Wireless Electric Vehicle Charging

IPT technology, Current status & Recent Developments

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The University of Auckland

- Highest ranked New Zealand university and 68th 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 departments 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 700+ 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

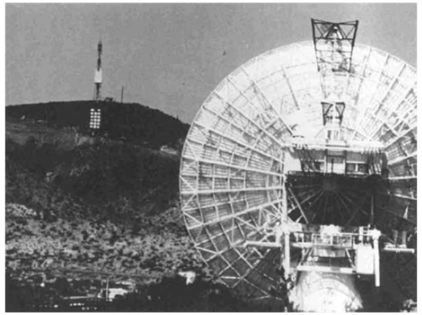
100+ Patent Families & 7 Licensees

Part I - Wireless Power Transfer

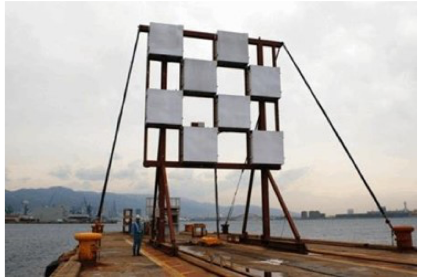
A Review of Current Status

Wireless Power Transfer

- Can be divided in to two broad categories
- Radiative transmission through far-field principles
  - Examples include power transfer through radio-frequency, microwave, optical and ultrasonic technologies
  - At an experimental stage of development
  - AirFuel Alliance is developing standards
- Non-radiative transmission through near-field principles
  - Inductive power transfer (IPT) and capacitive power transfer (CPT) technologies are utilised
  - IPT is the most mature technology
  - WPC, SAE, etc. standards are being developed



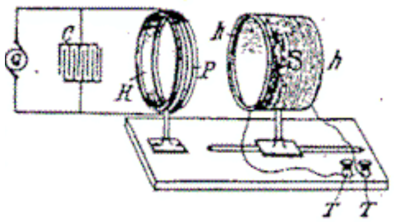
NASA JPL Goldstone Project (1975)
30 kW @ 80% efficiency over 1.5 km [1]

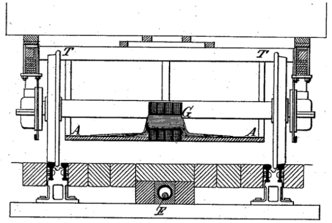


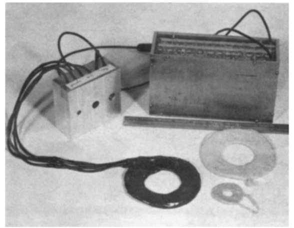
Mitsubishi Heavy Industries SSPS Test
(2015) 10 kW over 0.5 km [2]

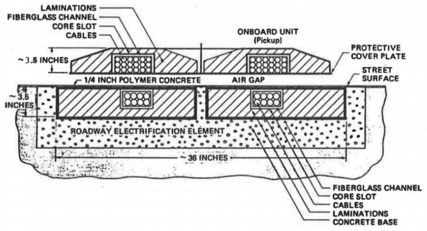
Early Developments

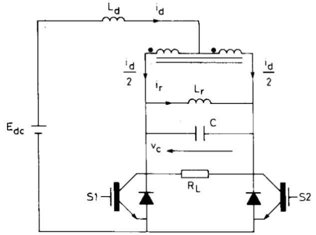
- 1890s to 1920s: Tesla (US), Hutin (FR) and LeBlanc (FR) demonstrated wireless power transfer
- 1960s: Shuder (US) and his team worked on high power IPT systems for biomedical applications
- 1970s: Otto (NZ) and Bolger (US) proposed roadway power
- 1980s: Santa Barbara electric bus project (US)
- Early 1990s: Boys (NZ), Green (NZ) and Covic (NZ) developed IPT systems for dynamic industrial systems & stationary people movers which were adopted and commercialized by Difuku and Wamplfer in materials handling applications
- Late 1990s: Meins (DE) developed multiphase IPT systems for industrial applications











Examples of work done by Tesla [3], Hutin & LeBlanc [4], Schuder [5], Santa Barbara project team [6] and Boys & Green [6] (left to right)

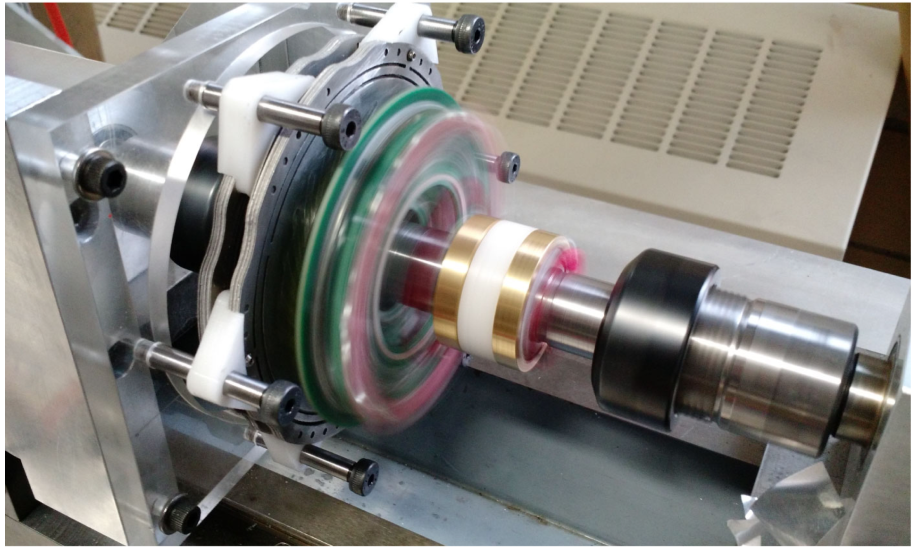
Recent Developments

- Early 2000s: Boys (NZ) and Covic (NZ) developed IPT systems with Conductix-Wamplfer and Daifuku for automated guided vehicles and busses
- Mid 2000s: Hui (HK), Hu (NZ) and Soljacic (US) developed low power IPT systems for powering/charging biomedical implants, sensors and consumer devices
- Late 2000s: Hu's (NZ) work lead to forming Power by Proxi, Soljacic's (US) work lead to forming WiTricity
- Early 2010s: Boys's (NZ) and Covic's (NZ) work lead to forming HaloIPT, which lead to Qualcomm Halo and Qi standard was released
- Late 2010s: WiTricity holds the largest patent portfolio as they acquired Qualcomm Halo, while Apple acquires Power by Proxi, and number of new research groups as well as companies starts to emerge
- Early 2020s: Standards for EV stationary charging completed

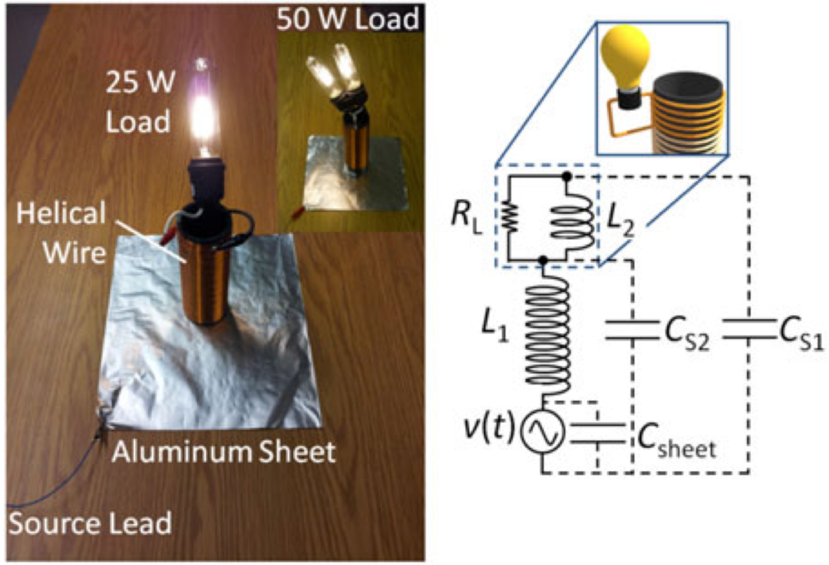
WI-Charge Technology

Energous WattUp Technology

CPT Technologies



Capacitive slip ring
(University of Wisconsin-Madison)



One wire capacitive power
(University of Alberta)

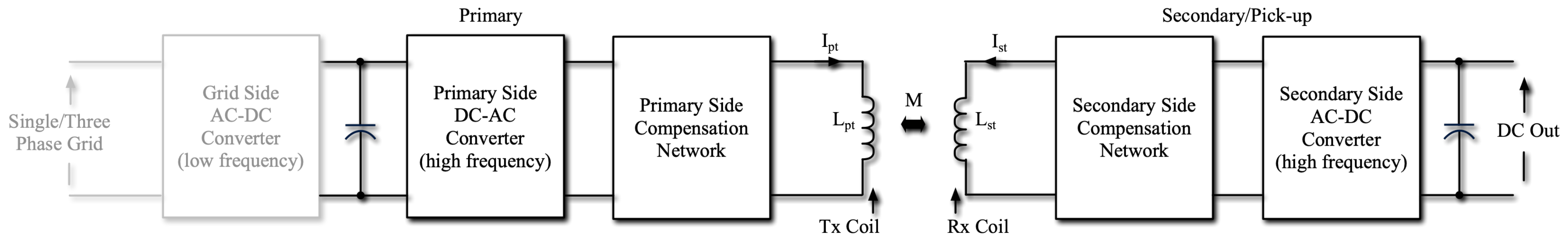
IPT Technologies

- Power ratings of tens of kWs with uni or bi-directional power flow
  - 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 300 mm with over ± 200 mm XY tolerance easily achievable
  - Efficiency typically over 85% but can be as high as 97%
  - Operating frequency typically ranges from tens of kHz to tens of MHz

Part II - IPT Fundamentals

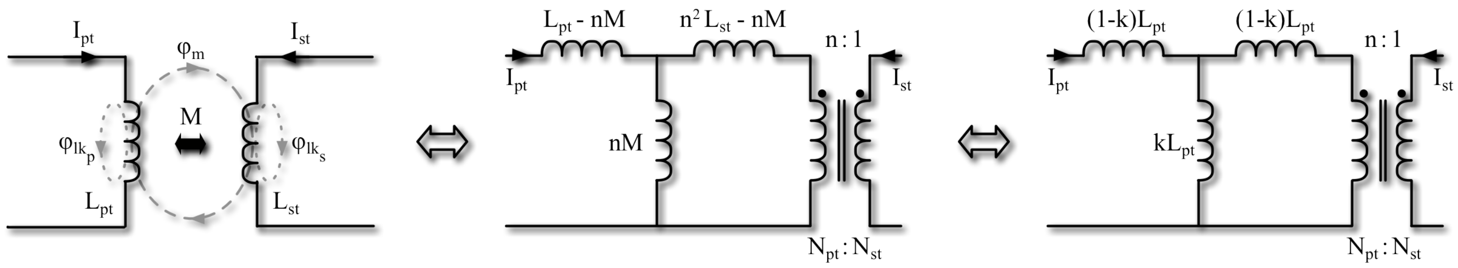
Modelling the Coils and Power Transfer

Components of an IPT System



- 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 source 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

Modelling the Primary and Pick-up Coils

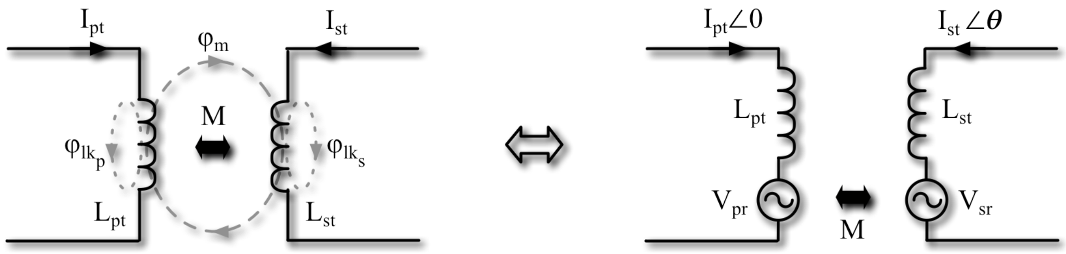


- The behaviour of the coils can be modelled using a T-equivelent transformer model
  - L_{pt} and L_{st} are the self-inductances of primary and pick-up coils, respectively
  - ϕ_m represents flux linkage while ϕ_{lk_p} and ϕ_{lk_s} represent leakage flux
  - The coupling coefficient, k, between the coils is less than 0.4 in a typical IPT system
- The mutual inductance, M, between the two coils is given by

$$M = k\sqrt{L_{pt}L_{st}}$$

- If the mean-turn lengths of the coils do not change, then $n = \frac{N_{pt}}{N_{st}} = \sqrt{\frac{L_{pt}}{L_{st}}}$, where n is the turns ratio

Coupled Inductor Model



- Although a T equivalent transformer model can be used to model the coils, the coupled inductor model is widely used when analysing an IPT system in the phasor-domain
- In the coupled inductor model, L_{pt} and L_{st} represent the self-inductances of primary and pick-up coils
- V_{sr} represents voltage induced across L_{st} due to current $I_{pt}\angle 0$ flowing through L_{pt} and is given by

$$V_{sr} = \omega M I_{pt} e^{j\pi/2}$$

- Similarly, V_{pr} represents voltage induced across L_{pt} due to $I_{st}\angle\theta$ and is given by

$$V_{pr} = \omega M I_{st} e^{j(\theta+\pi/2)}$$

Power Transferred Across Airgap

- Assume that the V_{sr} induced by $I_{pt}\angle 0$ causes a current $I_{st}\angle\theta$ to flow through a load, Z_{sc}, attached across the pick-up coil
- Under these conditions, power transferred is

$$P_o = \Re\left\{V_{sr} I_{st} e^{-j(\theta)}\right\} = |V_{sr}|\,|I_{st}|\cos(\pi/2 - \theta)$$

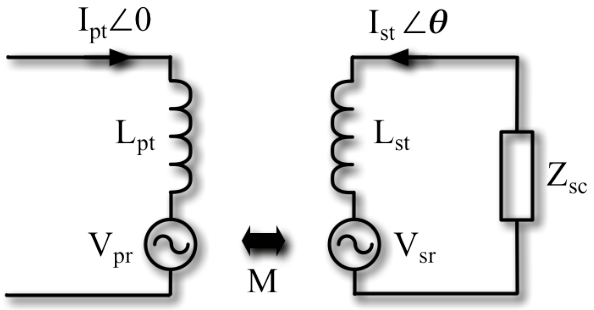
- The VA rating of the coils required to achieve this is

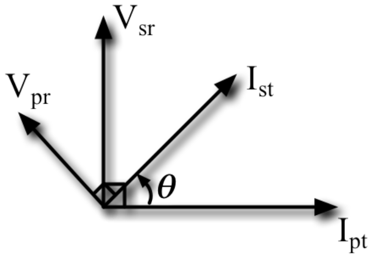
$$VA_{pt} = \omega L_{pt}\,|I_{pt}|^2 \quad \text{and} \quad VA_{st} = \omega L_{st}\,|I_{st}|^2$$

- Thus P_o is related to the VA in the coils as given by

$$P_o = k\sqrt{VA_{pt}\,VA_{st}}\,\sin(\theta)$$

  - Typically, $\sin(\theta) \approx 1$, and thus $P_o \approx k\sqrt{VA_{pt} VA_{st}}$





Coil Q, Losses & Maximum Efficiency

- Assume that the losses in L_{pt} and L_{st} are modelled using equivelent series resistances (ESRs) r_{pt} and r_{st}
- The quality factors, Q_{pt} and Q_{st}, of the primary and pick-up coils are

$$Q_{pt} = \omega L_{pt}/r_{pt} \quad \text{and} \quad Q_{st} = \omega L_{st}/r_{st}$$

- The total losses in the two coils can be expressed as

$$P_{loss(c)} = \left|I_{pt}^2\right| r_{pt} + \left|I_{st}^2\right| r_{st} = \frac{VA_{pt}}{Q_{pt}} + \frac{VA_{st}}{Q_{st}}$$

- The maximum efficiency is achieved when losses in the coils are matched (i.e. $VA_{pt}/Q_{pt} = VA_{st}/Q_{st}$)

$$\eta_{c_{max}} = \frac{k\sin(\theta) - \frac{1}{\sqrt{Q_{pt}Q_{st}}}}{k\sin(\theta) + \frac{1}{\sqrt{Q_{pt}Q_{st}}}}$$

Impact of k and Coil Q on Performance

- Typically, k is in the range 0.1 to 0.3 and coil Q is in the range 400 to 600 for EV charging
- Design of a 10 kW IPT system
  - Assume both Q_{pt} and Q_{st} are 400
  - Note that $P_o \approx k\sqrt{\mathrm{VA}_{pt}\mathrm{VA}_{st}}$ needs to be always met

When k is 0.3

Option	VA_{pt}	VA_{st}	$\sqrt{\mathrm{VA}_{pt}\mathrm{VA}_{st}}$	$P_{loss(pc)}$	$P_{loss(sc)}$	η_c
1	160 kVA	10 kVA	40 kVA	400 W	25 W	96.5%
2	40 kVA	40 kVA	40 kVA	100 W	100 W	98.3%
3	10 kVA	160 kVA	40 kVA	25 W	400 W	96.5%

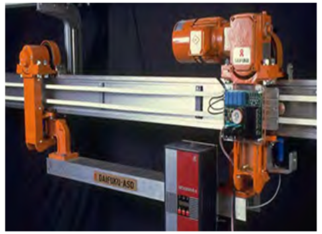
When k is 0.1

Option	VA_{pt}	VA_{st}	$\sqrt{\mathrm{VA}_{pt}\mathrm{VA}_{st}}$	$P_{loss(pc)}$	$P_{loss(sc)}$	η_c
1	480 kVA	30 kVA	120 kVA	1200 W	75 W	89.4%
2	120 kVA	120 kVA	120 kVA	300 W	300 W	95%
3	30 kVA	480 kVA	120 kVA	75 W	1200 W	89.4%

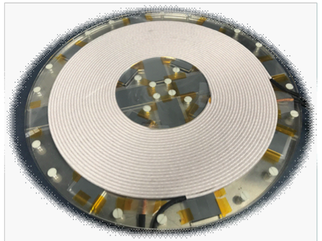
Part III - Coil Structures

Field Patterns and Coil Parameters

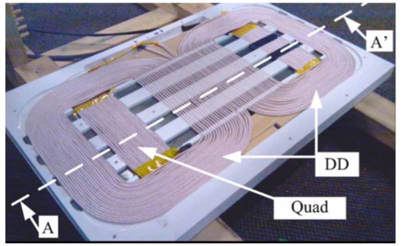
Types of Coil Structures



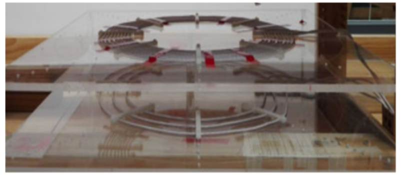
An IPT Track



A Circular Coil/Pad



A DDQ Coil/Pad

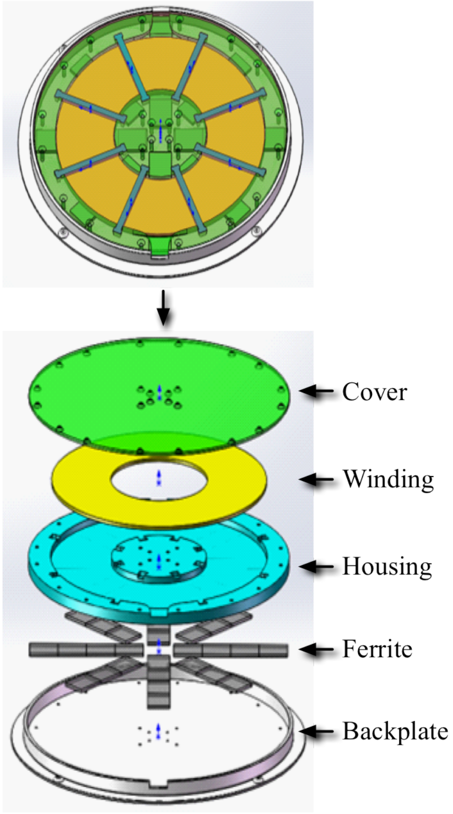


A Ferriteless Circular Coil/Pad

- Can be broadly divided into ditributed track type coil structures and lumped coil structures
- Typically, ferrites are used to help shape the field generated
  - Maximize coupling, minimize leakage and improve coil Q
- As an alternative for ferrites, energised or passive field shapping coils can be used
- Lumped coil structures can be further divided as non-polarised, polarised and multi-coil structures
- Multi-coil structures typically employ multiple decoupled coils
  - Each coil can be driven seperately to create the desired field pattern
- Repeater coils can be used to extend the range

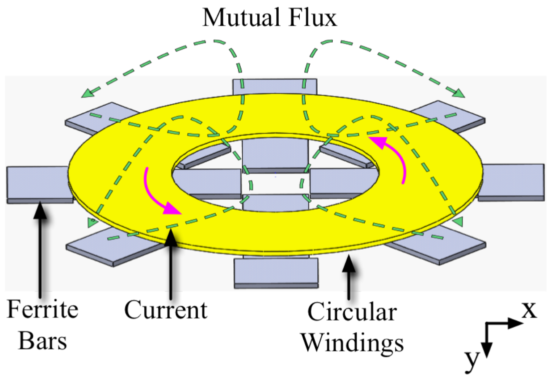
Construction of a Lumped Coil

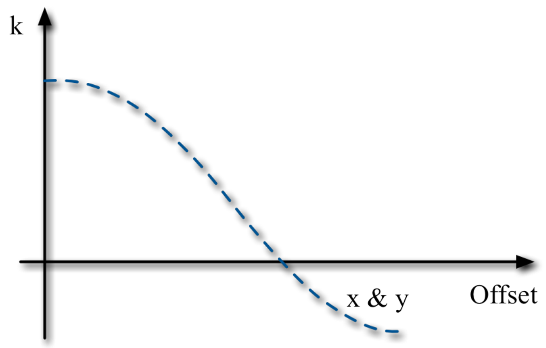
- Contructed as planar spiral winding and take the shape of a circle/square/rectangle/etc.
  - Multifilar windings can be used to increase the current rating, but special attention is required to ensure current sharing
- High-frequency Litz wire is used to improve coil Q
  - Need to ensure that the windings are appropriately isolated
- Ferrite plates/disks/bars are used to create a single sided flux pattern
- The housing that provides electrical isolation holds the Litz wire and the ferrites
  - Typically the windings and ferrites are potted
- Aluminum shielding is used to reduce leakage flux



Non-Polarised Coils

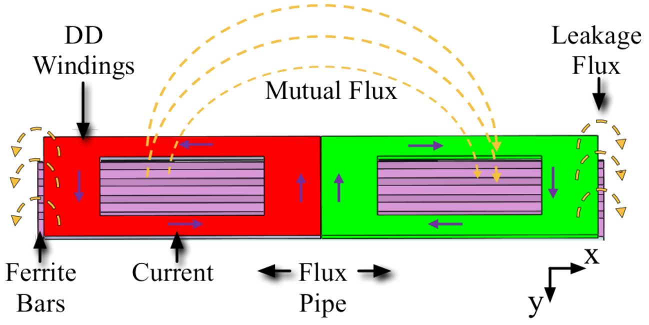
- The single sided magnetic field distribution is from centre to edge of the coil
- Typically used to transfer power over a gap that is roughly equivalent to one quarter of the coil diameter
- Changes in the displacement between the primary and pick-up coils causes
  - Changes to k between the coils
  - Changes to L_{pt} and L_{st} of the coils
- With lateral/longitudinal displacement k will drop to 0
  - The point at which k drops to 0 is referred to as the decoupled position of the coils
  - A negative k after the decoupled position indicates a 180^0 phase-shift in induced voltage

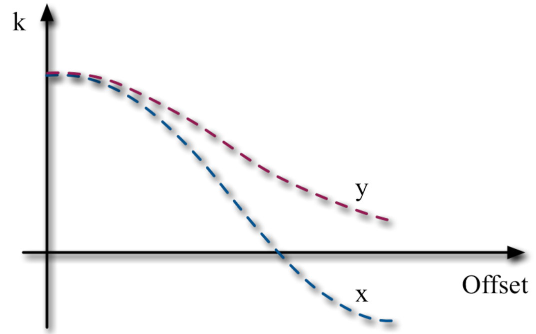




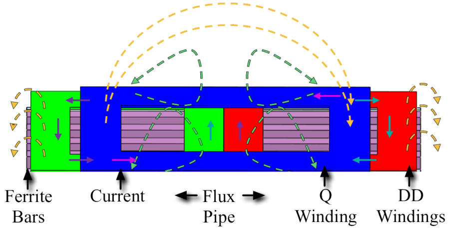
DD Type Polarised Coils

- The single sided magnetic field distribution is from one end to the other end of the coil
- Typically used to transfer power over a gap that is roughly equivalent to one half of the coil length
- Flux-pipe formed by the two coils at the center of the pad should be as large as possible
- Changes in the displacement between the primary and pick-up coils causes
    - Changes to k between the coils
    - Changes to L_{pt} and L_{st} of the coils
- With longitudinal (x) displacement k will drop to 0
    - At the point at which k drops to 0, primary and pick-up DD coils are decoupled

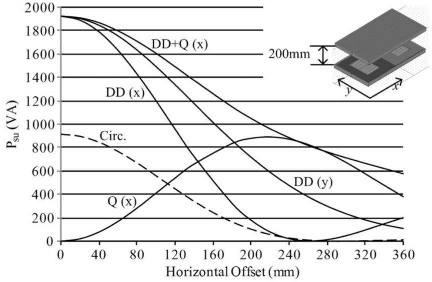


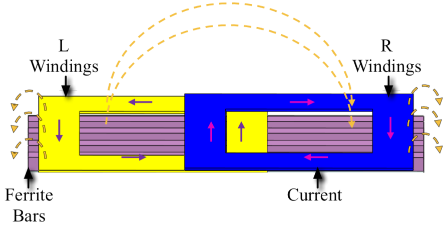


Multi Coil Structures



DDQ Coil





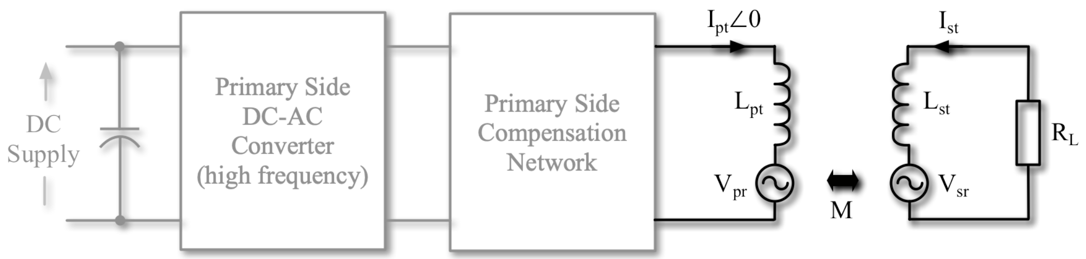
Bi-Polar Coil

- DDQ structure is one of the most common multi-coil structures
  - The quadrature (Q) winding is decoupled from the DD winding
  - Thus, both windings can be used independently to transfer power
  - A DD primary and DDQ secondary provides wide spatial tolerance since the Q winding helps transferring power when k between the DD windings drop
- Bi-polar structure employs two overlapping windings that are decoupled from each other
  - When used as a transmitter, each coil can be driven at a desired magnitude and a phase
- Tri-polar and other multi-coil structures typically employ decoupled overlapping windings

Part IV - Compensating the Coils

Behavior of the Compensated Coils

An Uncompensated Pick-up



- Assume a load resistor, R_L, is connected directly across a pick-up coil, which is coupled to a primary coil
- The primary coil is driven by the primary converter generating a current $I_{pt}\angle 0$ at an angular frequency $\omega = 2\pi f$
- The current flowing through pick-up coil as well as the load will be

$$I_{st} = \frac{-V_{sr}}{R_L + j\omega L_{st}} = \frac{-\omega M I_{pt} e^{j\pi/2}}{R_L + j\omega L_{st}}$$

- The impedance of L_{st} limits the ability to supply current to R_L

Power from an Uncompensated Pick-up

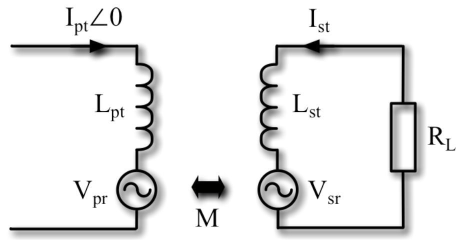
- The power delivered to the load is then

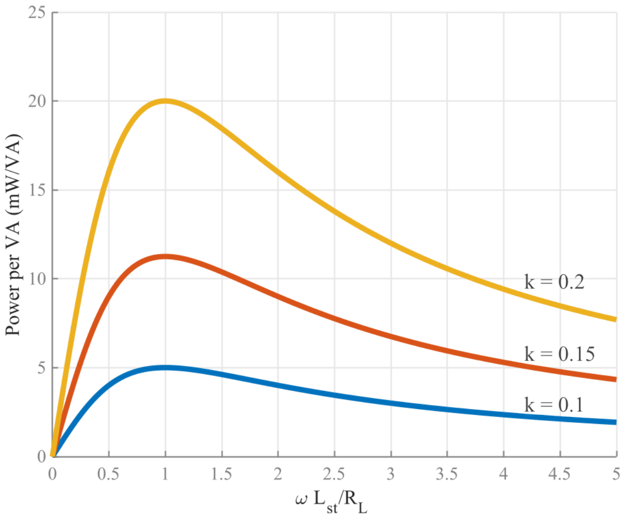
$$P_o = |I_{st}|^2 R_L = (\omega M I_{pt})^2 \frac{R_L}{R_L^2 + \omega^2 L_{st}^2} = k^2 VA_{pt} \frac{\omega L_{st}/R_L}{1 + \omega^2 L_{st}^2/R_L^2}$$

- At a load $R_L = \omega L_{st}$, maximum power is delivered

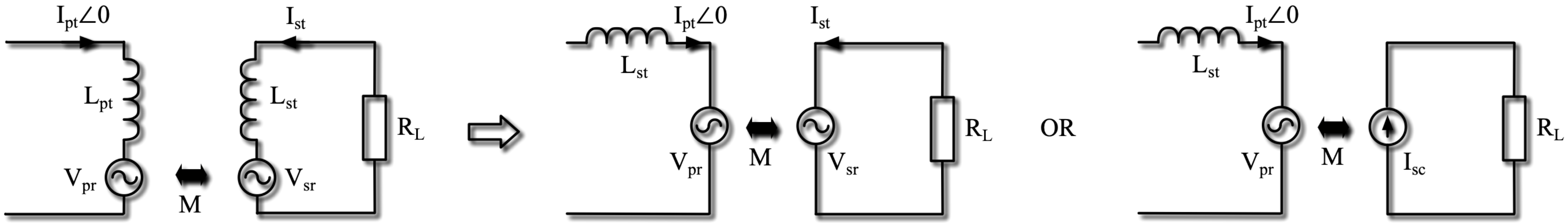
$$P_{o_{(max)}} = \frac{(\omega M I_{pt})^2}{2\omega L_{st}} = 0.5 V_{oc} I_{sc} = 0.5 k^2 VA_{pt}$$

- As an example, when $k = 0.1$, to deliver 5 mW to the load, the primary coil should be driven at least at 1 VA
  - The impedance of L_{st} limits the power transfer



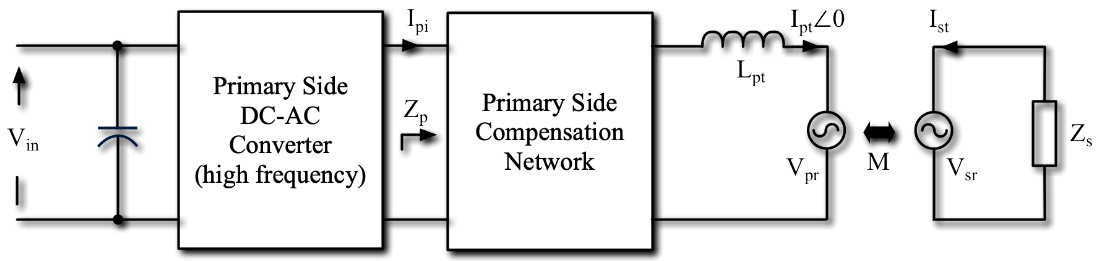


What Should an 'Ideal' Pick-up Look Like?



- The load R_L 'ideally' needs to be able to take any amount of power from pick-up
- This could be achieved, for example if the pick-up coil is made to to look like an ideal voltage source
  - The impedance of L_{st} need to be made zero
  - In this case we would have an ideal voltage source, V_{sr}, supplying the load, R_L
- Alternatively, the pick-up coil can be made to look like an ideal current source, I_{sc}
- Resonance can be used to achieve this 'ideal voltage source' or 'ideal current source' type behavior
  - A technique discovered by Hertz in the 1880's

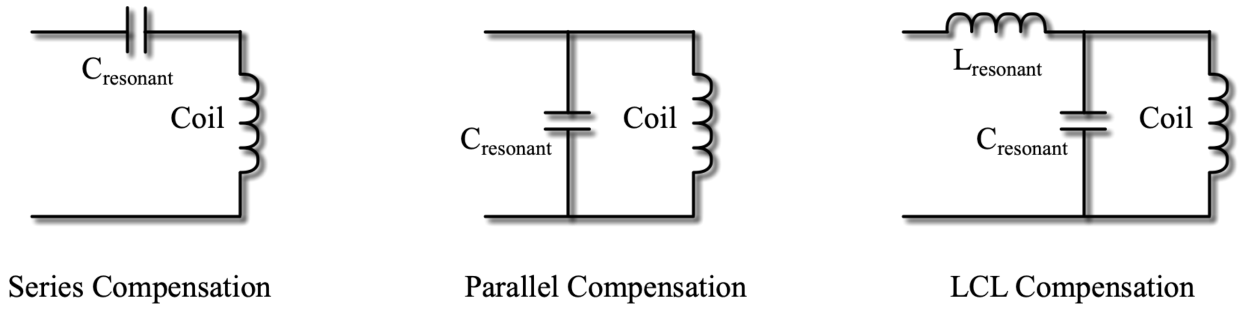
Primary Compensation Networks



- Directly driving the highly inductive load consisting of L_{pt} and Z_{pr} with a power converter can be very inefficient and costly
  - For example the VA rating of the converter, which is required to deliver $1W$ to the pick-up load, can be in excess of $1/(k^2 Q_{ss/sp_{(op)}})$
  - If $k = 0.1$ and $Q_{ss/sp_{(op)}} = 5$, which are typical for an IPT system, the primary converter will need to be supply 20VA to deliver 1W to the load
- Resonance is also used to reduce the VA demand of the primary converter
  - Many different resonant networks have been developed to-date to cater for different applications

Compensation Methods

- The two most common resonant/compensation networks are the parallel and series types
  - Parallel resonance is not common on primary in modern systems as it needs to be driven by a current sourced inverter
- Primary side commonly employ LCL compensation networks
- More complex compensation networks include
  - LCCL and LCLC
  - Hybrid compensation
  - Impedance compression networks

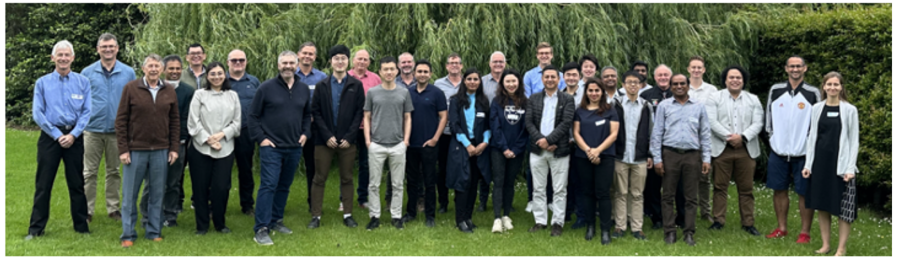


Research Advances

Highlights & Updates

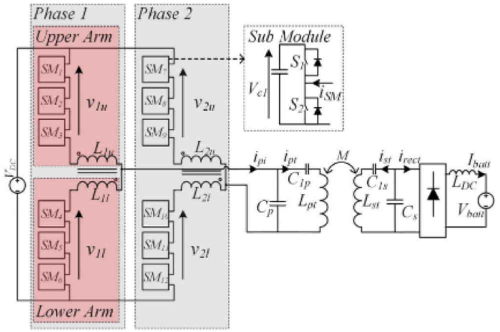
The Team

- Members from Power Electronics, Centre for Advanced Composites Materials, Transportation, Engineering Science, Business School, GNS Science, Victoria University, Mahi Maioro and AUT
  - Collaborations with industry, ASPIRE, Utah State University and Cambridge University

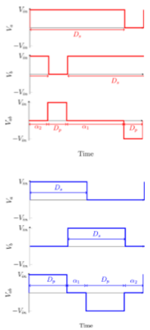



Capabilities

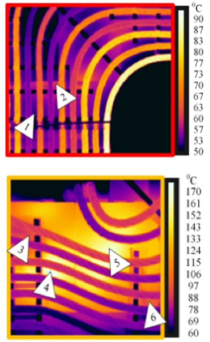
- The power electronics team work with the other teams to develop converter, magnetic and controller designs and extensively test them



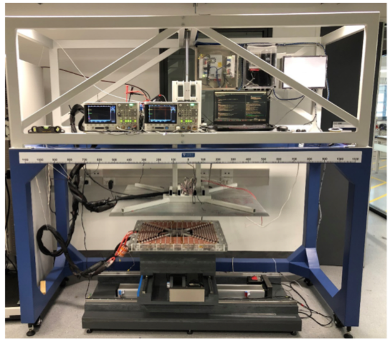
Novel/Improved Converters



Modulation/Control Techniques

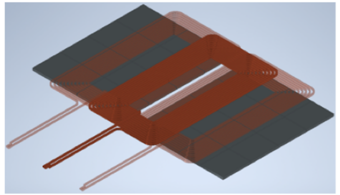


Thermals

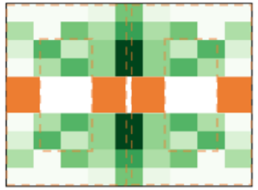


Econometrics & Parametric Evaluation

In Road Evaluation

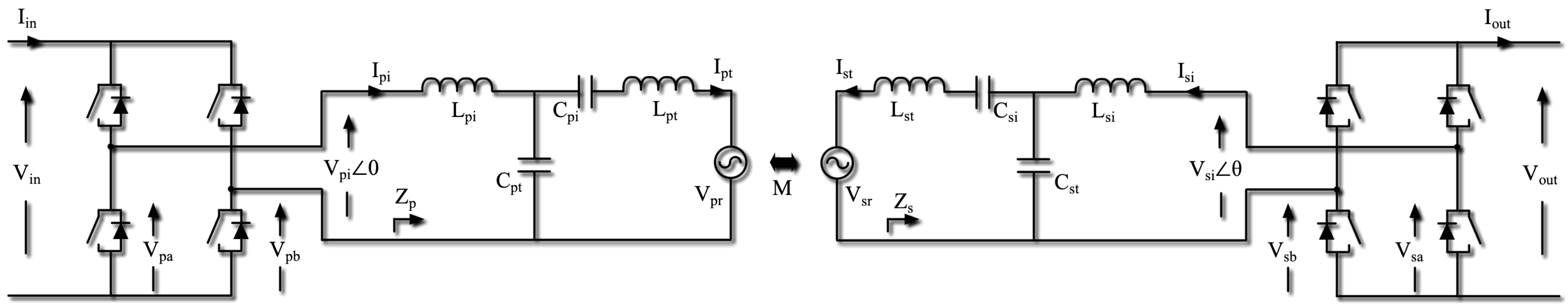


Novel/Improved Magnetics



Optimisation

Active Rectification of Pick-up Output

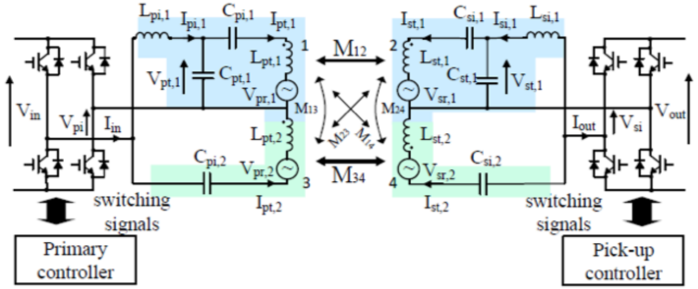


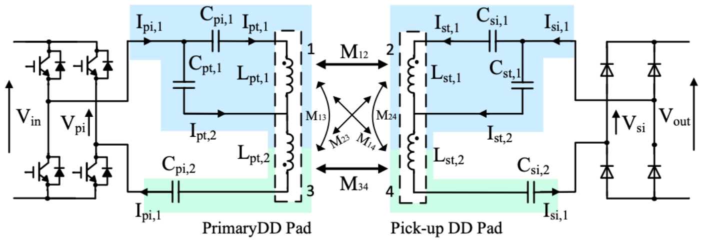
- Identical primary and pick-up circuits employ inductor-capacitor-inductor (LCL) T-resonant networks
    - Can use other types of compensation networks
- Both full-bridge converters are operated at the same frequency to drive the couplers
    - Compensation networks are typically tuned to the fundamental switching frequency
- Magnitude of power flow is regulated using voltage cancellation to control the RMS of V_{pi} and V_{si} and/or controlling the phase difference between V_{pi} and V_{si}
- Direction of power flow is controlled using the phase difference, θ, between V_{pi} and V_{si}

Hybrid Compensation Topologies

- Complementary compensation networks employed to improve misalignment tolerance
- Require less or no control
- Nearly constant power transfer across the entire operating region
- Minimize increase in VA due to detuning caused by changes in coupler inductanes
- For example the power throughput of a parallel hybrid system can be given by

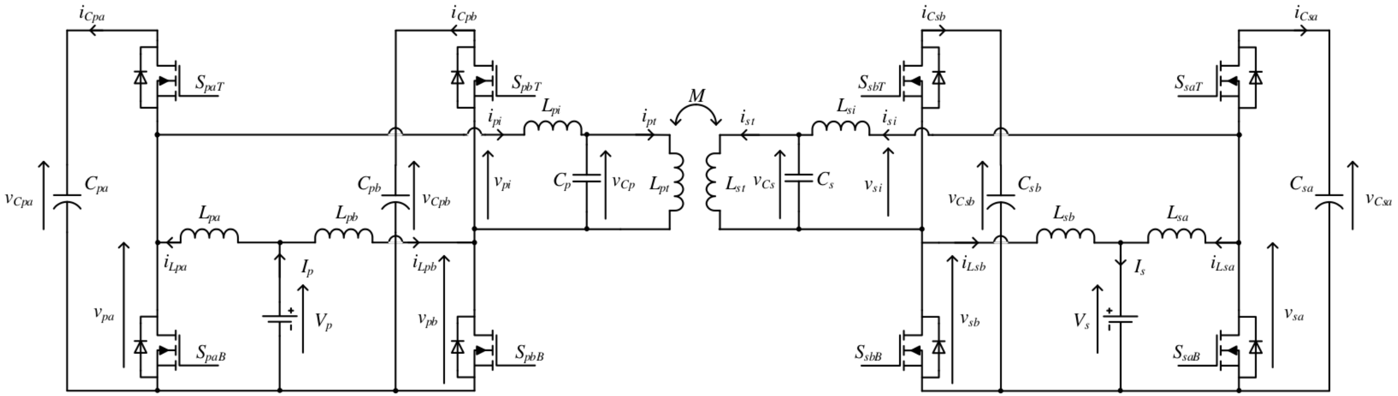
$$P_{out} = \frac{8V_{in}V_{out}}{\pi^2}\left(\frac{1}{\omega_T M_s} + \frac{M_p}{\omega_T L_{pi} L_{si}}\right)$$

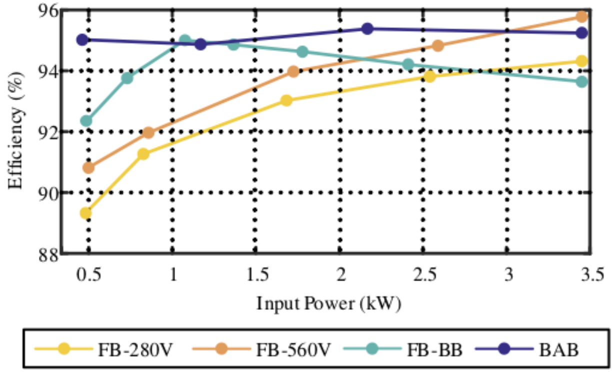


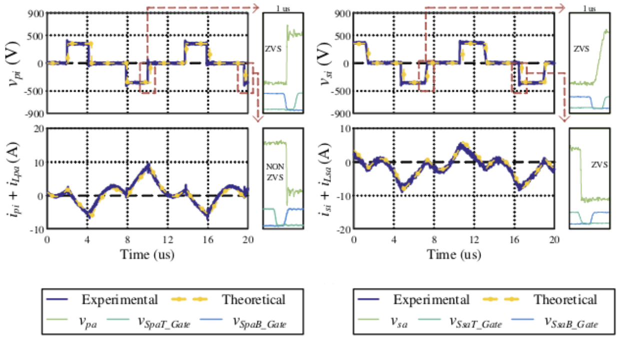


Boost Active Bridge (BAB)

- Integrated post/pre regulation capabilities enable maximum efficiency tracking
- Wide ZVS range and reduced current stresses
- Eliminates DC-blocking capacitor

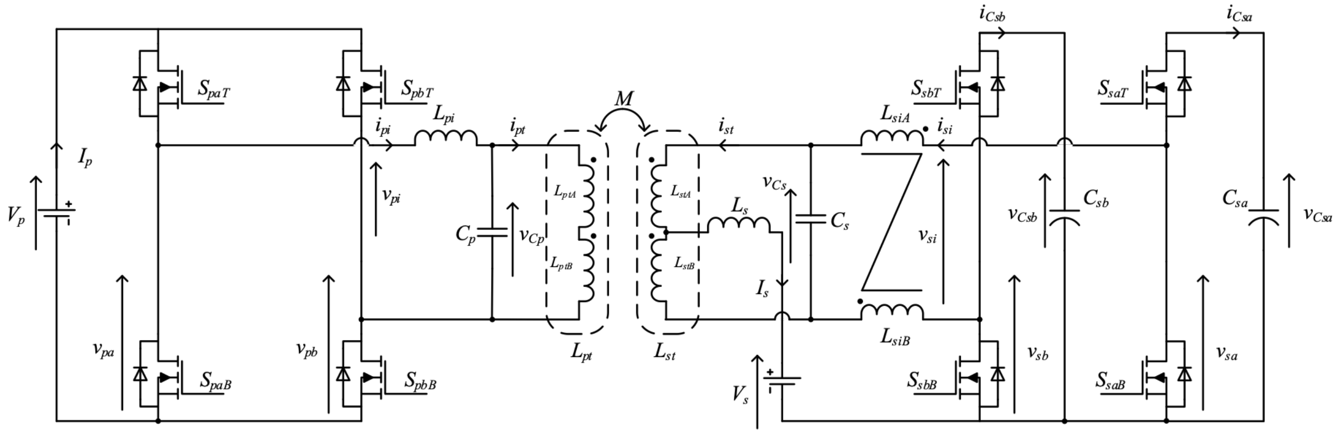


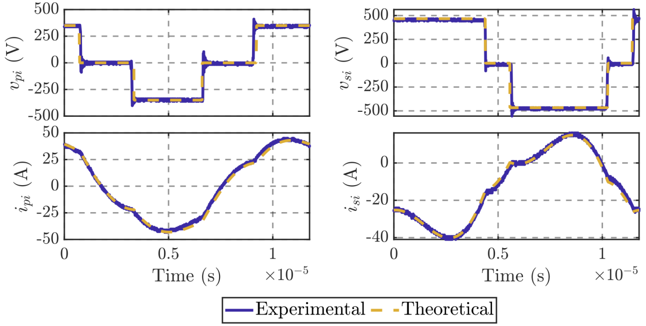


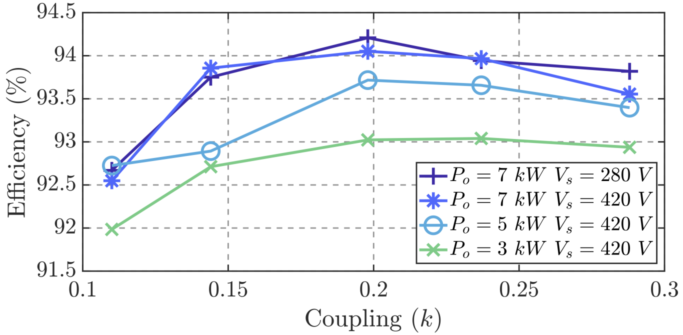


WPT2/Z2 VA with Integrated BAB

- Boost inductors integrated in to the DD pad
- Designed to comply with WPT2/Z2 specifications
- Controlled both the GA and VA to maintain a nearly constant efficiency under all operating conditions

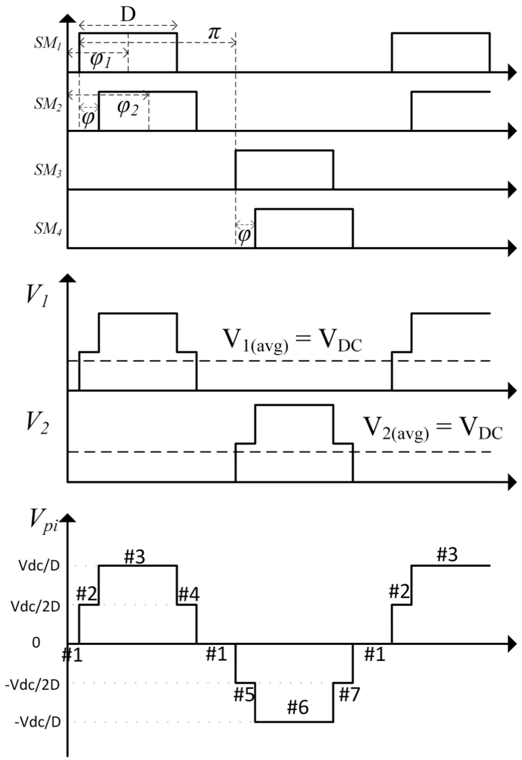


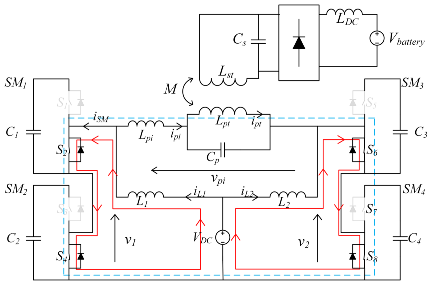




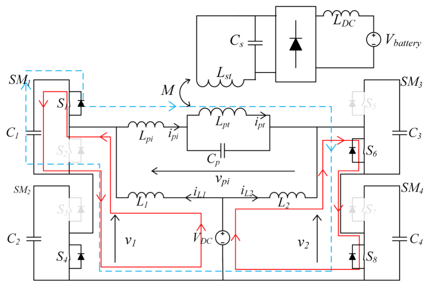
Integrated Boost Multilevel Converter (IBMC)

- Derives a higher voltage to drive the compensation network
  - Reduces current stress and may eliminate step-up transformer
- Inherently eliminates circulating currents
  - Series-blocking capacitor can be omitted
- Generate a low THD staircase modulated output voltage
  - Can generate wide range of voltages
  - Can use lower voltage higher performance devices

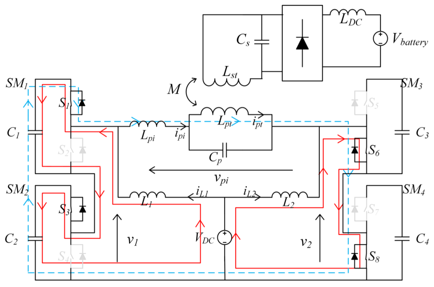




Circuit State 1 of 16

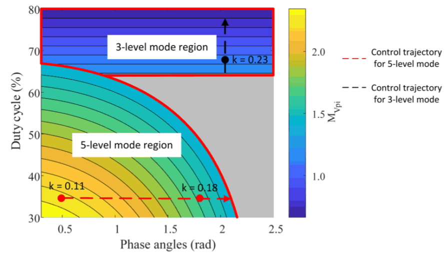


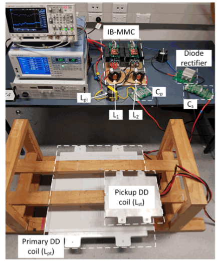
Circuit State 2 of 16

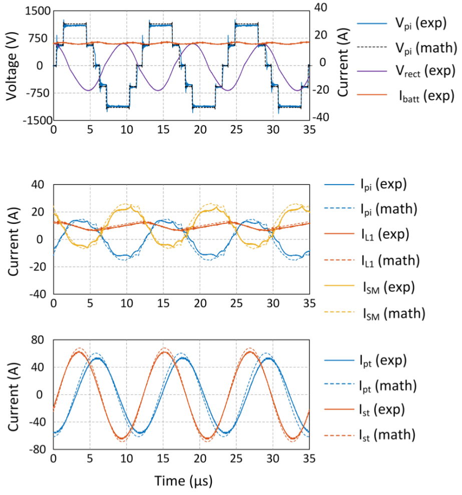


Circuit State 3 of 16

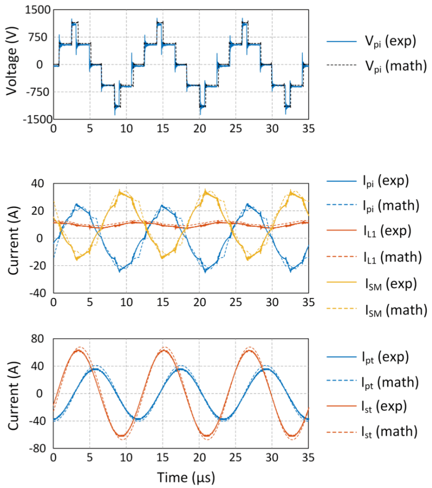
IBMC Performance



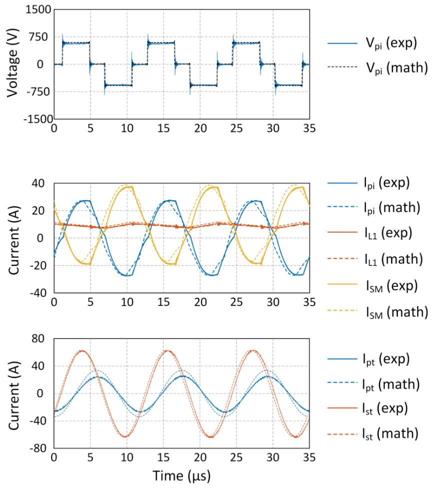




k = 0.11



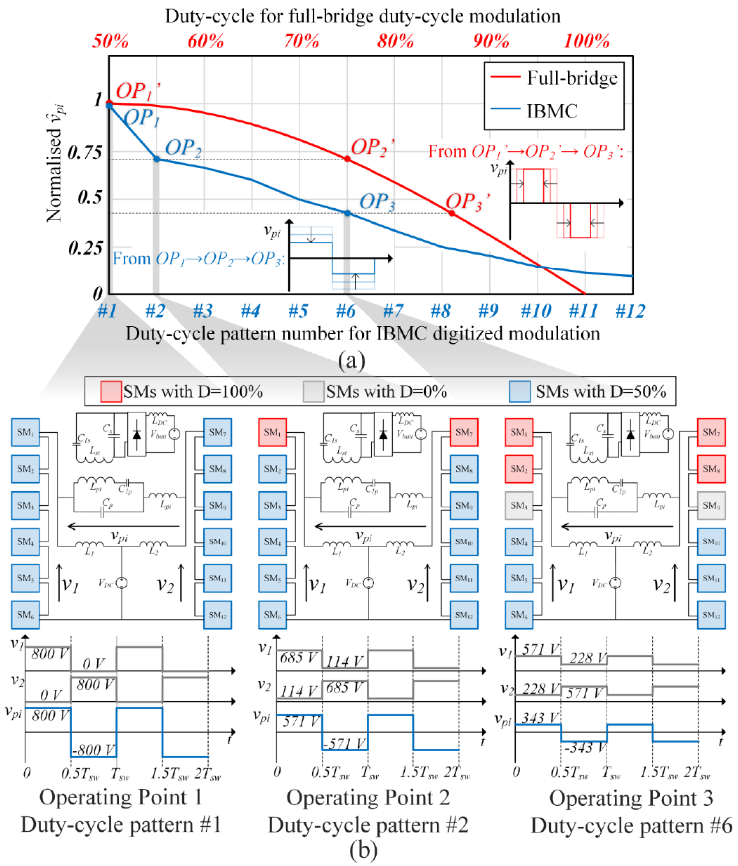
k = 0.18

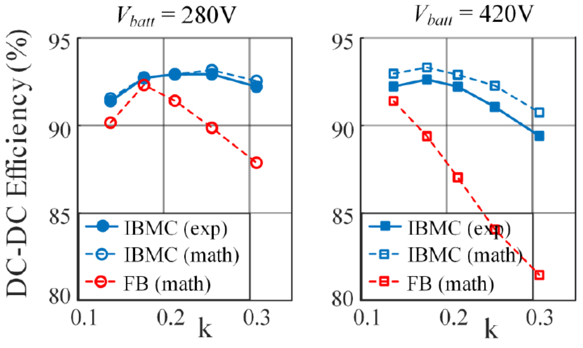


k = 0.23

- 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

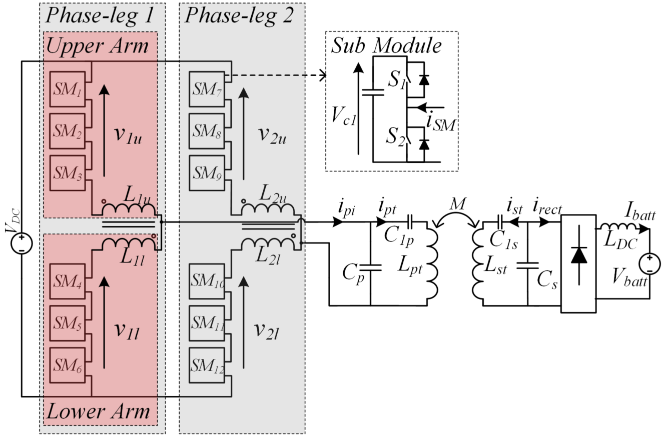
A Digitized Modulation Scheme

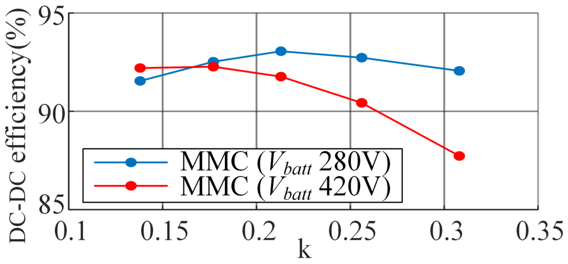


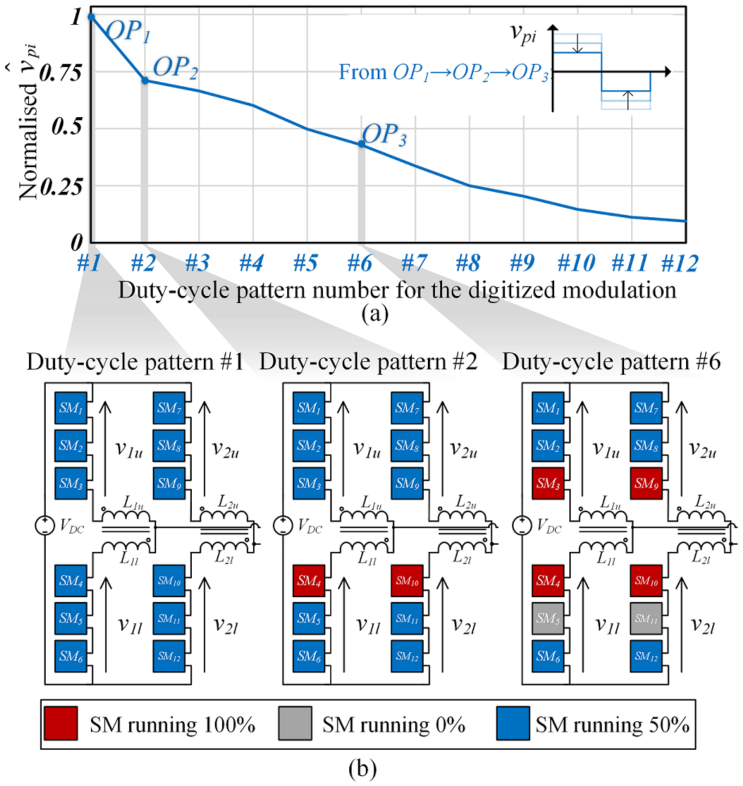


- Traditional duty/phase modulation causes loss of ZVS
- Pulse density modulation introduces unwanted resonances
- New scheme operates a module only at 0%, 50% or 100% duty ensuring ZVS
- Works like a DAC as the number of modules in each of the 3 states determine voltage amplitude

An MMC Based IPT System



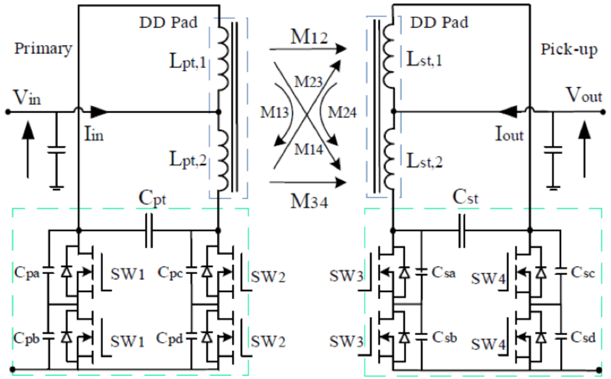


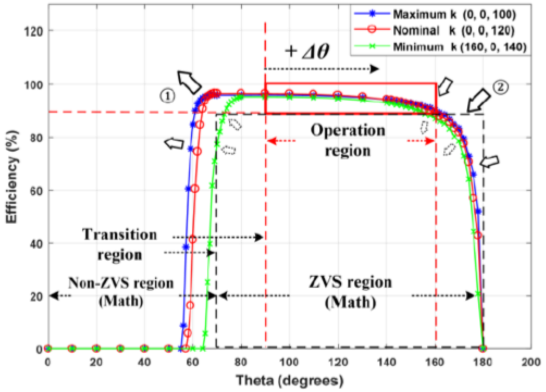


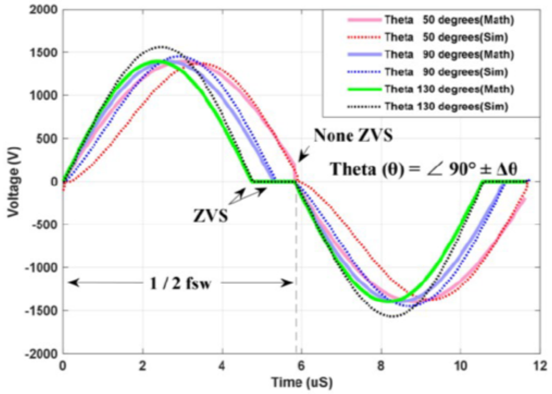
- In some applications, boosting capability of the IBMC may not be needed
  - An MMC based system can be used in such applications
- Arm inductors also functions as part of the resonant circuit
  - Performance is similar to an IBMC

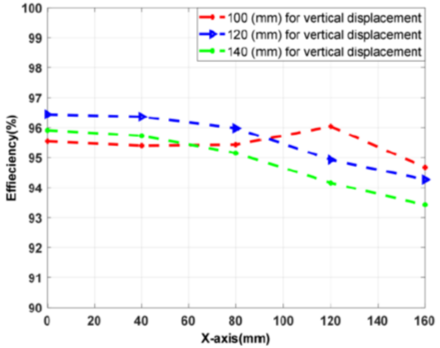
Low Cost IPT Systems

- For example push-pull converters employed in both VA and GA
  - DC indcutor(s) and current splitting transformer can be integrted in with the D coupler
  - Generates a higher voltage to drive the couplers
  - Relative phase between converters controls the power flow
  - Switches maintain ZVS across the entire operating region

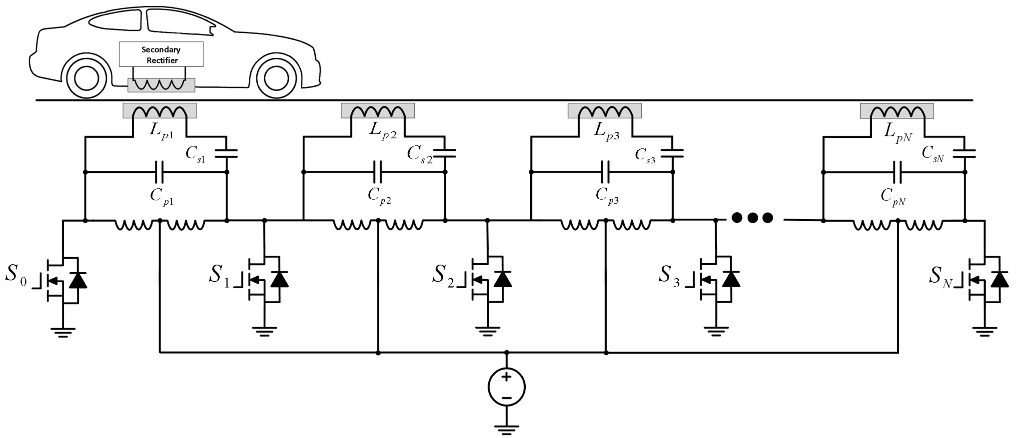


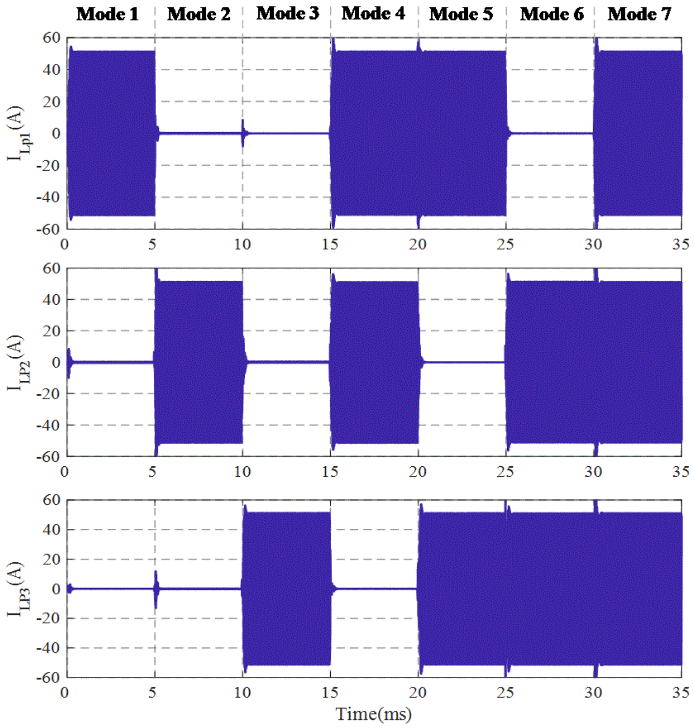






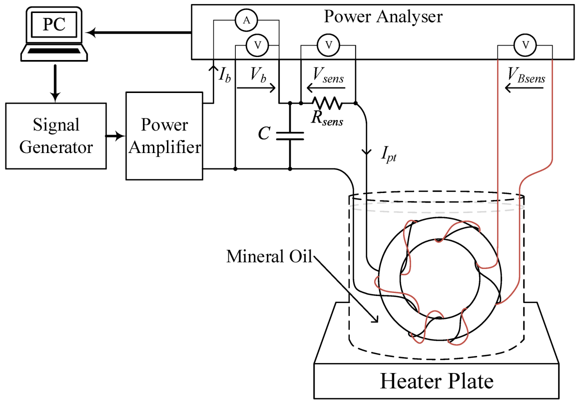
Push-Pull Coupler Array (PPCA)

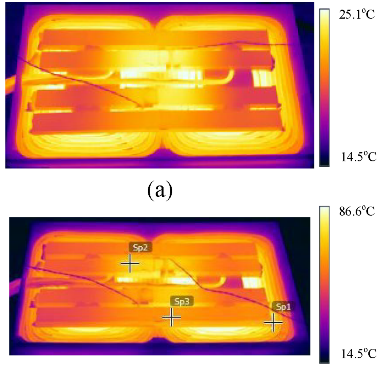




- Each coupler driven by a single switch and controlled independently
- Swtich stresses do not scale with the number of couplers
- Switches only conduct the DC current
- A damaged module only impacts the two neighbouring modules

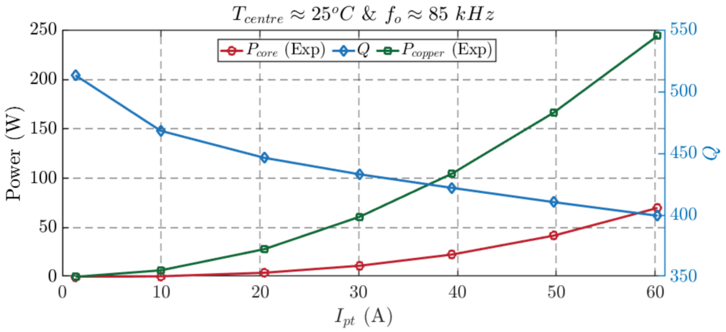
Optimizing the Coil Structures

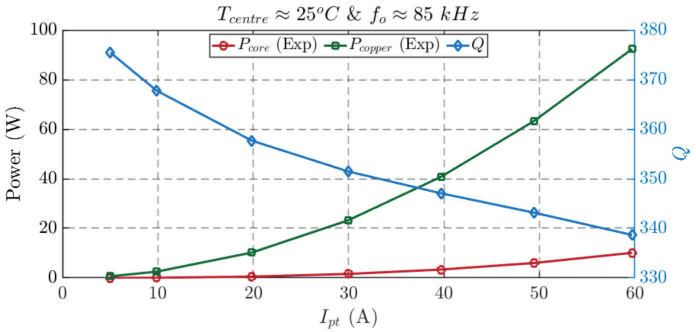




(a)

(b)





- An experimental method called the stepped resonant excitation (SRE) to obtain the core and copper losses is developed
  - Using SRE method high fidelity FEM models that also capture thermal behavior are developed
- As an example, the characteristics of WPT2/Z2 couplers show significantly higher copper losses

References

These slides were derived from a presentation prepared by the author on

"Fundametals of Inductive Power Transfer: A Workshop with Example Designs"

@wirelesspower.github.io/SeminarsWorkshops/FundamentalsofIPTDJT/presentation.html

Thank You