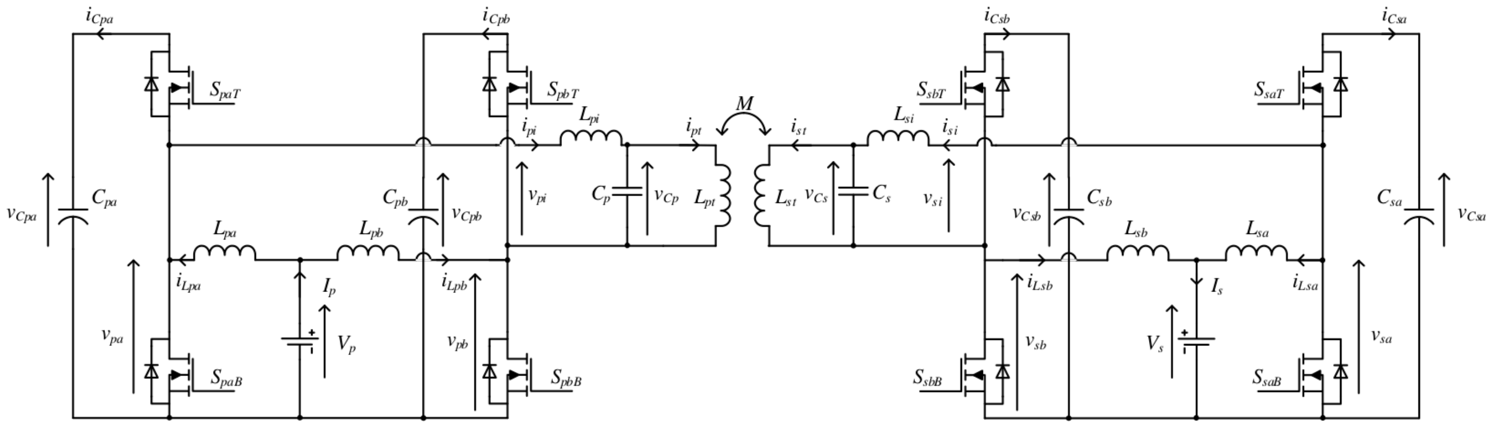
$$P_o = \frac{8V_{in}V_{out}}{N\pi^2\omega_s L_{pi(eq)}} \sin(\theta)\sin(\phi_p/2)\sin(\phi_s/2)$$

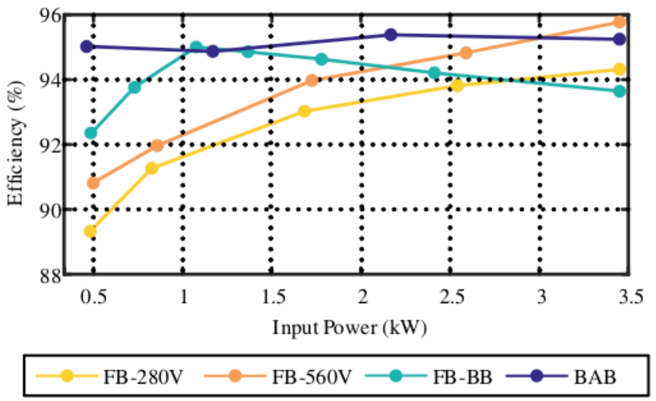


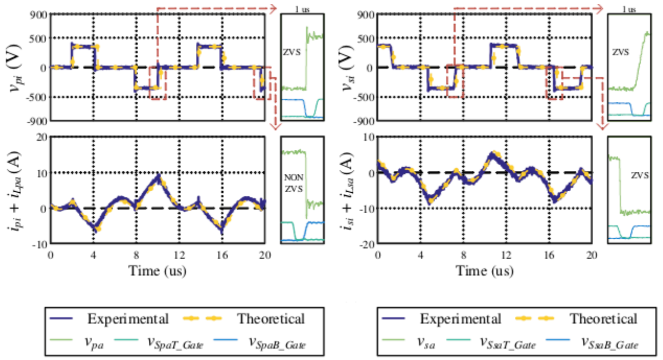


Boost Active Bridge (BAB)

- Integrated post/pre regulation capabilities enable maximum efficiency tracking
- Wide ZVS range and reduced current stresses
- Ensures zero DC-bias at AC output
- As an example consider the 7.7 kW IPT system below

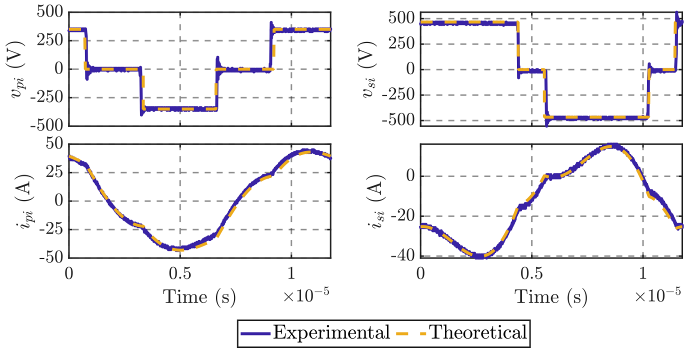


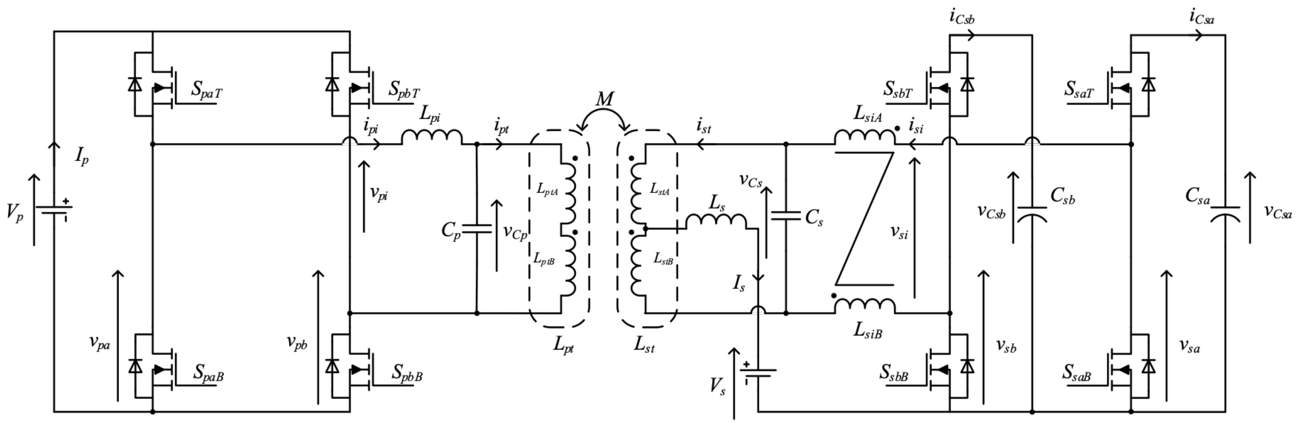


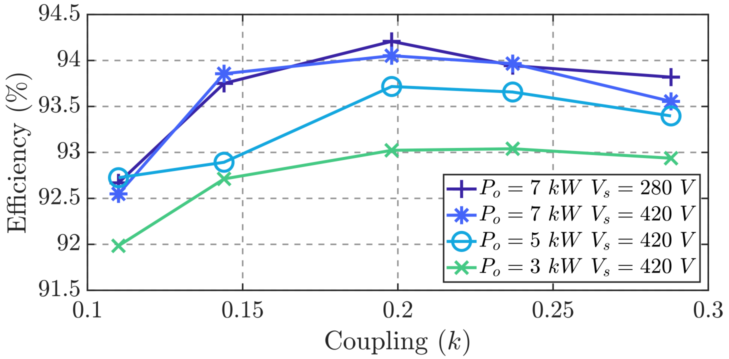


An Integrated BAB

- Boost inductors may be integrated in to the transformer
  - Flux generated by DC currents oppose each other
- Both converters may be controlled to maintain a nearly constant efficiency
  - As an example consider the 7.7 kW IPT system below

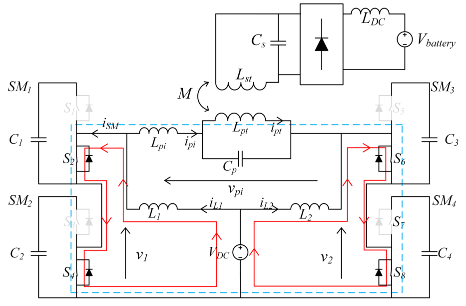




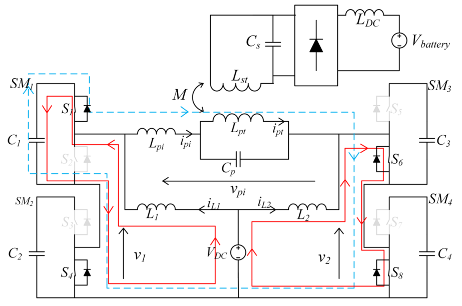


Integrated Boost MC (IB-MC)

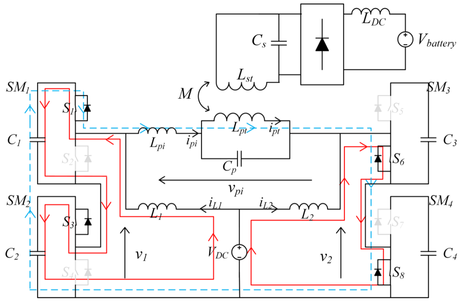
- Derives a higher voltage to improve power handling
  - Reduces current stress and may suit lower DC-links
- Inherantly eliminates circulating currents
- Can generate a low THD staircase modulated output voltage
  - Wide range of voltages
- Can use lower voltage higher performance devices



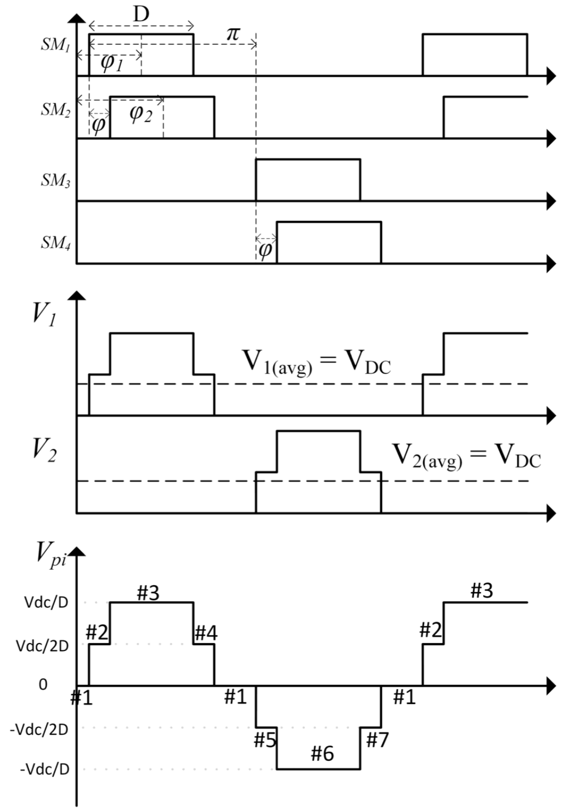
Circuit State 1 of 16



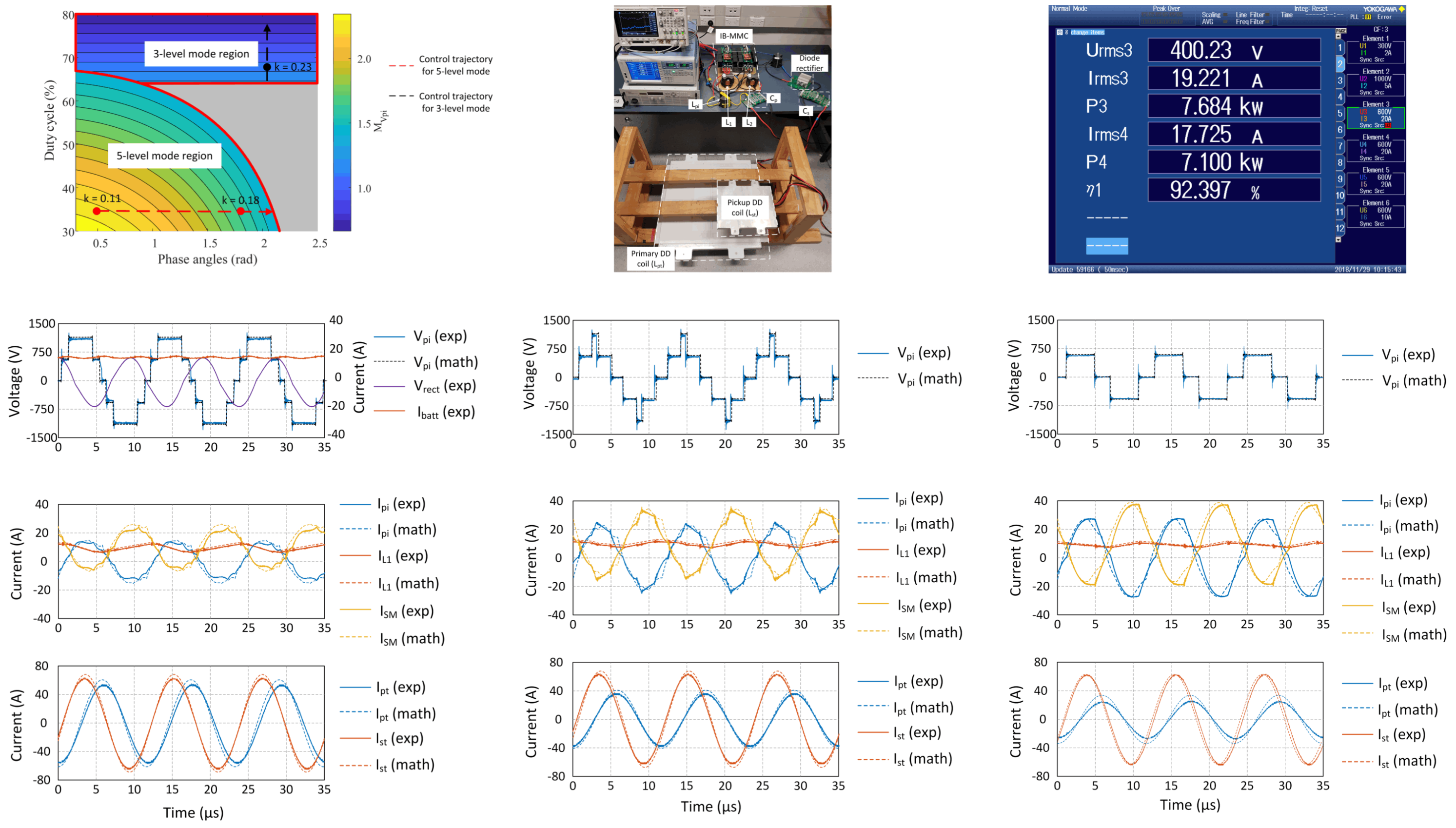
Circuit State 2 of 16



Circuit State 3 of 16



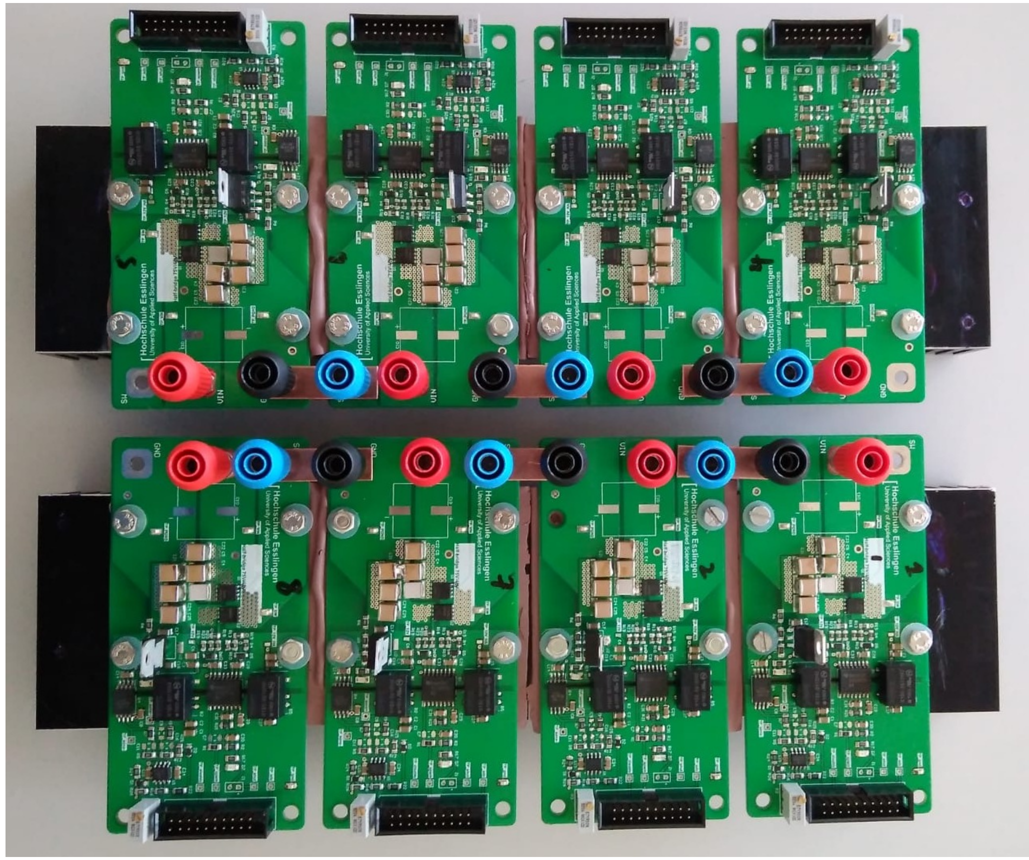
IB-MC Example: 7.7kW IPT



k = 0.11 k = 0.18 k = 0.23

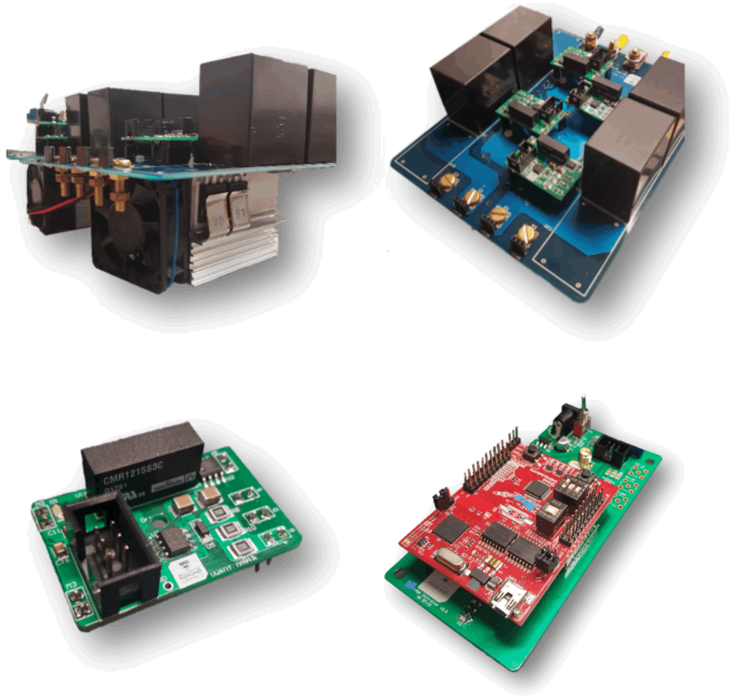
- Maintains a constant 7.7 kW power transfer through primary control
- Operate in 5-level mode at low k and 3-level mode at high k
- Efficiency ranges between 91.5% and 92.4% across entire operating region
- A simple algorithm used to ensure module voltages are balanced

IB-MC Example: 3kW Wireless Slipring



Ongoing Research Work

- Bi-directional IPT systems
  - Synchronisation & optimal control
  - Novel circuit topologies
- Misalignment tolerant high-power IPT systems
  - Compensation topologies & control techniques
- Dynamic charging
  - Circuit topologies & control techniques
  - Power distribution, thermal and packaging
- High-power plug-in chargers
  - Novel circuit topologies and control techniques
- Grid integration of EV chargers
  - Circuit topologies for grid services
  - EMC



Questions?

Thank you