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Inductive Power Transfer in the MHz ISM bands:

Drones without batteries

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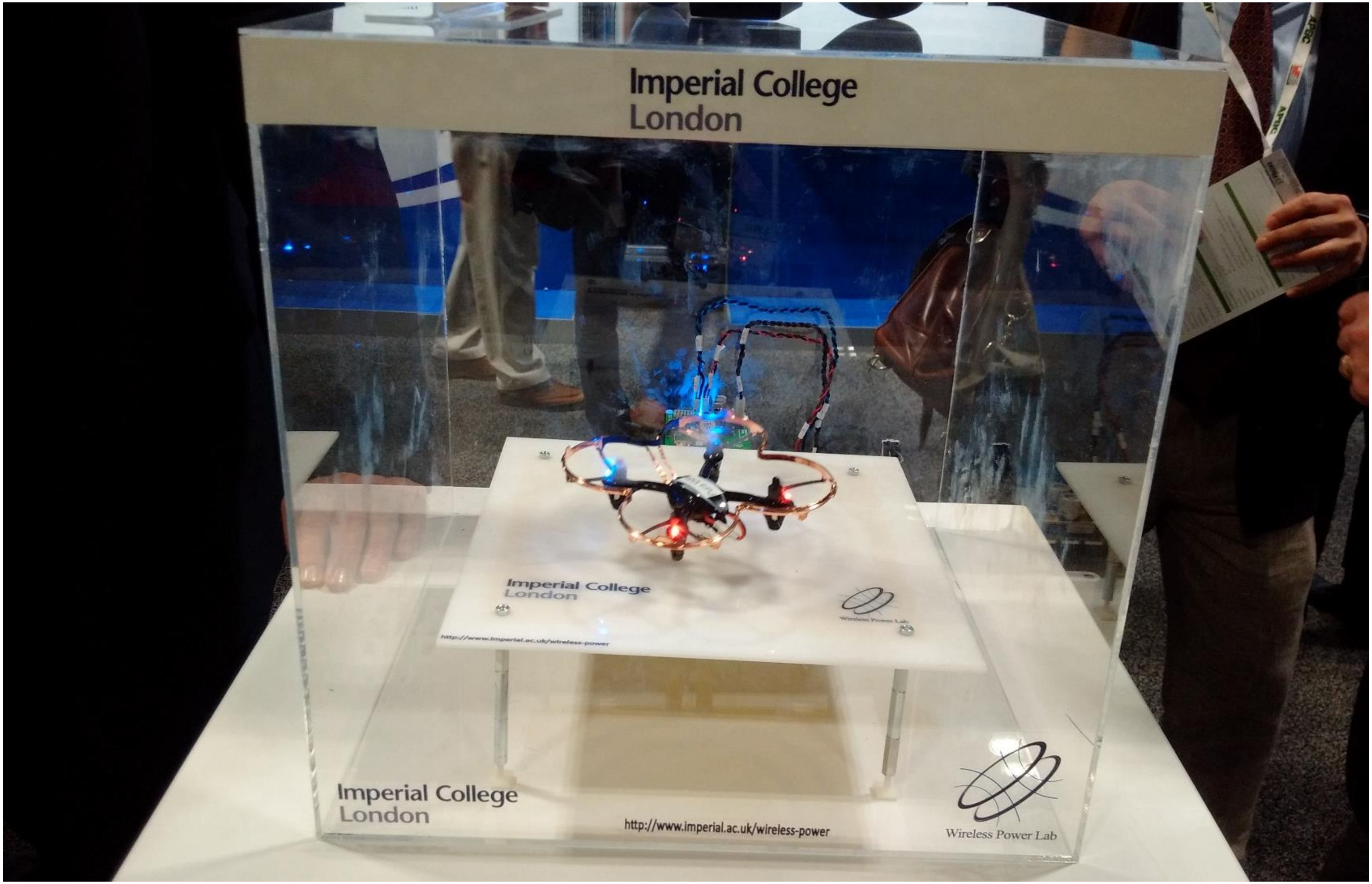
EH2017, Manchester

The Concept



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Challenges for Drone Charging

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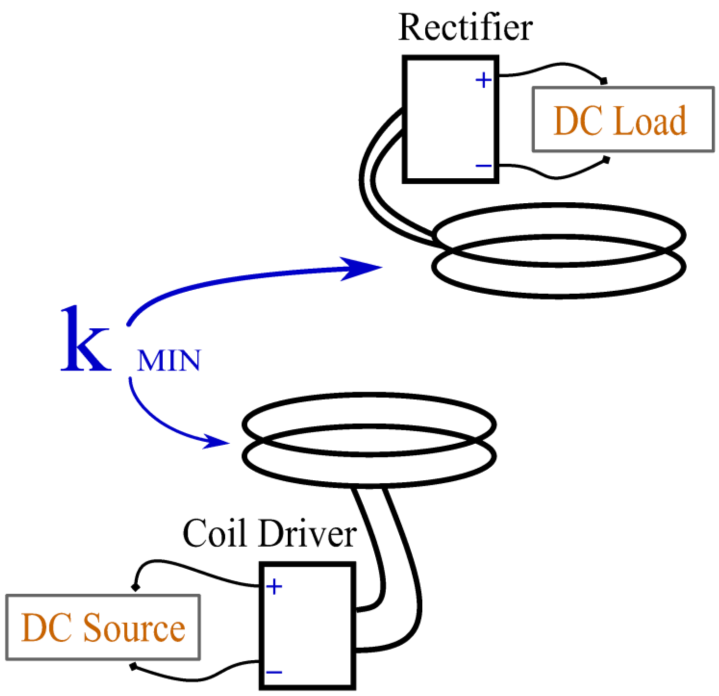


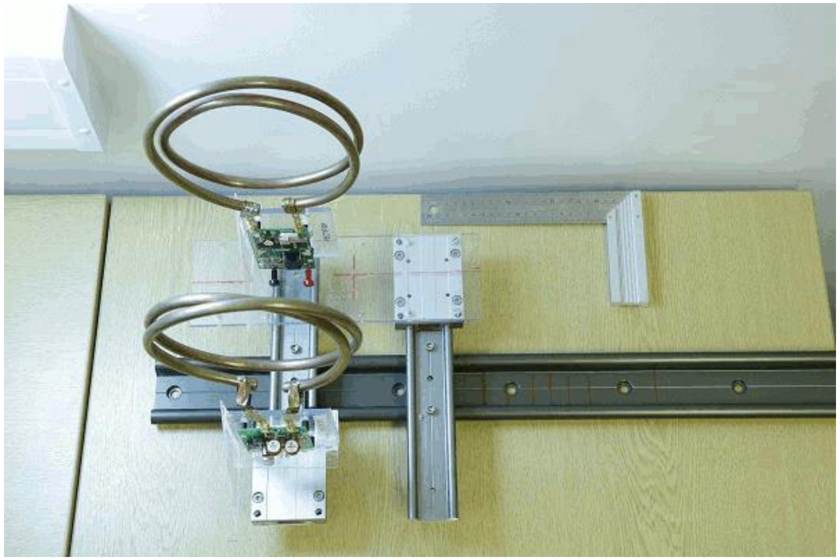
Dynamic system challenges:

1. Light weight system
2. High link efficiency capability independent of k
3. Optimal reflected load with varying k
4. High efficiency of the inverter and rectifier with varying k and varying power throughput

Overview

- Light weight system and high link efficiency capability independent of k
- Optimal reflected load with varying k
- High efficiency of the inverter and rectifier with varying k and varying power throughput
- Demo video
- Conclusions

Light Weight and Link Efficiency Capability



Commercial systems: Automotive and phones

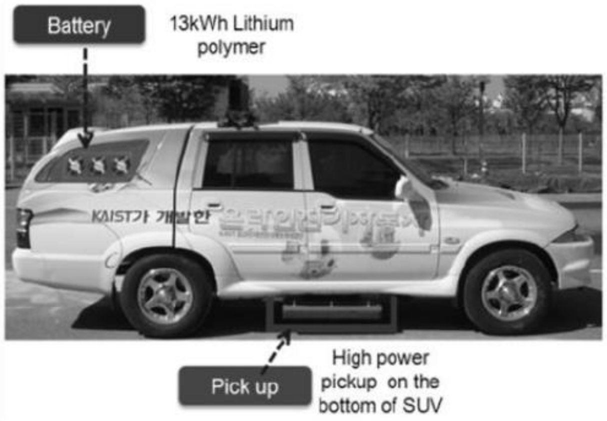
Most use ferrite to enhance coupling: too heavy

Witricity EV charger

- RX ~10 kg, TX ~30 kg, 85 kHz

Qualcomm Halo

- 20 kW, 20 kg, 20kHz

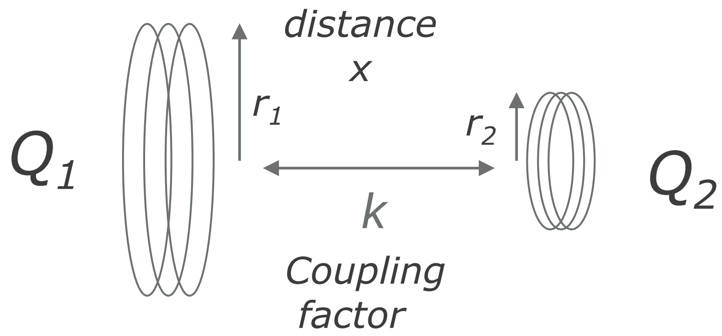


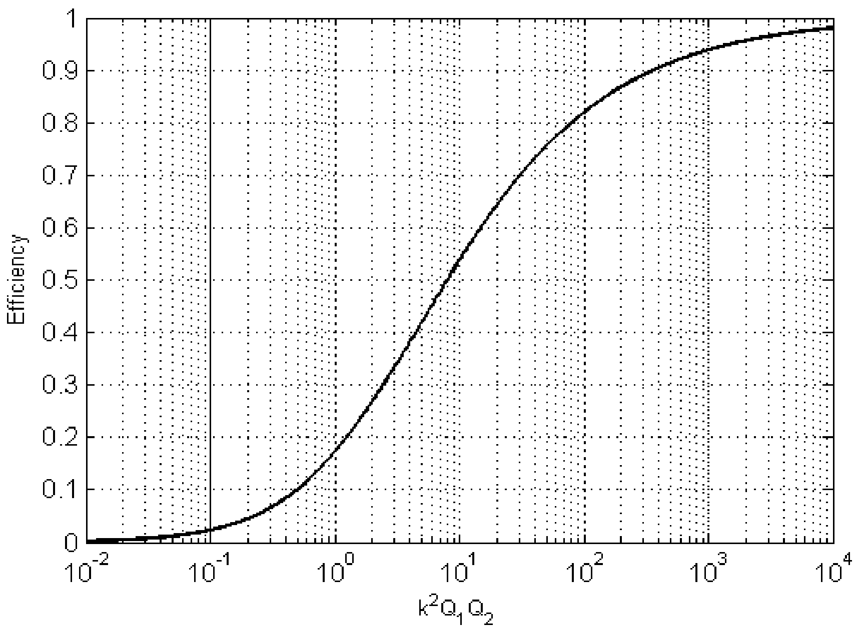
- Qi standard very short range
- Limited power levels

Reliance on High Q, not high k

Efficiency given by: $$\eta = \frac{k^2 Q_1 Q_2}{\left(1+\sqrt{1+k^2 Q_1 Q_2}\right)^2}$$

Secondary resonance
Optimal load





Need to maximise $k^2Q_1Q_2$

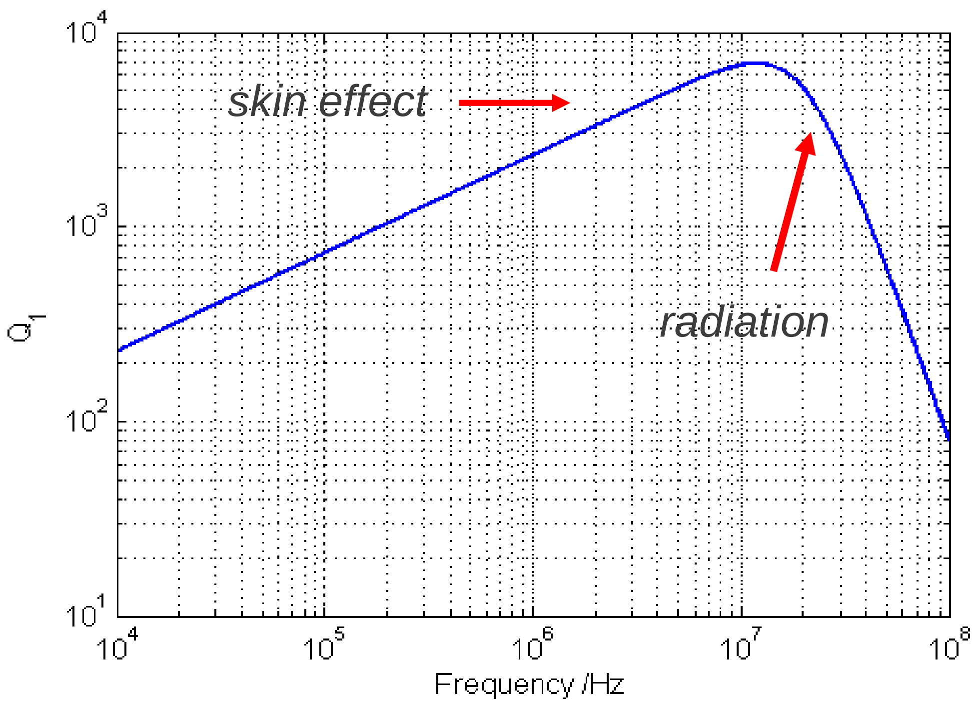
$k^2Q_1Q_2 > 10$ for $\eta > 50\%$

$k^2Q_1Q_2 > 350$ for $\eta > 90\%$

High Frequency is Key

Efficiency given by: $$\eta = \frac{k^2 Q_1 Q_2}{\left(1+\sqrt{1+k^2 Q_1 Q_2}\right)^2}$$

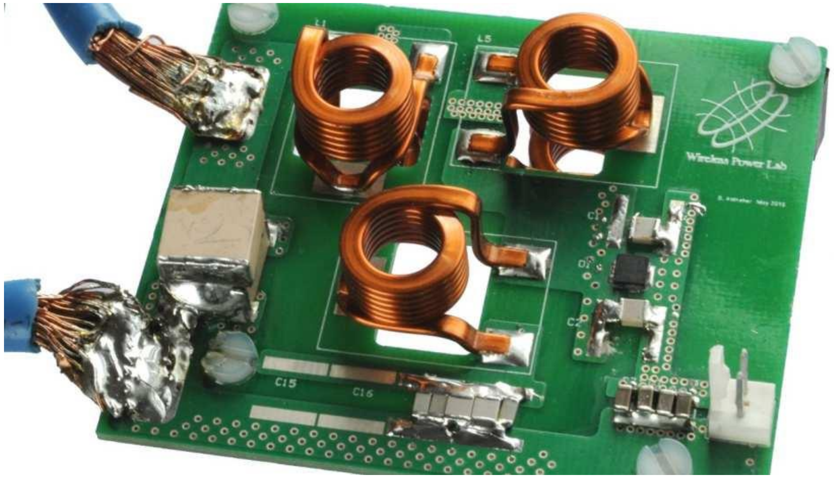
Secondary resonance
Optimal load



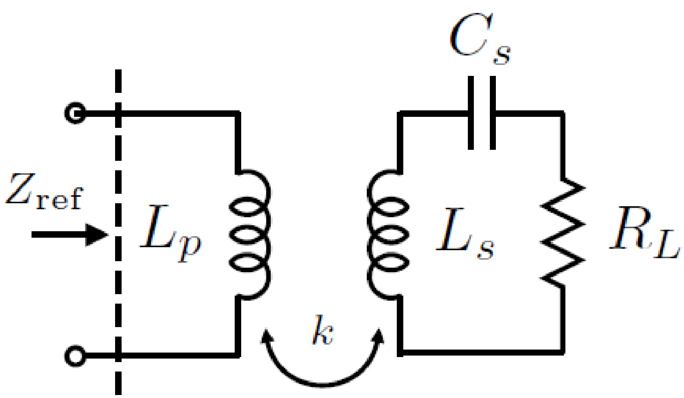
- High frequency (MHz) allows high Q
- High frequency allows removal of ferrite
- Skin effect allows very thin conductors

Light weight and varying k capability are possible with high frequency, high Q coils

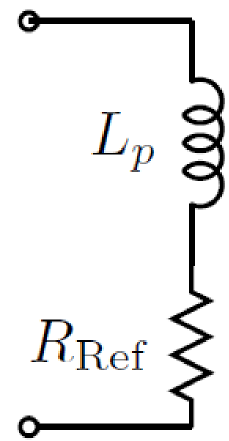
Optimal Reflected Load



Inductive Link Properties – varying R_L and varying k



(a) ideal circuit representation



(b) equivalent circuit

$$Z_{ref} = \frac{\omega^2 M^2}{R_L + jX_{Ls} - jX_{Cs}}$$

$$Z_{ref} = R_{ref} = \frac{\omega^2 M^2}{R_L}$$

- Purely real across all values of values of R_L and k with secondary resonance.
- Reflected reactance
  - Cause detuning of inverter – and transmit current rapidly drops
  - Inefficient to transfer reactive power across link

Not true for parallel secondary resonance: hence we choose series compensation

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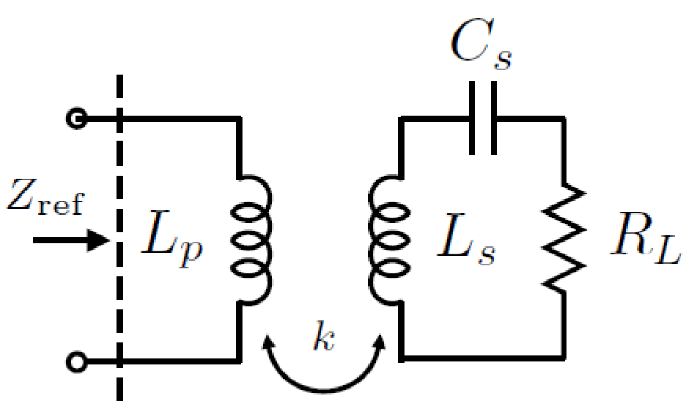
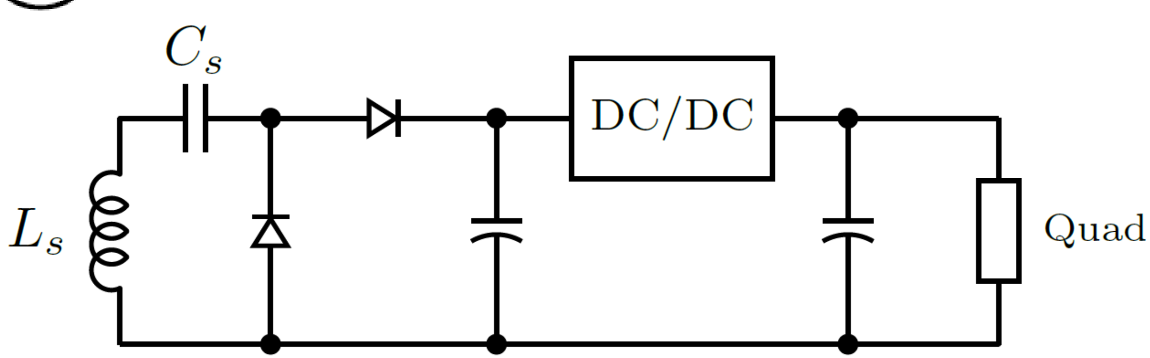
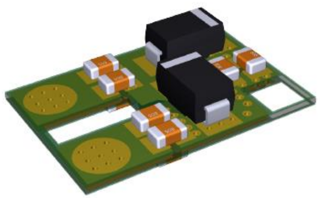
Rectifier's effect on reflected load

- The previous analysis is only valid if the rectifier has resistive input impedance.



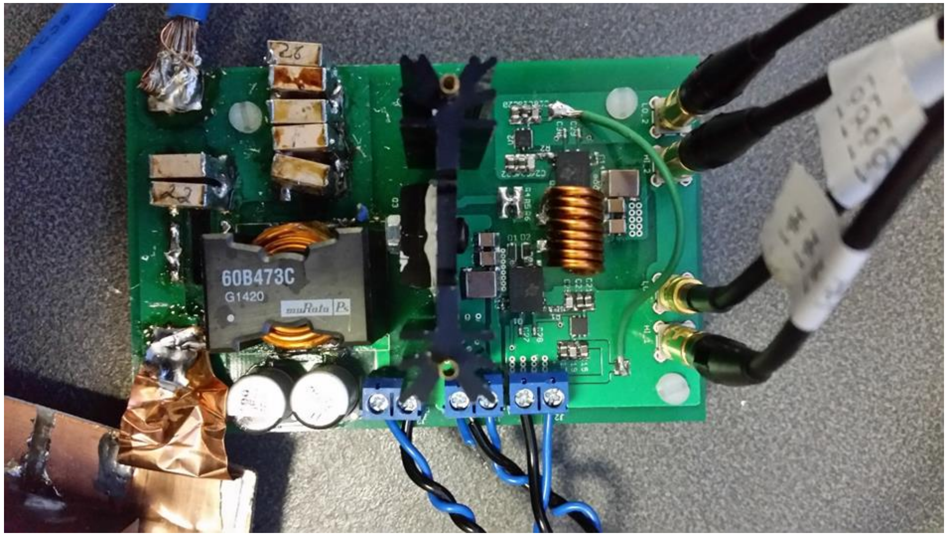
- The class-D rectifier is current source driven (suitable for a series tuned secondary)
- The class-D rectifier presents a purely real load on the series tuned circuit, independent of its DC load





"sim card" rectifier

High Efficiency with Varying *k* and R



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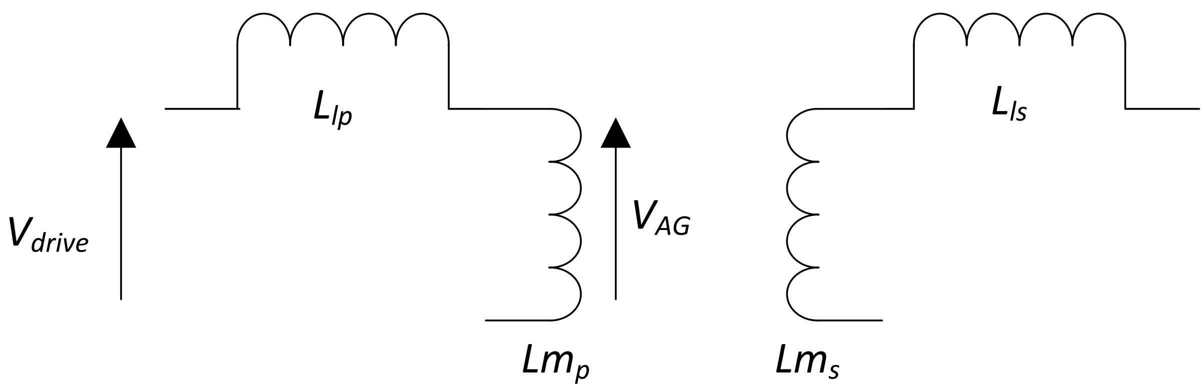
Requirements to drive the link

- Poor power factor unless leakage inductances are resonated out – because coupling factor typically < 10%
- Only a fraction of the applied voltage is seen at air gap voltage



- Traditional to resonate out primary inductance to reduce VA rating of drive circuit

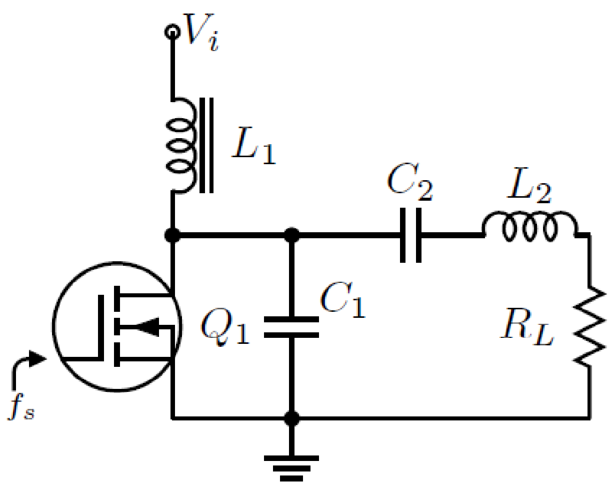
Common misconception: poor coupling factor = poor efficiency

Inverters

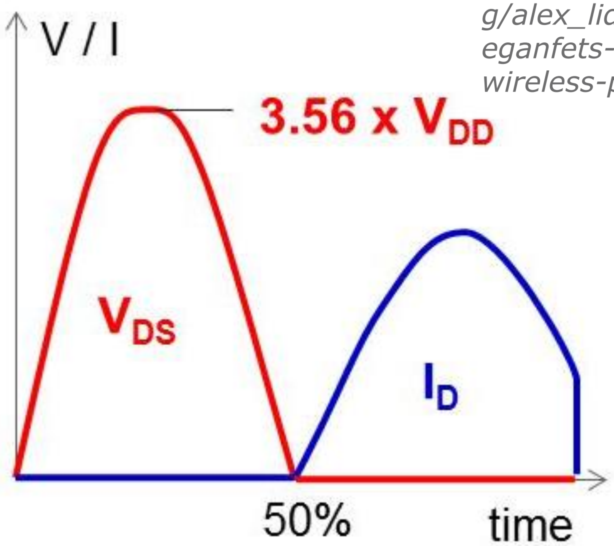
- Conventional hard-switching not suitable in MHz region
  - Device switching times become comparable to driving signal period
  - Can be inefficient at higher frequencies
- Soft switching inverters (eg ZVS Class-D and Class-E) employ zero-voltage switching to minimise power dissipation
- Class-D inverters: popular with low-power systems adhering to Qi or A4WP standards
  - Lower normalised output power compared to Class-E
  - Require floating gate drive
  - But can operate over larger load range with ZVS if the switching frequency is below resonant frequency of output load network.

Class E

- Standard Class E circuit allows soft switching, and has only 1 switch, which is low side referenced. For this to be true, the load network is slightly inductive
- In this circuit, the load resistor is connected via an LC series circuit (operating slightly above the resonant frequency to present an inductive load) so that a square wave gate signal presents an almost pure sine wave voltage across the load

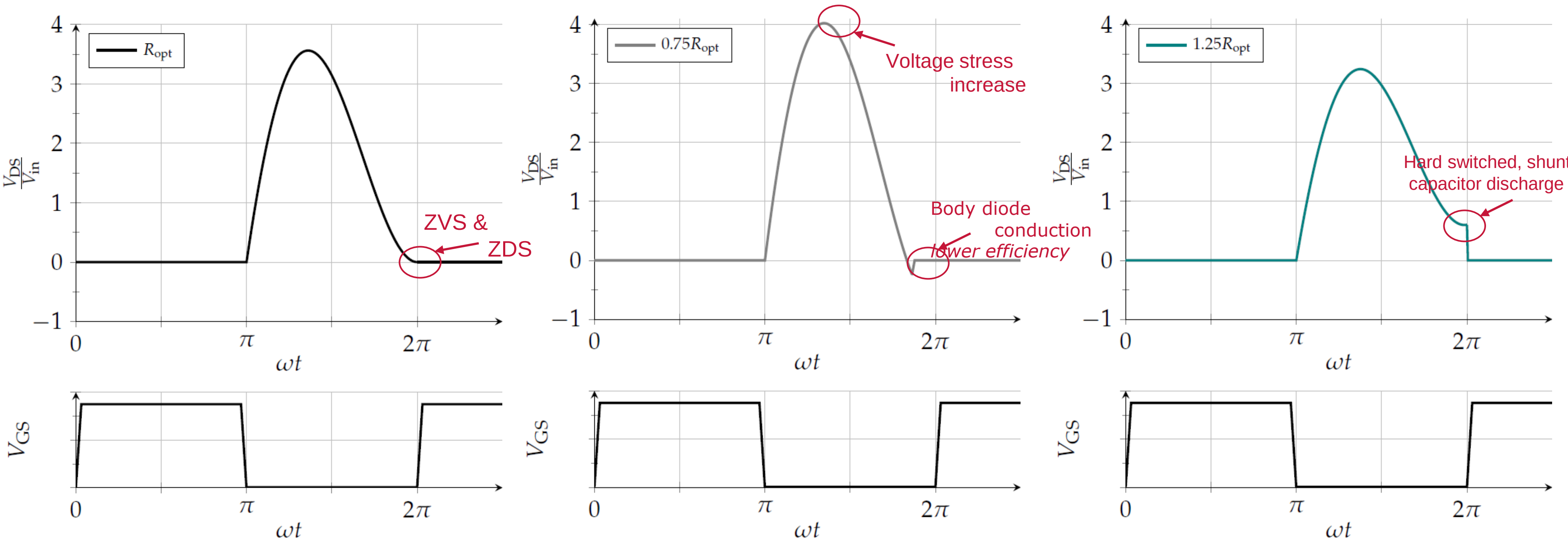


Graph from https://www.eeweb.com/blog/alex_lidow/how-to-gan-eganfets-for-high-frequency-wireless-power-transfer



Class E switching waveforms

Class E switching waveforms



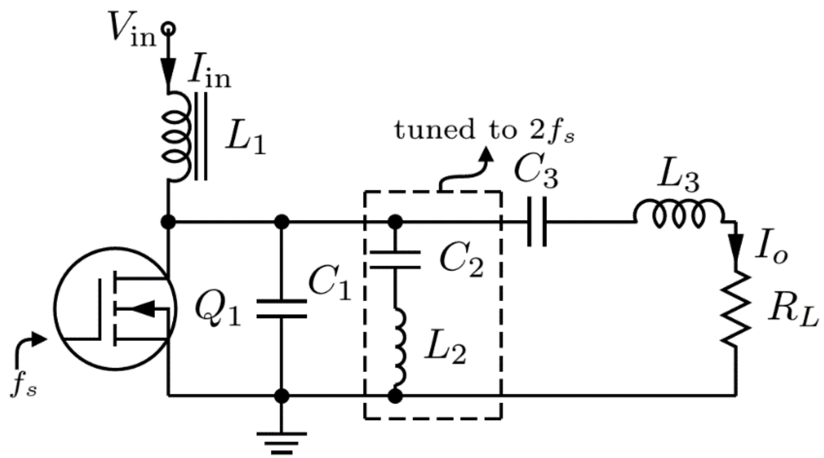
Optimum switching	Suboptimum switching	Non-optimum switching
$R_L = R_{opt}$	$R_L < R_{opt}$	$R_L > R_{opt}$

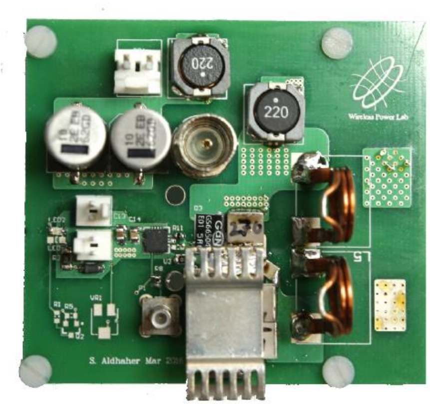
- Optimum switching operation is lost once the load shifts from its optimum value
- Voltages and current can be quite large

Load Independent Class EF Inverters

Class-EF_2 and Class-E/F_3 inverters

- Although Class-E inverters can achieve ZVS and ZCS, their voltage and current stresses can be large
- Adding series LC resonant network in parallel with MOSFET of Class-E inverter can reduce voltage and current stresses
  - Improved efficiency of inverter
  - Greater than twice the power handling
- Traditional to added network tuned to either 2nd harmonic (Class-EF_2) or 3rd harmonic (Class-E/F_3) of switching frequency
- However, tuning to around 1.5 times the resonant frequency allow load independent operation to be achieved





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Load-independent Class EF inverter

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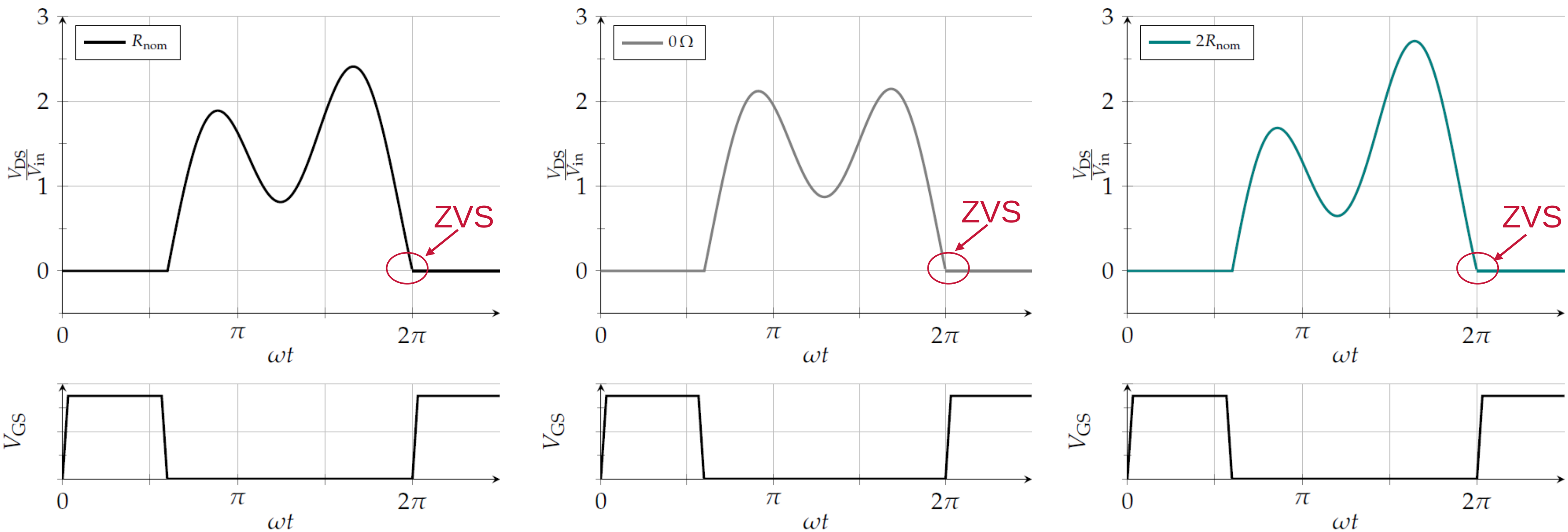
Tune the network to around 1.5 times the driving frequency



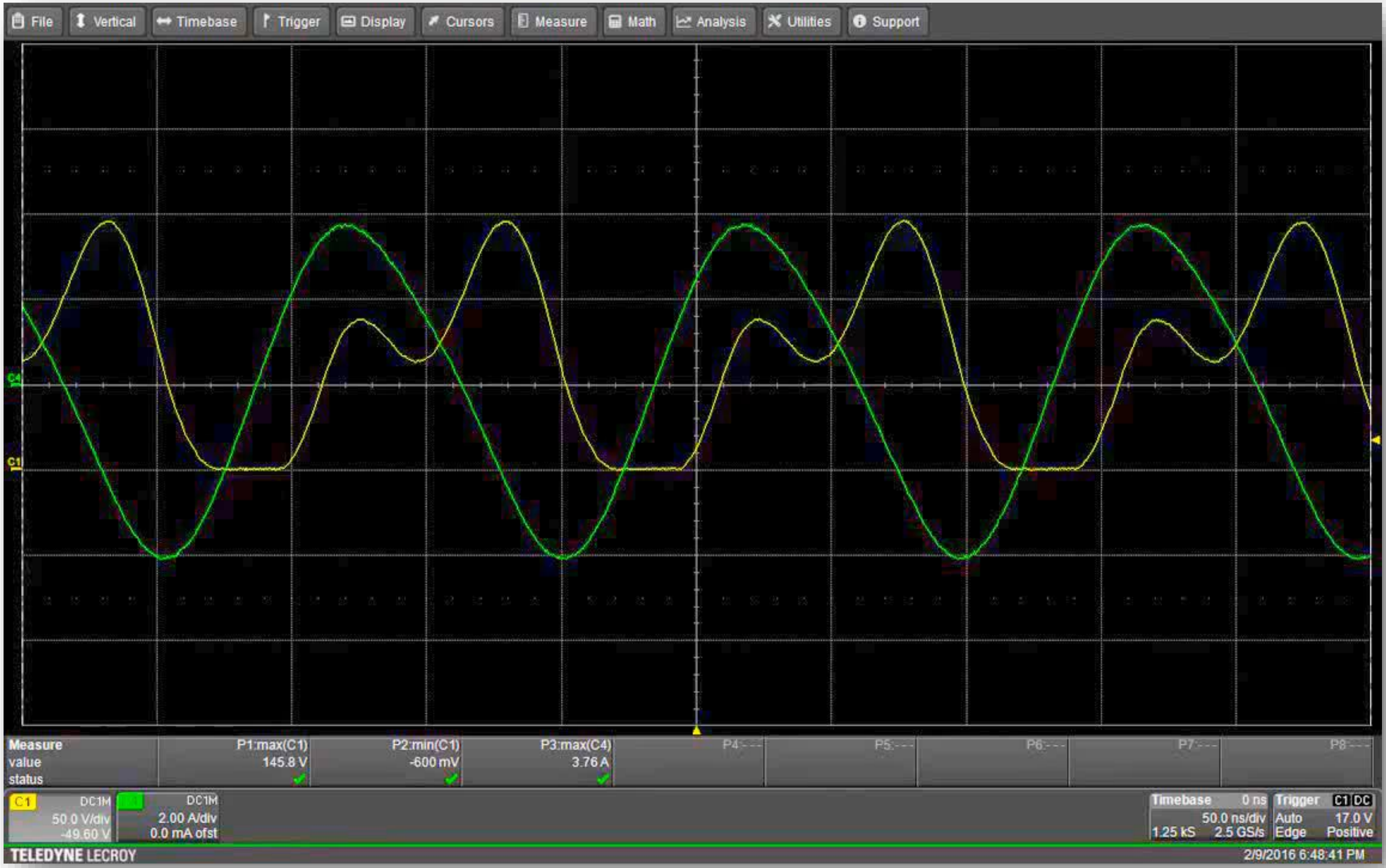
ZVS switching
$R_L = R_{nom}$

ZVS switching
$R_L = 0$ (short circuit)

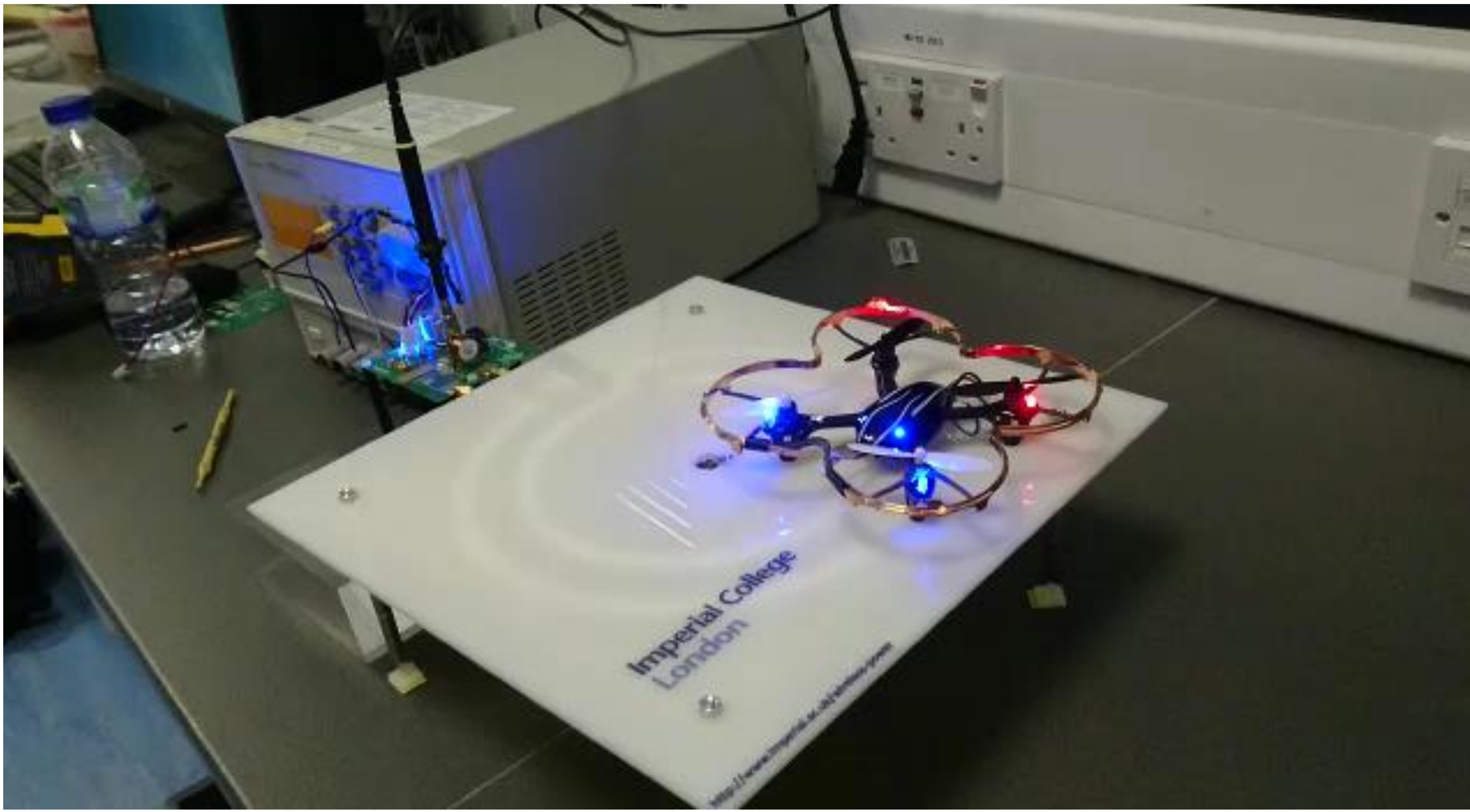
ZVS switching
RL=2Rnom

ZVS operation is maintained over a wide load range

Load-independent Operation with Constant Current



It Flies! Batteries NOT included!



Conclusions

- Flying a drone via IPT is difficult because
  - Light weight
  - Rapidly varying load
  - Rapidly varying k
- Use series tuning to reflect a purely real load to the primary via use of a class D rectifier, or a class E with minimal input reactance change
- The load independent inverter can achieve zero voltage switching as k changes and as demand power changes
- The rectifier is constructed on a PCB around the size of a standard sim card
- The transmitter uses Gallium Nitride FETs to allow efficient operation

A century after Tesla – we can operate at much higher frequencies with high efficiency drive circuits and this gives us high Q, light-weight systems with low reliance on k

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Acknowledgements

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