ELETENG734 – Wireless Power Transfer

2023 – Dr Jackman Lin

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Wireless Power Transfer (WPT)

- WPT is the technology which enables power to be transferred between two points without the use of a physical connection
- Two broad categories
  - Radiative transmission through far field principals
    - Power transfer through radio frequencies, microwaves, optical (lasers), ultrasonic
    - Start-ups such as uBeam, Energous are in this space
    - Airfuel Alliance have developed standards in this space
  - Non-radiative transmission through near field principals
    - Inductive Power Transfer (IPT) and Capacitive Power Transfer (CPT) technologies
    - Many companies in this space
      - Daifuku, Conductix Wampfler, Power by Proxi (now Apple NZ), WiTricity (US and NZ), Bombadier, WAVE IPT.
      - Wireless Power Consortium (WPC), and Society of Automotive Engineers (SAE) have developed standards in this space

Why WPT?

- Removes human interaction from the charging equation
- Convenience
- Safety
- Enabling future technologies
    - Automated fleets

IPT vs CPT

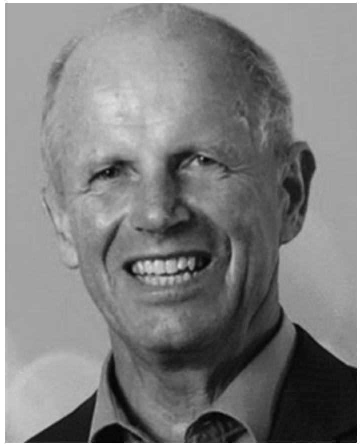
- UoA has many research groups in near field technologies
- IPT uses magnetic fields to transfer power
    - Main power coupling mechanism is the magnetic coupling (k) between a primary and a secondary coil
        - Coil can be 'track' shapes or lumped shapes'
    - The primary (transmitting) coil produces a time-varying magnetic field
        - Achieved by driving a high frequency current through the coil
    - The magnetic field is intercepted by the receiving coil
        - Induces a voltage which is then processed to derive output power

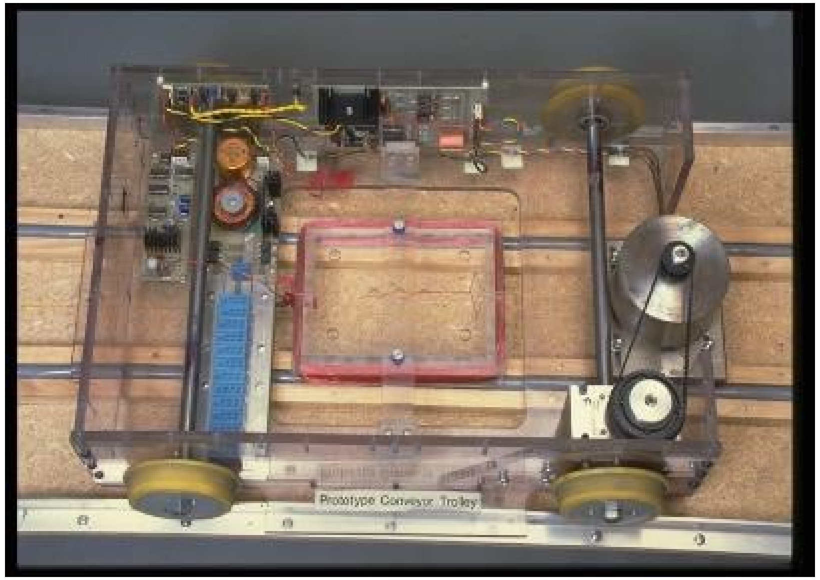
IPT vs CPT

- UoA has many research groups in near field technologies
- CPT uses electric fields to transfer power
    - Power is transmitted between the primary and secondary plates (like a capacitor)
        - Can consist of forward and return plates, or multiple plate
    - A time varying electric field is produced between the plates
        - Produced by driving the transmitter plate with a high frequency voltage
    - The changing electric field causes current flow to the receiver plate
        - Induced current is used to derive power

History of IPT at UoA

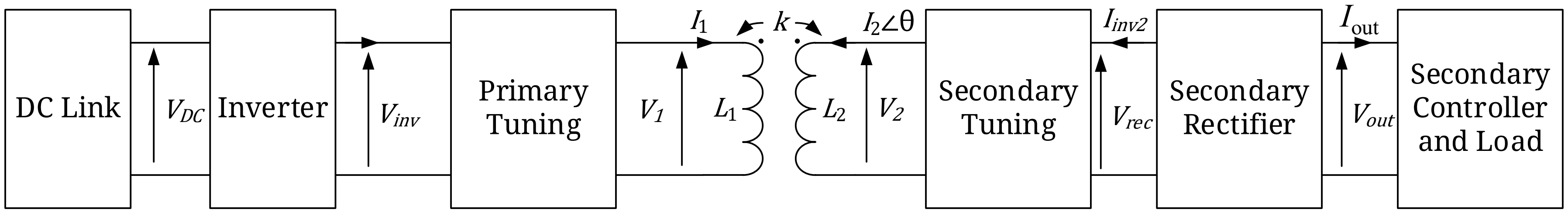
- Pioneering work in this space has been done at UoA
  - Started and led by Emeritus Professor John T Boys in the late 80’s
  - Prof Boys and his team (Prof Grant Covic, Prof Udaya Madawala, Prof Patrick Hu) develop the first commercial IPT systems
    - Partnering with companies such as Daifuku and Conductix Wampfler
    - Clean room automation applications
  - This led to the possibility of EV charging applications
    - In 2011 – HaloIPT, a start-up consisting of UoA students was acquired by Qualcomm to develop IPT systems for EV charging
    - In 2018 – WiTricity acquired Qualcomm’s stake and is now developing stationary wireless charging systems for stationary EV charging
    - In 2017 – PowerByProxi (est 2007) was acquired by Apple to develop wireless charging systems for their devices
    - In 2017 – Prof Grant Covic secured $12M NZD from MBIE to do research into dynamic EV charging, renewed in 2022 for another 5 years for the same amount.
- Lots of success in WPT at UoA!





IPT – A summary

A set of magnetics that are coupled with some coupling factor (k)



Primary inverter needed to convert a dc voltage into an ac waveform.

- Full- bridge, half-bridge, push-pull, multi-level, or matrix converter topologies

Primary and secondary compensation networks are needed to ensure efficient power transfer.

- Series
- Parallel
- LCL

Secondary rectifier to convert ac waveform to dc to charge a battery

- Passive
- Full- bridge, half-bridge, push-pull, multi-level, or matrix converter topologies

Secondary controller needed to control output power.

- Buck
- Boost
- Buck boost

IPT – A summary

- Power ratings from uW to hundreds of kW
- Magnetic designs include tracks, circular , solenoidal , DD, DDQ, Bi/Tri/Quad-polar coils
- With and without ferrites
  - Managing weight
- Large misalignment tolerances
  - Can achieve over 300 mm air gaps (with appropriately sized magnetics)
  - $\pm$200 mm misalignment (with appropriately sizes magnetics)
  - High efficiencies (>80% misaligned, >95% aligned)
  - Operating frequencies ranging from tens of kHz to multi-MHz

Wireless Power Transfer (WPT)

- The technology which allows power transfer without the use of a cable
  - Perfect for dirty/hazardous environments
- Power ranges from low (uW to ~20 W)
  - Medical devices
  - Cellphones
  - Roadway/Tunnel/Mine lighting
- Medium (~20 W – ~3 kW)
  - Remote charging of drones
  - Laptop chargers
  - Clean factory automation
- High power (~3 kW – 1 MW+)
  - EV charging
  - Truck charging
  - Airplane charging
  - Industrial applications

Inductive Power Transfer

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NEW ZEALAND

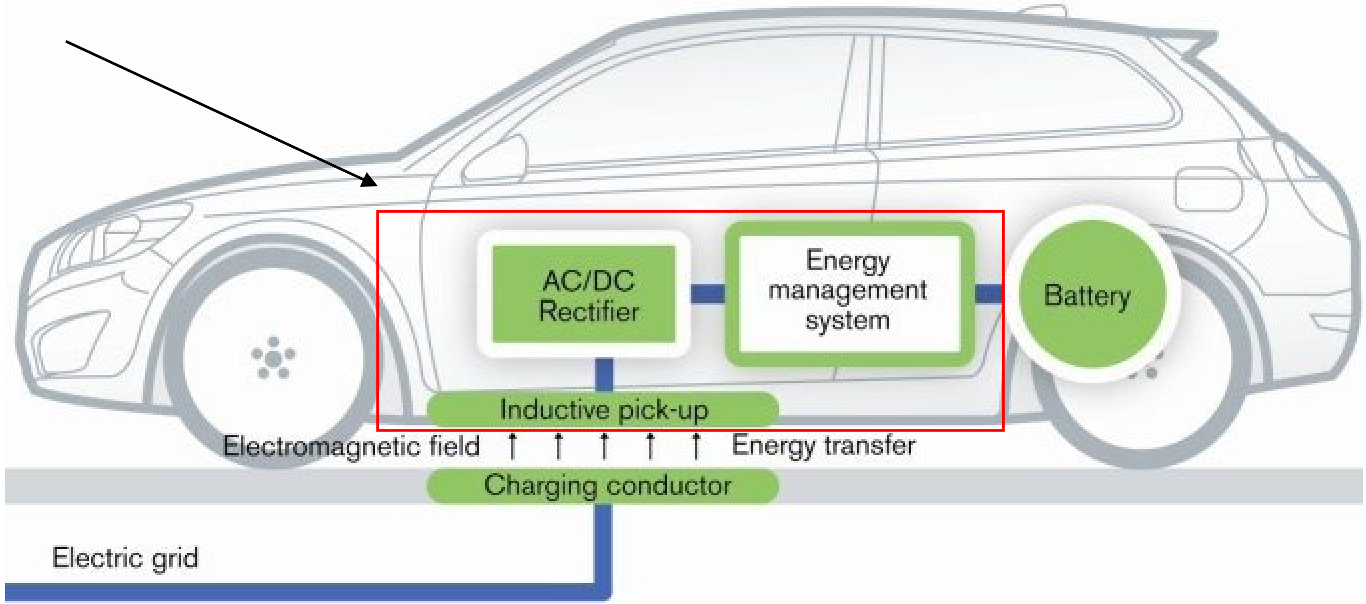
Learning Outcomes

- By the end of the magnetics section, students will be able to:
  - Identify important design parameters for IPT magnetics
  - Understand the need for tuning and the impact of mistuning on IPT systems
  - Understand how practical limitations restrict power transfer in IPT systems

- How you will be assessed:
  - Lab 1 task 1 and 2 will cover the IPT compensation taught
  - Test
  - Practical component links up theory to a practical example

Components of an IPT system

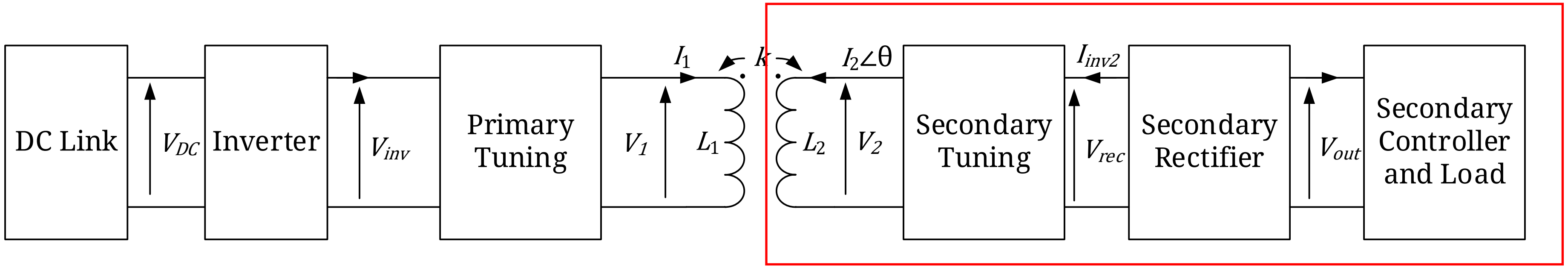
Main focus of this course and project



IPT - Assumptions

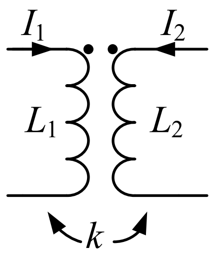
- This course focuses on the secondary side of the system, so the following assumptions are made:

1. The primary side inverter and tuning topology provides a constant I_1, regardless of load
2. The primary side inverter and tuning topology operates at a constant frequency f, which translates to $\omega = 2\pi f$

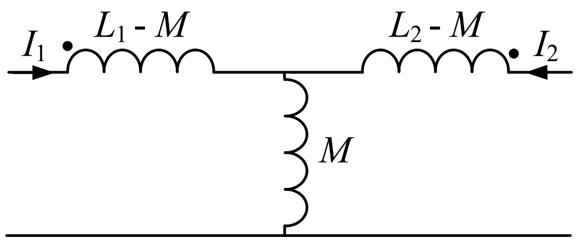


Coupling factor in an IPT system

- Two magnetic coils in close proximity with each other will have a coupling factor (k) between them
  - Transformers are designed with extremely high k (~0.999)
  - Incredibly important to minimize leakage fluxes for specific applications (flyback converters)
- In IPT, there is a large air gap between the two magnetic coils
  - k is much lower than 0.999
    - Typically, in the range of 0.05 – 0.35
- In an IPT system, k and the inductances of the two coils (L_1 and L_2) determines the mutual inductance (M) between the two coils
  - Can be modelled using the T-model
  - $M = k\sqrt{L_1 L_2}$



Coupled coils

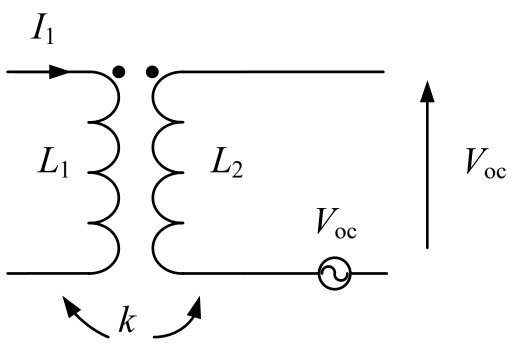


T model

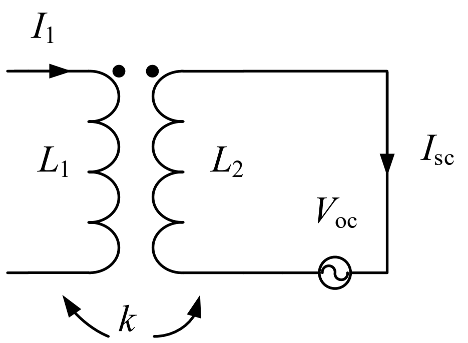
V_{oc} and I_{sc} in an IPT system

- Two **critical** parameters which characterizes the performance of an IPT system are:
  - V_{oc} - the open circuit voltage induced in the secondary coil
  - I_{sc} - the short circuit current induced in the secondary coil
- System assumes that the primary coil with an inductance L_1 is driven at a constant I_1 at a fixed frequency f_s ($\omega = 2\pi f_s$). $M = k\sqrt{L_1 L_2}$
- V_{oc} is the voltage measured across the pick up coil when there is no load connected to the secondary side
  - Output current is 0 A due to open circuit
  - $V_{oc} = j\omega M I_1$
- I_{sc} is the current flowing through the pick up coil when it is shorted
  - Output voltage is 0 V due to short circuit
  - $I_{sc} = \frac{V_{oc}}{j\omega L_2} = \frac{M}{L_2} I_1$

- No output power



V_{oc}

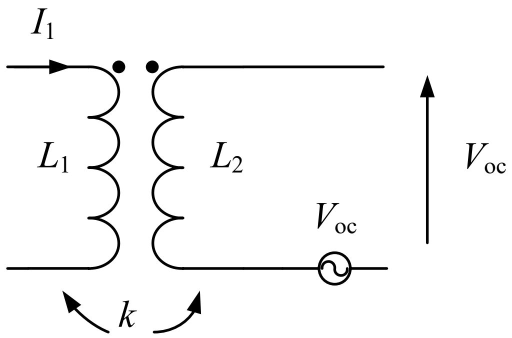


I_{sc}

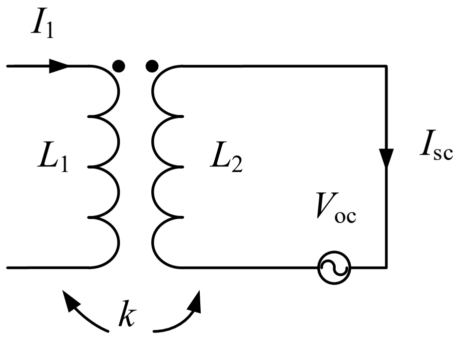
V_{oc} and I_{sc} in an IPT system

- $V_{oc} = j\omega M I_1$
  - Open circuit voltage **leads** primary current by 90 degrees

- $I_{sc} = \frac{M I_1}{L_2}$
  - No Phase shift between primary current and secondary current
  - **IF I_{sc} is defined as shown**
    - **This may change based on how you analyse circuits in detail later on**
    - For the first part of this course, we will define currents as shown for simplicity



V_{oc}



I_{sc}

Uncompensated Volt-amps (S_U) of an IPT system

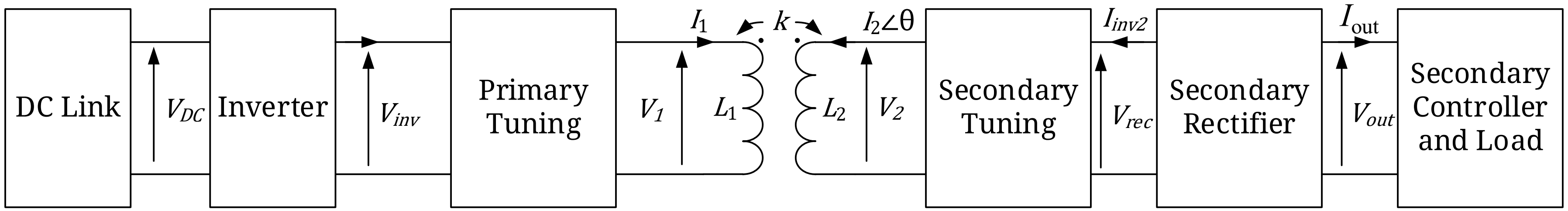
- S_u is the uncompensated volt-amps coupled to the secondary coil in an IPT system
  - $S_u = V_{oc} I_{sc}$
  - $S_u = |I_{sc}^2 j\omega L_2| = I_{sc}\omega L_2$
  - $S_u = \left|\frac{V_{oc}^2}{j\omega L_2}\right| = \frac{V_{oc}^2}{\omega L_2}$
- S_u is **not** output power
  - The unit for S_u is volt-amps (VA)
- S_u cannot be physically measured
  - V_{oc} and I_{sc} cannot be measured at the same time
- S_u is one of the limiting factors for power transfer in an IPT system

Q factor in an IPT system

- How does S_u relate to output power (P_{out})?
  - By a mechanism called Q factor **(loaded Q)**
  - Like taught in filters
- In IPT systems, a simple definition for Q factor exists:

$$Q = \frac{P_{out}}{S_U} = \frac{V_{out} I_{out}}{V_{oc} I_{sc}}$$

- For a given desired output power, and an induced S_u, the Q factor of the system must be fixed to a certain value
  - If S_U is too low –> Higher Q factor needed – System becomes more sensitive to component tolerances
    - OR P_{out} must be lower for the same Q factor
  - If S_U is too high -> Lower Q factor needed -> overdesigned magnetics
    - OR P_{out} is higher than expected -> system on fire
- **Q factor is limited by: Component sensitivity, Thermal limitations, changes in values due to environmental impacts**



Q factor in an IPT system - Example

- An IPT system has a coupled $S_u = 5\ VA$, the required output power is $50\ W$, what is the Q factor of the system?

- The maximum Q factor that can be achieved is 8, what is the maximum possible output power of the system?

- How is this maximum Q factor determined?

Uncompensated Power

- If a resistive load (R_2), is connected across the secondary coil, a current ($I_2\angle\theta$), will start flowing through the coil

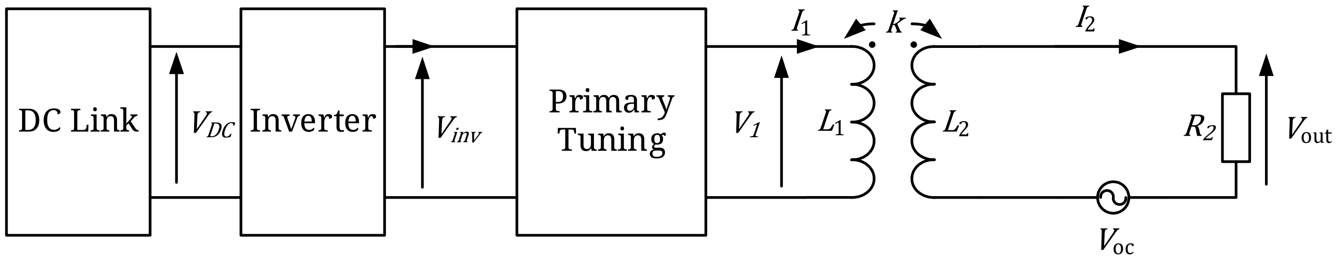
$$I_2 = \frac{V_{oc}}{R_2 + j\omega L_2} = \frac{j\omega M I_1}{R_2 + j\omega L_2}$$

- The output power is therefore

$$P_{out} = |I_2|^2 R_2$$
$$= \frac{|j\omega M I_1|^2}{|R_2 + j\omega L_2|^2} R_2$$
$$P_{out} = \frac{(\omega M I_1)^2}{R_2^2 + \omega L_2^2} R_2$$

Important note:
To find magnitude of a complex vector ($|z|$)

1. $|z| = \sqrt{u\bar{u}}$, where $\bar{u}$ is the complex conjugate of u



Uncompensated Power - Example

- If $V_{oc} = 5\ V_{RMS}$ and $I_{sc} = 1\ A_{RMS}$, determine the maximum power that can be delivered to the load
  - Hint: differentiate P_{out} w.r.t. R_2 using the product rule $(f \cdot g)' = f'g + fg'$ and brush up on other differentiation methods (reciprocal rule/chain rule)
    - Ans: 2.5 W
- Sketch P_{out} with respect to R_2
- What limits the ability of the secondary coil to deliver power?

Uncompensated Power - Summary

- Uncompensated systems have an upper power limit
  - $P_{out,max} = \frac{1}{2} S_u$
  - **Q is limited to 0.5**
- The power transfer is limited by the presence of the inductive load in the system
- Maximum power occurs when $R_2 = |j\omega L_2|$
- How can the system deliver more power?

Series Compensation – Ideal scenario

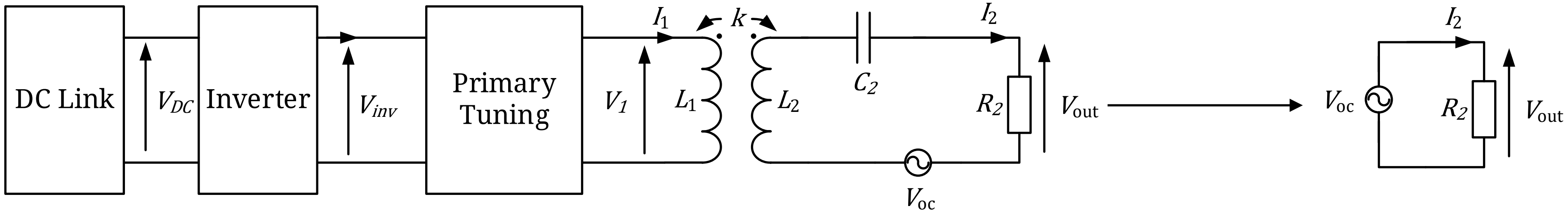
- Power transfer can be improved by compensating (tuning) the inductance, L_2, of the secondary coil, with a capacitor C_2
- C_2 is chosen such that the impedances of the inductor and capacitor cancel each other out at the chosen operating frequency ω

$$j\omega L_2 = -\frac{1}{j\omega C_2} \rightarrow \omega = \frac{1}{\sqrt{L_2 C_2}}$$

- **Assuming:**
  - System is perfectly tuned (impossible in practice)
  - Secondary behaves as an ideal voltage source (given our previous assumptions)

$$V_{out} = V_{oc}\,; I_2 = \frac{V_{oc}}{R_2}$$

$$\therefore P_{out} = \frac{V_{oc}^2}{R_2} = I_2^2 R_2$$



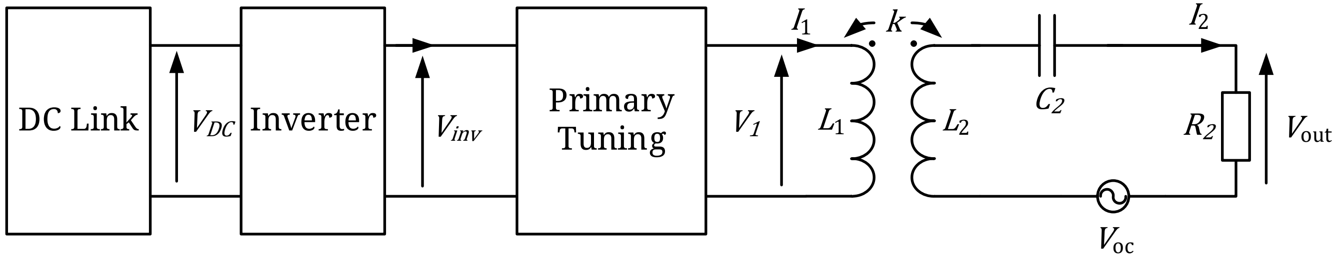
Series Compensation – Ideal scenario example

- Sketch P_{out} of an ideal series compensated secondary system with respect to R_2 given a constant V_{oc}

- An IPT system is designed with a secondary $V_{oc} = 5\ V_{RMS}$ and $I_{sc} = 1\ A_{RMS}$. What is the maximum power that can be delivered to an ideally tuned system?

- Can this be achieved in practice? Why or why not?

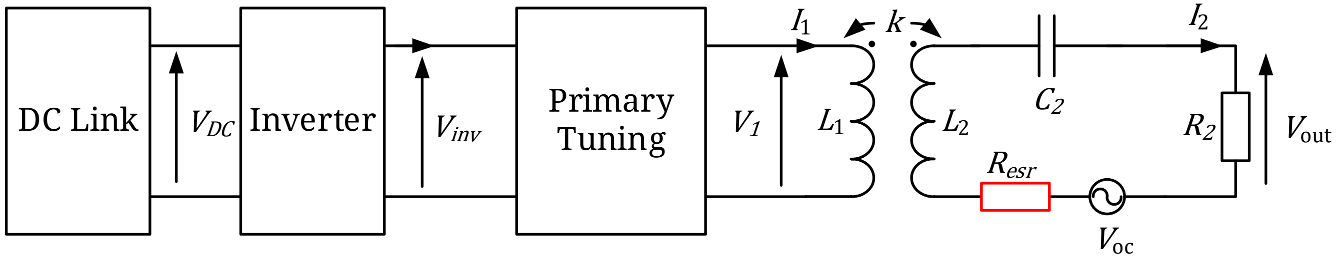
Series Compensation – Ideal scenario



- In an ideal series compensated secondary system:
- $P_{out} = V_{out}I_2 = V_{oc}I_2$, where I_2 is set by the load R_2
- $S_u = V_{oc}I_{sc}$
- $Q = \frac{P_{out}}{S_u} = \frac{V_{oc}I_2}{V_{oc}I_{sc}} = \frac{I_2}{I_{sc}}$
  - In a series tuned system, only the short circuit current is "Q'd up"
- $Q = \frac{V_{out}^2}{R_2}\frac{1}{V_{oc}I_{sc}} = \frac{1}{R_2}\frac{V_{oc}}{I_{sc}} = \frac{\omega L_2}{R_2}$
  - Q is also a function of the coil impedance and load resistance
- System is limited by:
  - V_{oc}: V_{out} cannot be higher than the induced open circuit voltage
  - I_{sc}: A low I_{sc} means the system needs to operate at a high Q for high output powers

Series Compensation – non-ideal case

- $P_{out} = \frac{V_{OC}^2}{R_2} = I_2^2 R_2$, as $R_2 \to 0$, $P_{out} \to \infty$
- Practical coils have an equivalent series resistance associated with the coils (R_{esr})
- I_2 increases as $R_2 \to 0$
  - High I_2 will result in increased losses in the coils
  - Dissipated as heat
- Practical capacitors will also have a tolerance



Series Compensation – non-ideal example

- An IPT system is designed with a series tuned secondary $V_{oc} = 5\ V_{RMS}$ and $I_{sc} = 1\ A_{RMS}$. Determine the maximum power that can be delivered to the load if C_2 is 10% **higher** than the ideal value needed to compensate for L_2. Assume that R_{esr} is negligible.
  - Answer: $P_{out} = 27.5\ W$

- What is the maximum Q of a system with this level of mistuning?

Important note 1:
To find magnitude of a complex vector ($|z|$)
1. $|z| = \sqrt{u\bar{u}}$, where $\bar{u}$ is the complex conjugate of u

Important note 2:
Maximum P_{out} is solved using the same technique as the uncompensated system

Series Compensation – summary

- An ideal series compensated secondary can deliver infinite output power as the load approaches 0
  - Practically limited by thermal constraints
  - Tuning accuracy
  - Consistency of the primary current
- The output voltage of a series tuned secondary can be at best V_{oc}
- The Q factor (maximum output power) of a non-ideally tuned secondary pad is limited by the degree of mistuning

Parallel Compensation – Ideal scenario

- Power Transfer can be improved by compensating the inductance, L_2, of the secondary coil, with a parallel capacitor C_2
- C_2 is chosen such that the impedances of the inductor and capacitor cancel each other out at the chosen operating frequency ω

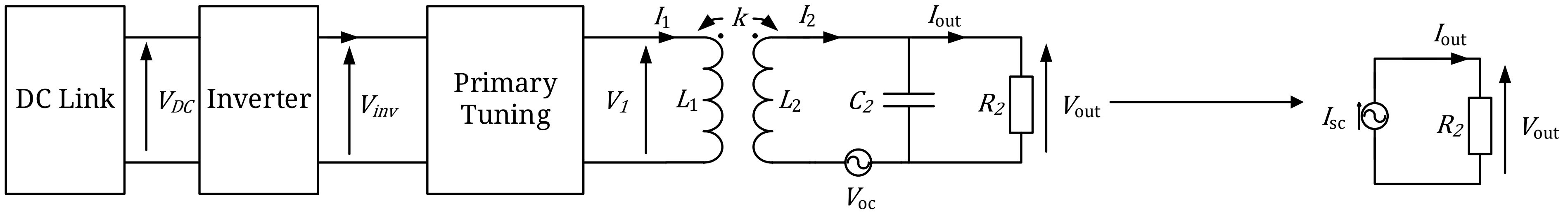
$$j\omega L_2 = -\frac{1}{j\omega C_2} \rightarrow \omega = \frac{1}{\sqrt{L_2 C_2}}$$

- **Assuming:**
  - System is perfectly tuned (impossible in practice)
  - Secondary behaves as an ideal current source (Norton equivalent)

$$I_{out} = I_{sc}\,; V_{out} = I_{sc} R_2$$

$$\therefore P_{out} = \frac{V_{out}^2}{R_2} = I_{sc}^2 R_2$$

  - Note that I_2 and I_{out} are different (unlike the series and uncompensated systems)



Parallel Compensation – Ideal scenario example

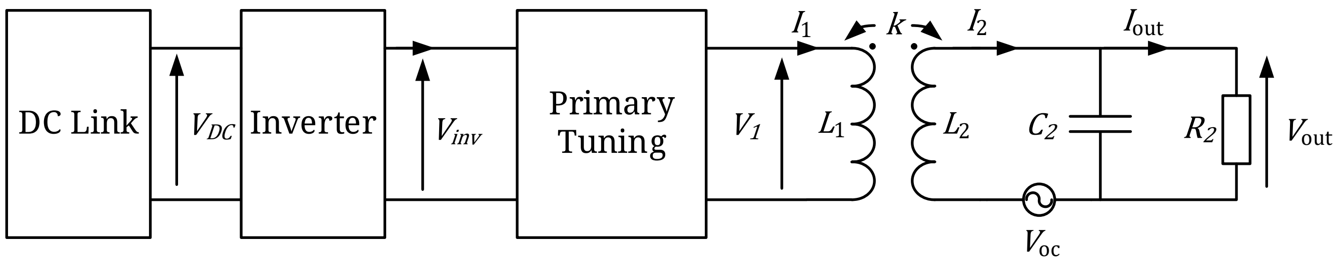
- Sketch P_{out} of an ideal parallel compensated secondary system with respect to R_2 given a constant I_{sc}

- An IPT system is designed with a secondary $V_{oc} = 5\ V_{RMS}$ and $I_{sc} = 1\ A_{RMS}$. What is the maximum power that can be delivered to an ideally tuned system?

- Can this be achieved in practice? Why or why not?

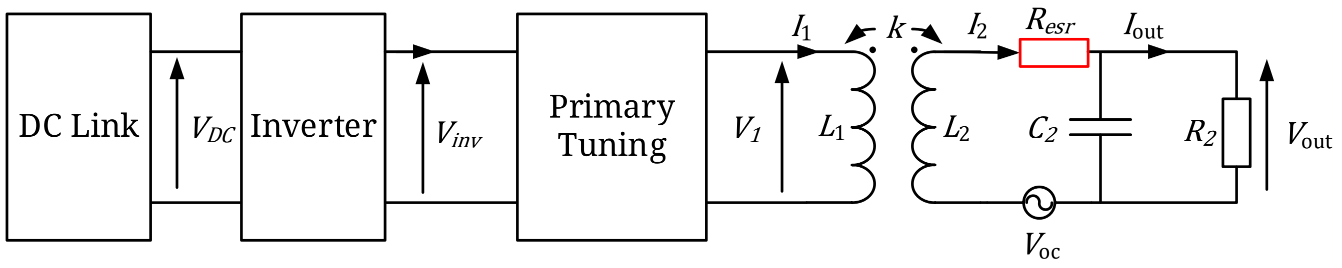
Parallel Compensation – Ideal scenario

- In an ideal parallel compensated secondary system:
- $P_{out} = V_{out} I_{out} = V_{out} I_{sc}$, where V_{out} is set by the load R_2
- $S_u = V_{oc} I_{sc}$
- $Q = \frac{P_{out}}{S_u} = \frac{V_{out} I_{sc}}{V_{oc} I_{sc}} = \frac{V_{out}}{V_{oc}}$
  - Only the output voltage is "Q'd up"
- $Q = \frac{I_{sc}^2 R_2}{V_{oc} I_{sc}} = \frac{R_2}{\omega L_2}$
- System is limited by:
  - V_{oc}: A low V_{oc} means that the system needs to operate at a high Q for higher output powers
    - System can become more sensitive. How?
  - I_{sc}: The output current cannot be higher than I_{sc}



Parallel Compensation – non-ideal case

- $P_{out} = I_{sc}^2 R_2$, as $R_2 \to \infty$, $P_{out} \to \infty$ for an ideal case
- Practical coils have an equivalent series resistance associated with the coils (R_{esr})
    - As do practical capacitors and tracks (not included in the diagram below)
- I_2 increases as $R_2 \to \infty$
    - $I_2 = \frac{V_{out}}{j\omega L_2} = \frac{I_{sc} R_2}{j\omega L_2}$
    - High I_2 will result in increased losses in the coils
    - Dissipated as heat - $I_2^2 R_{esr}$
- C_2 also has a tolerance due to practical manufacturing processes



Parallel Compensation – non-ideal example

- An IPT system is designed with a parallel tuned secondary $V_{oc} = 5\ V_{RMS}$ and $I_{sc} = 1\ A_{RMS}$. Determine the maximum power that can be delivered to the load if C_2 is 10% **lower** than the ideal value needed to compensate for L_2. Assume that R_{esr} is negligible.

- Answer: $P_{out,max} = 27.5\ W$

- What is the maximum Q that a parallel tuned circuit with a 10% mistuning be?

Parallel Compensation – summary

- An ideal series compensated secondary can deliver infinite output power as the load approaches infinity
  - Practically limited by thermal constraints
  - Tuning accuracy
  - Consistency of the primary current
- The output voltage of a series tuned secondary can be at best I_{sc}
- The Q factor (maximum output power) of a non-ideally tuned secondary pad is limited by the degree of mistuning

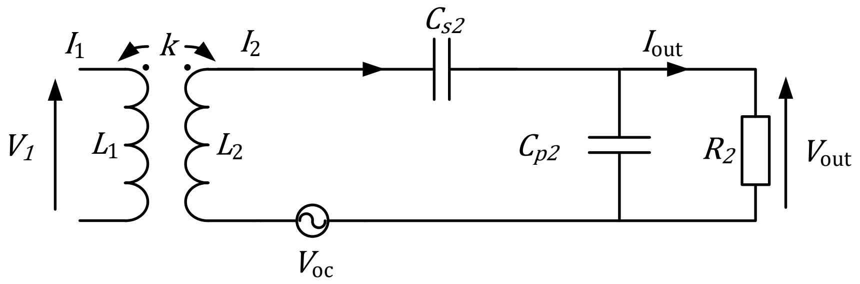
Comparison of series and parallel tuning

- What's the difference. Why choose series or parallel?
- In previous examples, V_{oc} and I_{sc} are given. In practice, you are given a secondary pad inductance
  - V_{oc} will vary based on position
  - I_{sc} will vary based on the inductance of the coil and the position
- Output is limited by the type of tuning chosen
  - Series tuning limits output voltage
  - Parallel tuning limits output current
- 10% tolerances are practically improbable in a real system
- What can you do if the system cannot meet your specifications?

Partial series-parallel compensation

- Practical systems will always have some physical constraints
  - Coupling factor may be limited
  - Inductance must be a minimum/maximum value
  - System may have voltage/current ratings
  - Magnetics are difficult to wind as opposed to capacitor boards being populated (you will find out personally)
- Practical systems will always have some minimum requirements
  - Voltage output
  - Current output

- Partial series parallel tuning can be used to meet output current requirements



Partial series-parallel compensation

- The secondary inductance L_2 is *partially* compensated by a series capacitance C_{s2}.
- This boosts the short circuit current by a factor relative to the amount of partial compensation

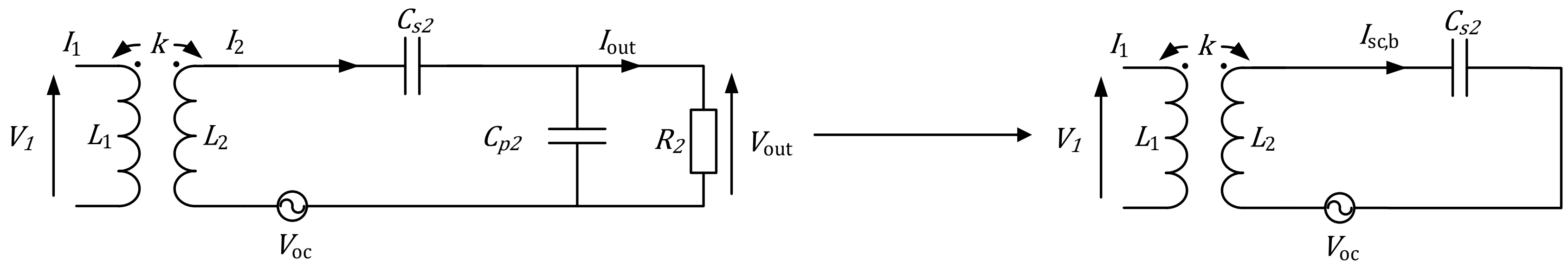
$$I_{sc,b} = \frac{V_{oc}}{j\omega L_2 + \frac{1}{j\omega C_{s2}}}$$

- The secondary pad branch has an effective inductance (L_{2b})

$$L_{2b} = \frac{j\omega L_2 - j\frac{1}{\omega C_{s2}}}{j\omega} = L_2 - \frac{1}{\omega^2 C_{s2}}$$

- In the partial series – parallel tuning case, C_{p2} needs to be tuned to the effective inductance!

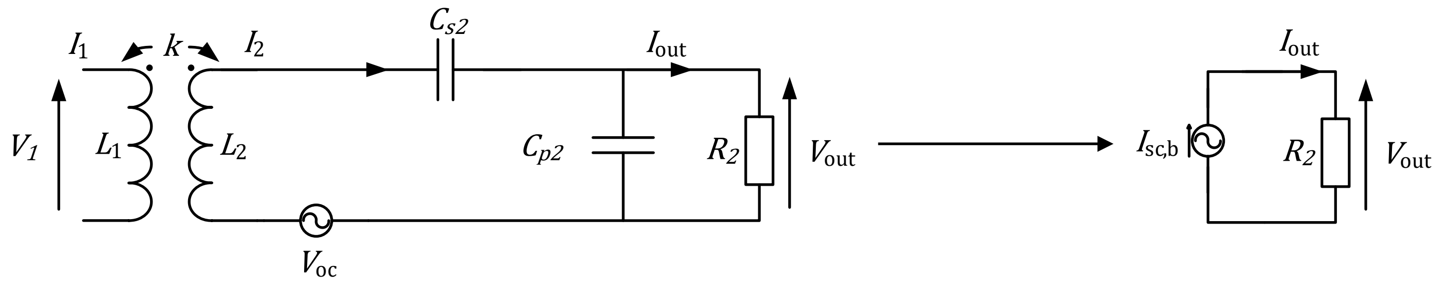
$$j\omega L_{2b} = \frac{1}{j\omega C_{p2}} \rightarrow \omega = \frac{1}{\sqrt{L_{2b} C_{p2}}}$$



Partial series-parallel compensation

- If all the components are perfectly tuned then the output current I_{out} is equal to the new boosted short circuit current $I_{sc,b}$

$$I_{out} = \frac{V_{oc}}{j\omega L_{2b}} \rightarrow P_{out} = |I_{out}|^2 R_2 = \left|I_{sc,b}\right|^2 R_2$$
$$V_{out} = I_{sc,b}\, R_2$$
$$P_{out} = I_{sc,b}^2 R_2$$



Partial series-parallel compensation example

- An IPT system is designed with a parallel tuned secondary $V_{oc} = 5\ V_{RMS}$ and $I_{sc} = 1\ A_{RMS}$. The system is partially series-parallel tuned with a load of 5Ω. Determine the capacitances required for the series capacitor and the parallel capacitor if there the desired output power is 10 W.
  1. Calculate L_2 using V_{oc} and I_{sc}
  2. Determine desired output current by rearranging $P_{out} = I_{sc,b}^2 R_2$
  3. Back calculate for capacitor values using $I_{sc,b} = \frac{V_{oc}}{j\omega L_2 + \frac{1}{j\omega C_{s2}}}$ and $\omega = \frac{1}{\sqrt{L_{2b} C_{p2}}}$

Partial series-parallel compensation

- Useful because now the output power can be modified without altering the magnetic design
- Achieves this without using any more capacitors
  - No extra cost

- However
  - More connection points have more points of failure
  - System operates at a higher Q, need better components
- Other ways to boost output power include:
  - Increasing primary current I_1
    - Adds cost as larger primary windings are needed
    - System efficiency decreases due to increases I^2R losses
  - Better magnetic designs
    - Design coils to have higher coupling
    - Design coils to have lower change in coupling over the misalignment range
    - Can lower cost, but needs lots more effort

Summary

- Basic structure of an IPT system and important design parameters
    - k (coupling factor)
    - Q (Q factor)
    - V_{oc} (Open circuit voltage)
    - I_{sc} (Short circuit current)
- Different compensation topologies
    - Uncompensated – Max Q = 0.5
    - Series compensated
        - Ideal and non ideal cases
    - Parallel compensated
        - Ideal and non ideal cases
- Boosting output power
    - Partial series parallel
    - Other methods
- Practical limitations of power transfer in IPT systems