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Inverter and Rectifier Design for Inductive Power Transfer

COST WIPE Summer School, Bologna, April 2016

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How did my group get interested and what is IPT?

A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, ‘Wireless Power Transfer via Strongly Coupled Magnetic Resonances’, Science, vol. 317, no. 5834, pp. 83–86, Jul. 2007.

Overview

- The magnetic link
  - Link theory
  - Optimisation
- Primary side drive circuits
  - Traditional power electronics topologies
  - High frequency topologies
- Rectifiers
  - Optimal link loading
- Long range IPT for IOT
- Regulations
- Conclusions

Existing High Power Systems

SUV equipped with the 3rd generation of OLEV ultra slim W-type:17 kW, 71% efficiency at 17 cm air gap, 110 kg (from KAIST)

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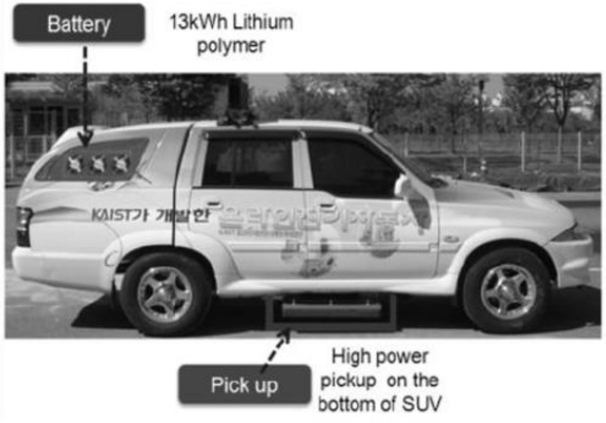


Sungwoo Lee et al, "On-Line Electric Vehicle using inductive power transfer system," IEEE Energy Conversion Congress and Exposition, 2010

Witricity EV charger

- 145 kHz, 3.3 kW, 12.5 kg RX, 90% peak efficiency, 10-20 cm range
- Licensing deal with Toyota, 2013

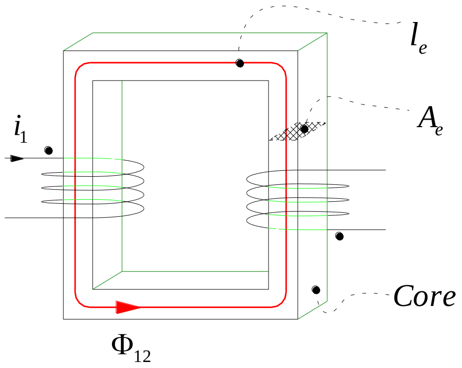
Qualcomm Halo

- 20 kW, 20 kg, 20kHz

The Inductive Link

Transformer

In a regular transformer, the iron core on which the coils are wound allows almost all of the flux generated by current in one coil to flow to the other.



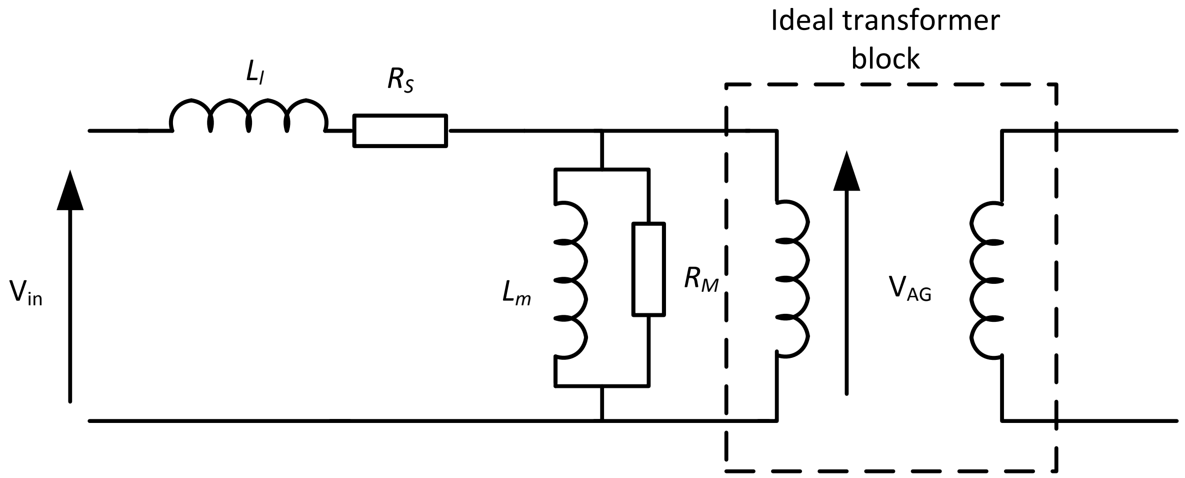
We define a coupling factor, *k*, as the faction of flux from one coil that links with the other coil:

$$k = \frac{\Phi_{12}}{\Phi_1}$$

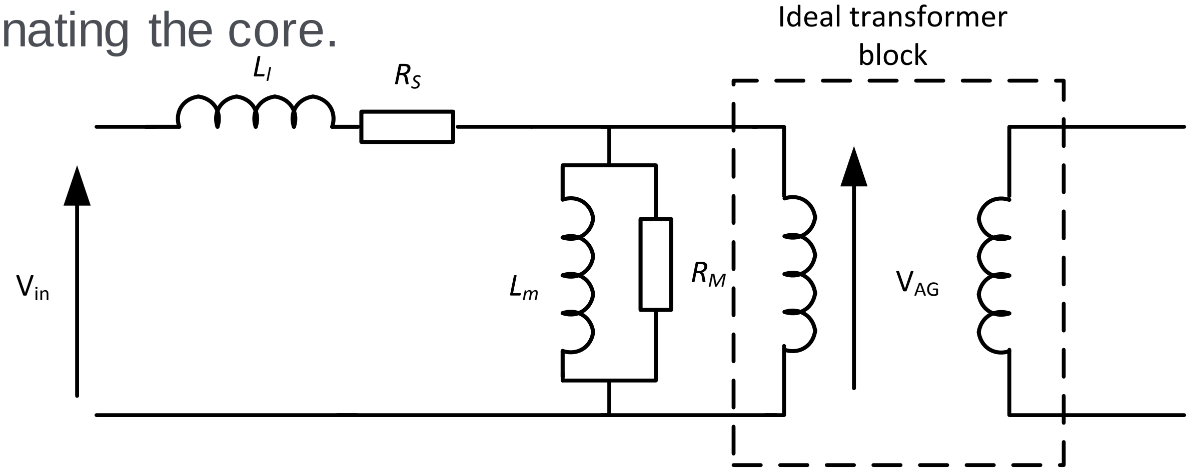
$$k = \frac{M_{12}}{\sqrt{L_1 L_2}}$$

Transformer (2)

- In a transformer, *k* is very high, typically 0.99.
- This means that transfer of energy between the coils is relatively simple - a current induced in the primary induces a current in the secondary.
- As long as the copper wires are thick enough that there are minimal copper losses and as long as the transformer core does not have too much hysteresis loss, the efficiency of the transformer can be very high (99% being typical).



- For large coupling factors, the leakage inductance L_l is low,
- Magnetising inductance tends to be high when the iron core is present.
- For a low primary winding resistance, R_p, almost all of the voltage appears across the air gap, as V_{AG}.
- Little of the primary current flows through the magnetising inductance as this is a large inductor.
- Consequently, almost all of the input power to the non-ideal transformer reaches the air gap.
- The losses due to core magnetisation (modelled as R_M) can be kept low by laminating the core.



Can be 99% efficient

What if we remove the iron core?

For mobility, we remove the core. This has some bad consequences:

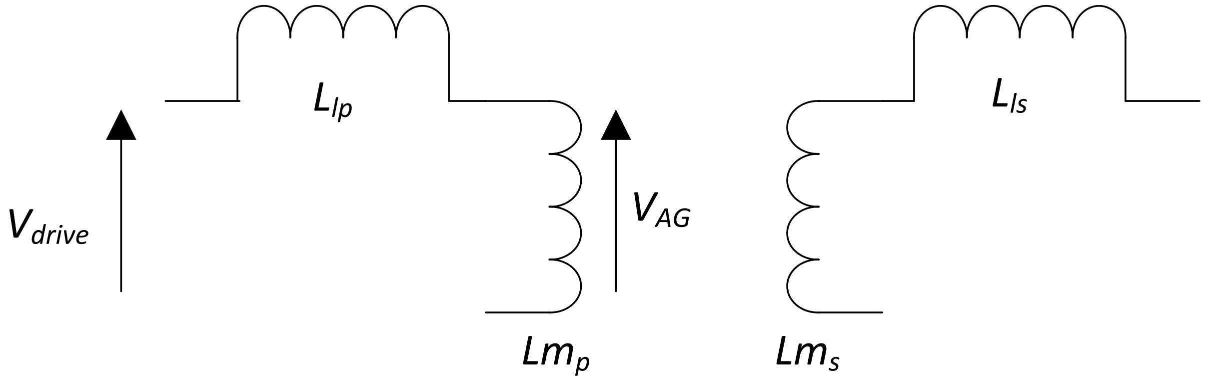
- The leakage inductance becomes larger than the magnetising inductance (as the flux does not link very well with the secondary)
- The magnetising inductance falls dramatically (because the magnetic permeability of air is over 1000 times less than iron).

- This is bad for the system efficiency. If $L_l >> L_m$, most of the applied voltage is dropped across L_l and does not reach the air gap, so cannot reach the secondary.
- In addition, the generally low values of L_l and L_m (due to the removal of the iron) cause big reactive currents to flow, which cause losses in the winding series resistance, R_s.

How can we make the system efficient and easy to drive, whilst keeping an air core? There are several things…

Link Physics Summary

- 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

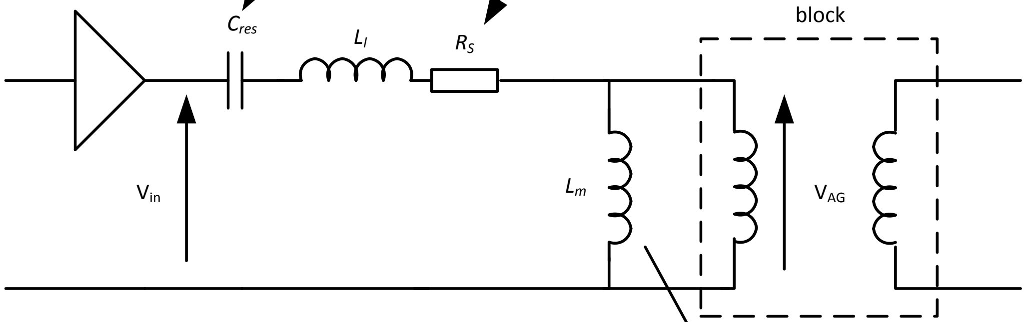


- Traditional to resonate out on both primary and secondary leakages to reduce VA rating of drive circuit and stop reactive power transfer between primary and secondary sides

Common misconception: poor coupling = poor efficiency

Improving Performance without a core

- Make the winding resistance as low as possible, to reduce losses due to real and imaginary currents
- Avoid radiation (this is not an antenna – the coupling is only magnetic) by making the primary coil electrically small.
- Add a capacitor in series between the drive circuit and the primary side, to reduce the voltage output requirements of the primary side drive circuit.
- The magnetising resistance goes open circuit as air, unlike iron, has virtually no magnetisation loss.



Reduces the required driver output voltage

Make as small as possible

Ideal transformer block

For an air core the magnetising resistance is an open circuit (no loss)

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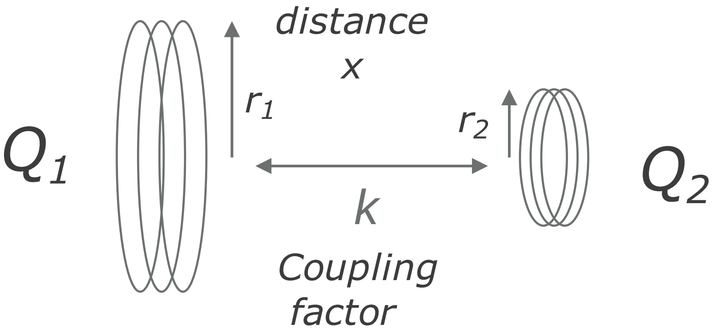
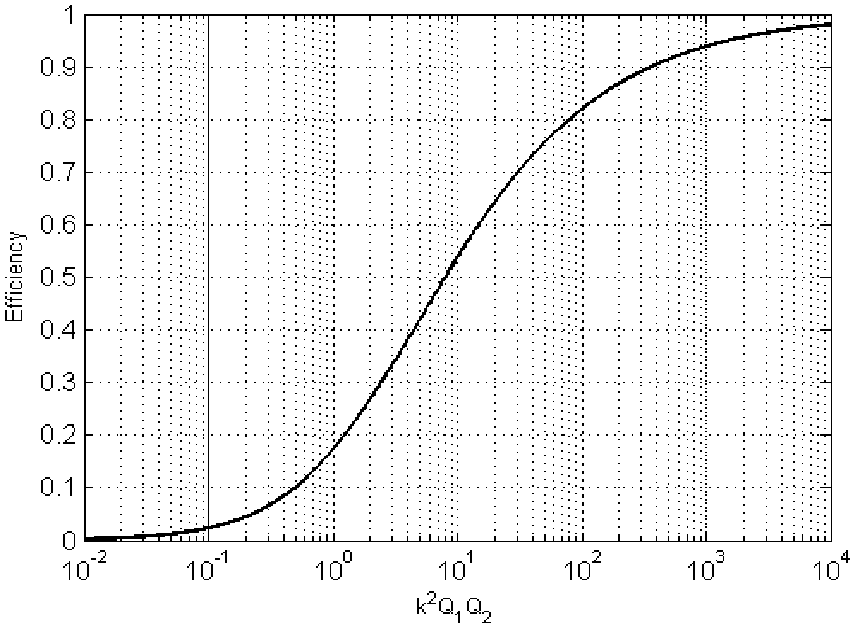
Efficiency

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 $\eta > 90\%$

The traditional approach is to increase k, reducing leakage inductance and improving link efficiency…. But….

Motivation

- Coils with ferrite cores are heavy – and ferrite is costly and brittle
- Their directed magnetic flux leads to restricted freedom of movement
- Air-core coils, with their wide flux coverage, are more suitable for many IPT applications
  - Lightweight for EVs
  - Dynamic charging of moving vehicles
- With coils acting as weakly coupled transformer, link efficiency deteriorates rapidly with distance
- Driving high Q coils with weak coupling presents an interesting set of challenges for the power electronics.

Maximising $k^2Q_1Q_2$

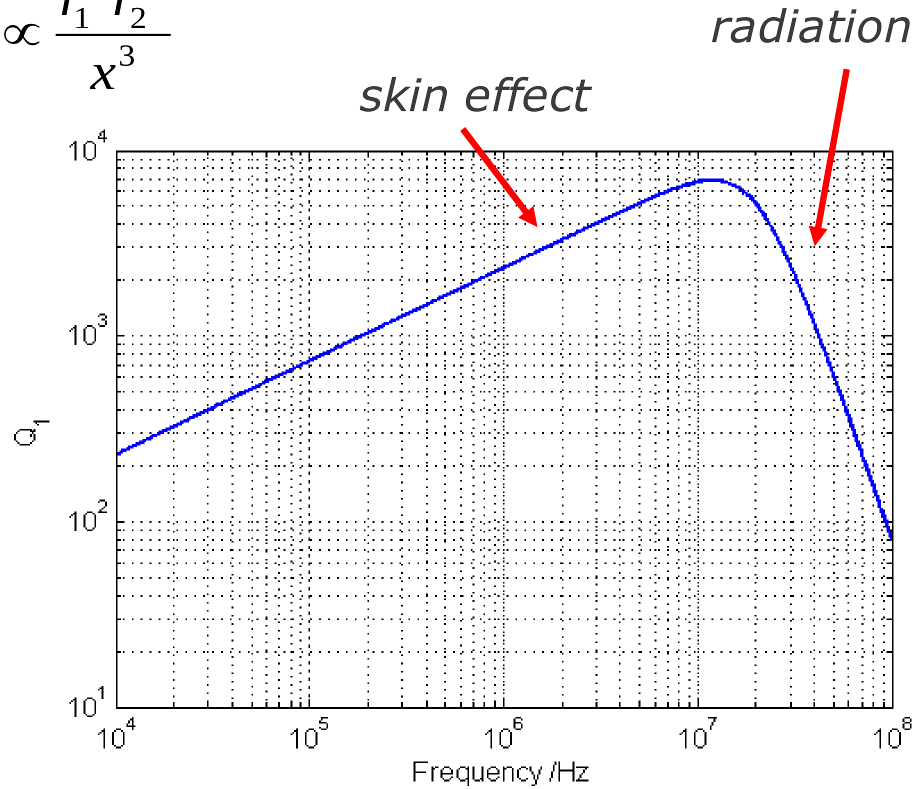
- Coupling factor depends on coil geometry and distance only
- Maximise the radius in the space available

$$k \propto \frac{r_1^{\frac{3}{2}} r_2^{\frac{3}{2}}}{x^3}$$

But what about Q?

Choose optimal frequency

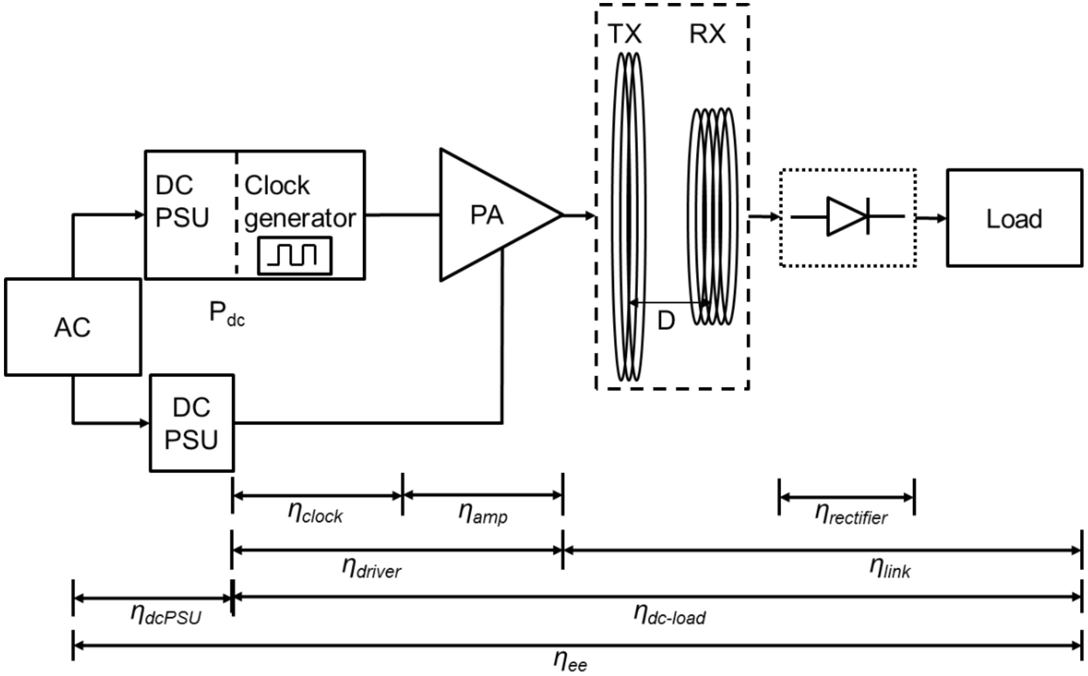
  - Point at which radiation begins to dominate losses for a given coil size constraint



Q versus frequency for 3 turn coil of 10 cm radius

We are quickly pushed into needing MHz power electronics

IPT System Blocks



$$\eta_{link} = \frac{k^2 Q_{TX} Q_{RX}}{\left(1+\sqrt{1+k^2 Q_{TX} Q_{RX}}\right)^2}$$

$$\eta_{ee} = \eta_{dcPSU}\eta_{dc-load}$$

where $\eta_{dc-load} = \eta_{driver}\eta_{link}$

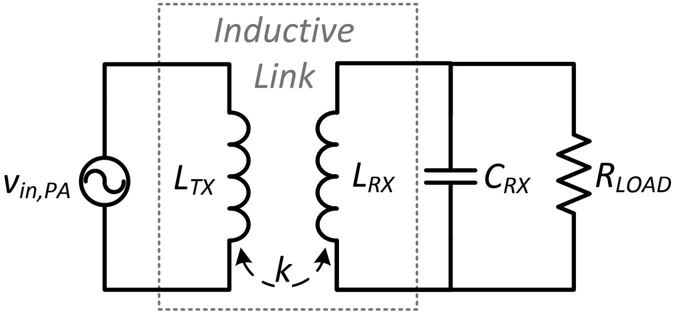
and $\eta_{dc-load} = \frac{P_{load}}{P_{dc}}$

Kurs *et al.*

$\eta_{link} = 50\%$ $\eta_{ee} = 15\%$

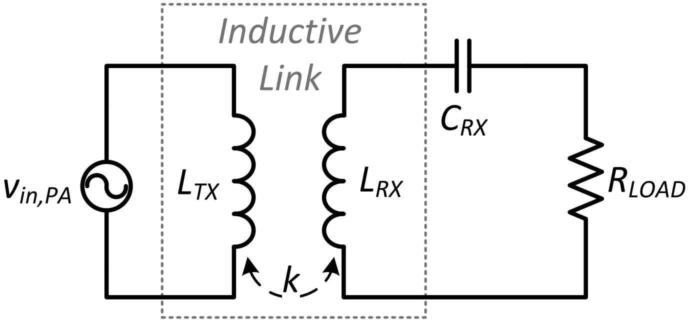
A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, ‘Wireless Power Transfer via Strongly Coupled Magnetic Resonances’, Science, vol. 317, no. 5834, pp. 83–86, Jul. 2007.

Receiver Resonance Choices



[a]

$$R_{LOAD} = \frac{\alpha}{\omega C_{RX}}$$



[b]

Parallel tuned – “voltage source”

Optimal Load resistance tends to be high

Output voltage tends to be high

$$\alpha = \frac{Q_{RX}}{\sqrt{1+k^2 Q_{TX} Q_{RX}}}$$

Series tuned – “current source”

Optimal Load resistance tends to be low

Output voltage tends to be low

$$\alpha = \frac{\sqrt{1+k^2 Q_{TX} Q_{RX}}}{Q_{RX}}$$

Inverters

(Driving the inductive link)

Losses and VA rating

To keep our systems efficient we must minimise losses in the semiconductor devices

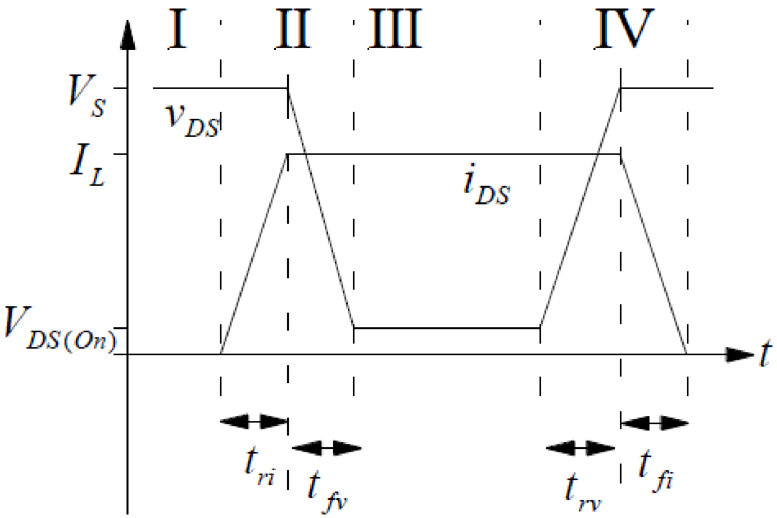
There are two types of power losses in semiconductor devices:

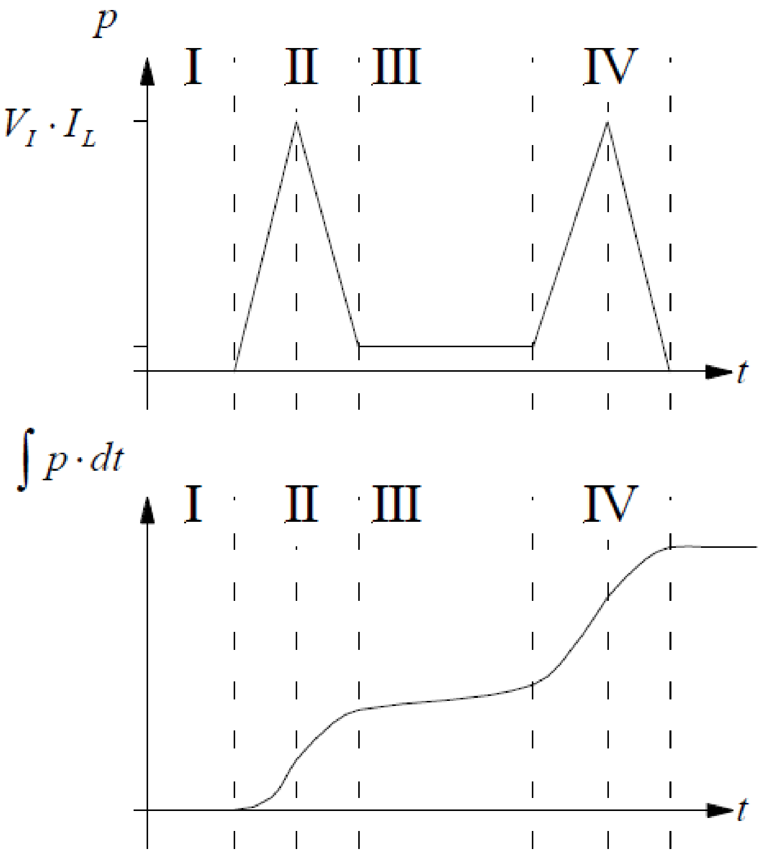
- Conduction Loss (proportional to the square of current)
- Switching loss (proportional to frequency)
  - Can be significant at the high frequencies of IPT
  - Can be reduced (almost eliminated) using a technique called “soft switching”

- The poor power factor of the coils (due to leakage inductance means we should try to create topologies where the semiconductors do not have to provide all the VA product

Switching Losses

The loss occurs at each turn on and turn off if there is an overlap in device voltage and current





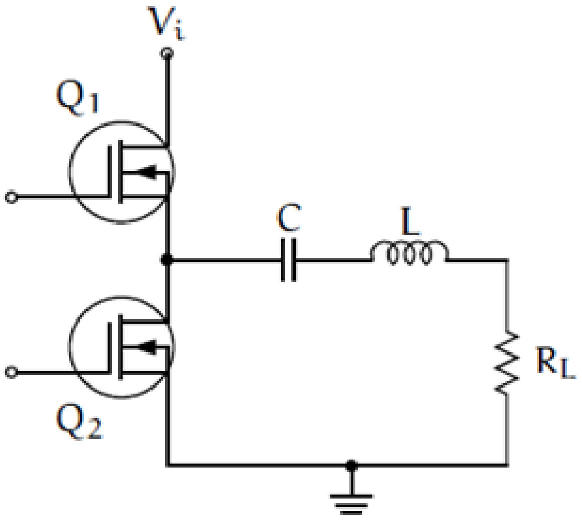
Inverters

- Conventional hard-switching not suitable in MHz region
  - Device switching times become comparable to driving signal period
  - Can be inefficient at higher frequencies

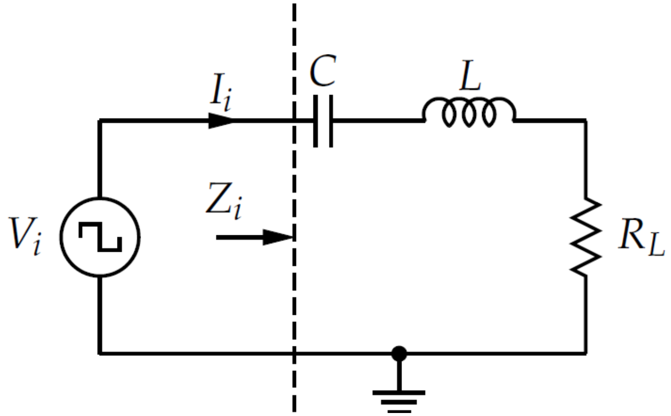
- Soft switching inverters (eg ZVS Class-D and Class-E) employ zero-voltage switching to minimise power dissipation

- 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.

Resonant Class D "Half bridge"



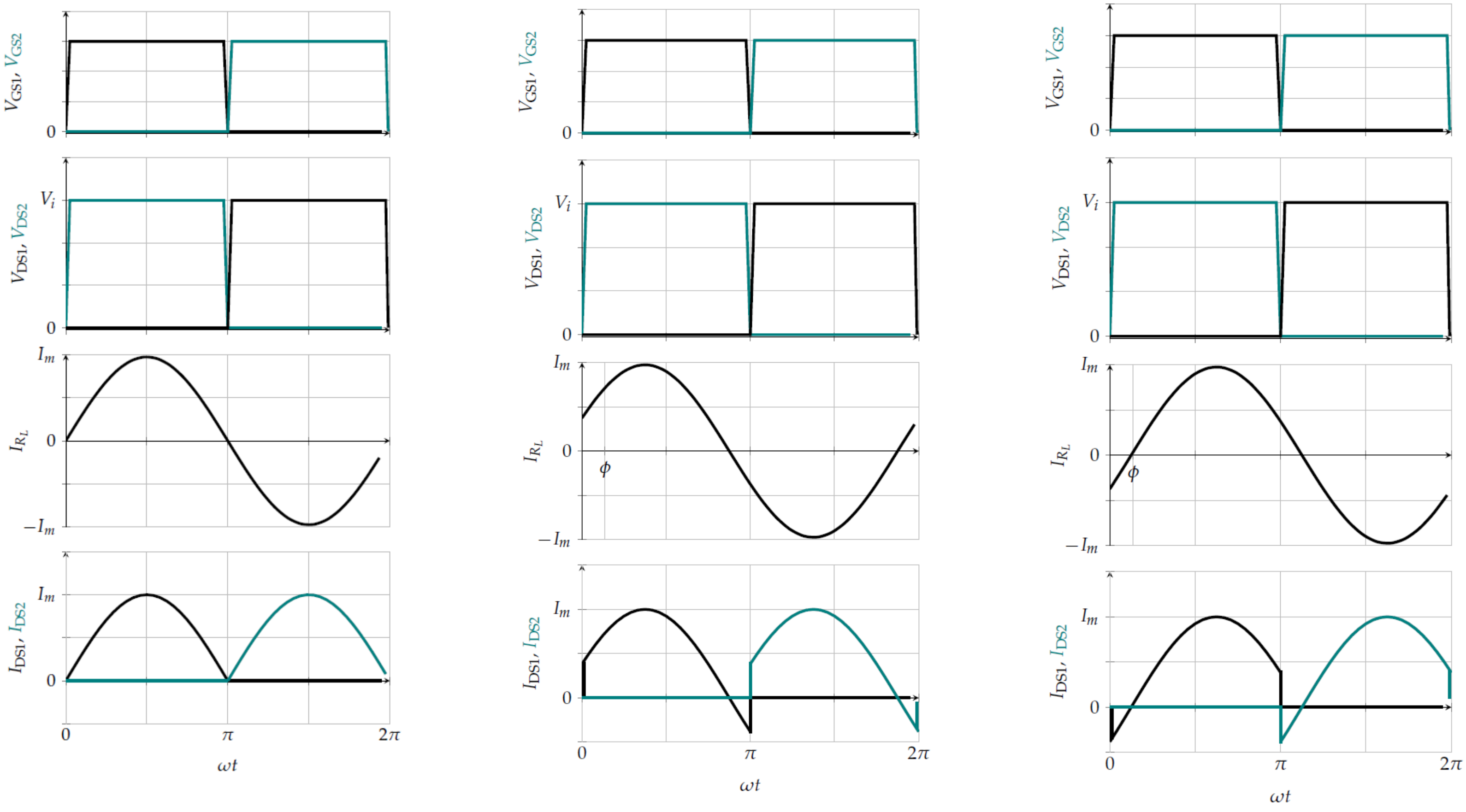
Practical circuit



Equivalent circuit

- The series resonance allows the leakage inductance to be resonate out to get a high effective air gap voltage
- Can achieve soft switching
- But has a high side gate drive and two devices

Waveforms

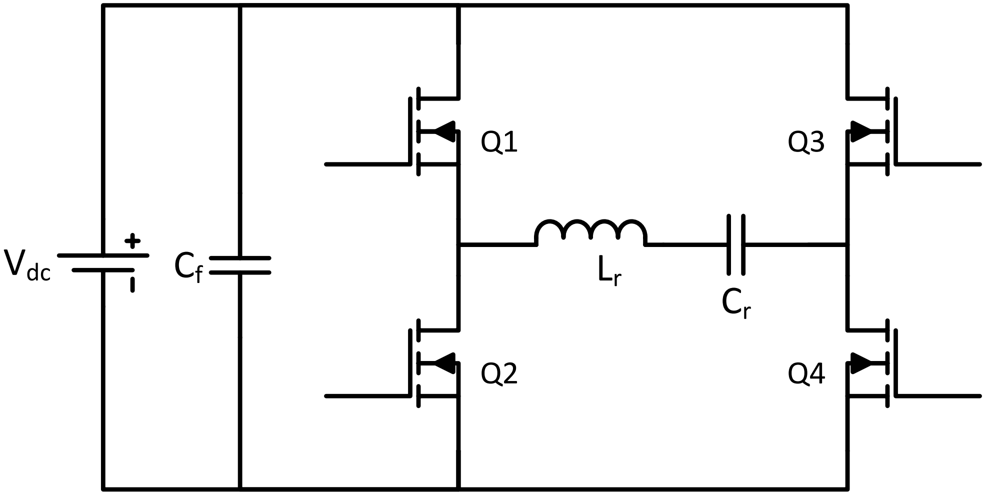


a) Resonance b) Below resonance c) Above resonance

Soft switching lost if tuning is not perfect

Resonant Class-D "full bridge"

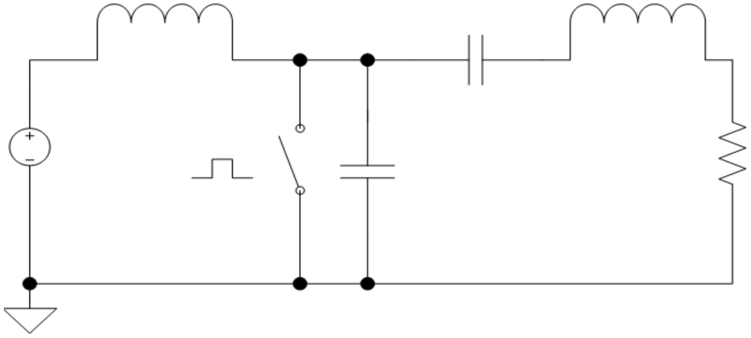
- Well known H-bridge topology
- The series resonance allows the leakage inductance to be resonate out to get effective air gap voltage
- But, has 4 switches and required high side gate drivers
- Twice the voltage capability over half bridge (4 times the power), but twice as many components

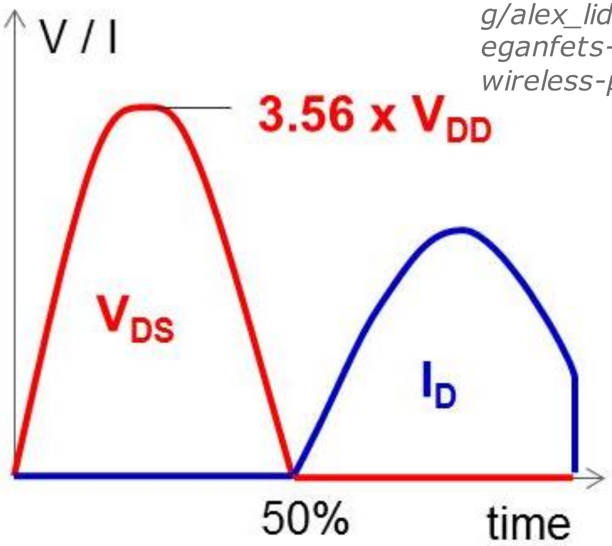


- Ideally we want circuits with fewer transistors, all low-side referenced

Class E – a simpler, better solution

- 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 and 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

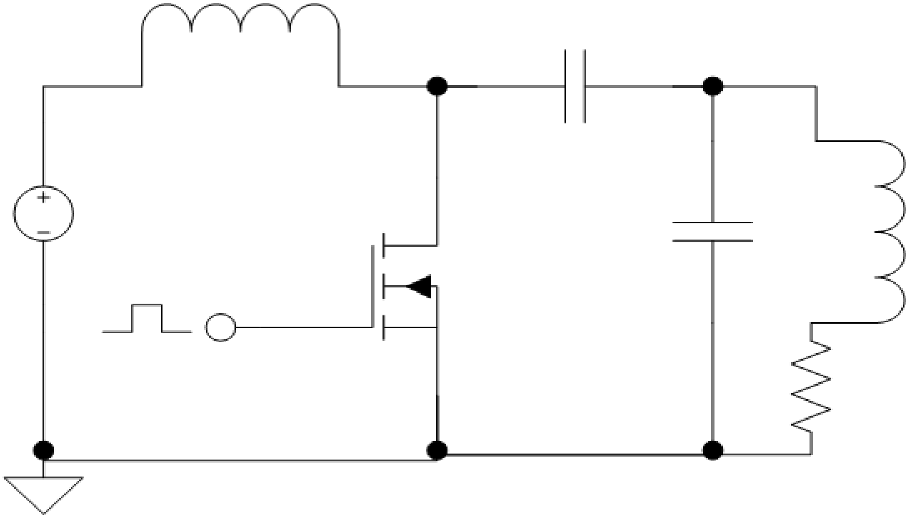




Graph from https://www.eeweb.com/blog/alex_lidow/how-to-gan-eganfets-for-high-frequency-wireless-power-transfer

Class E for IPT

- In the traditional class E arrangement, the main coil current must flow through the transistor. This can be avoided using a parallel resonance.
- To keep the load network slightly inductive, the resonant tank is now operated below its resonant frequency – “semi resonance”

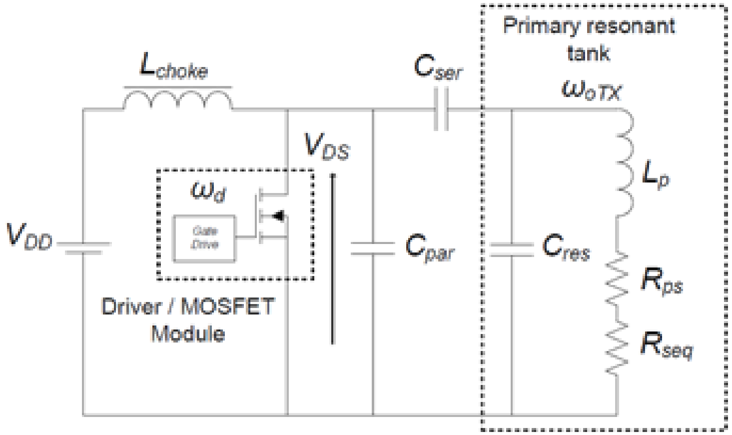


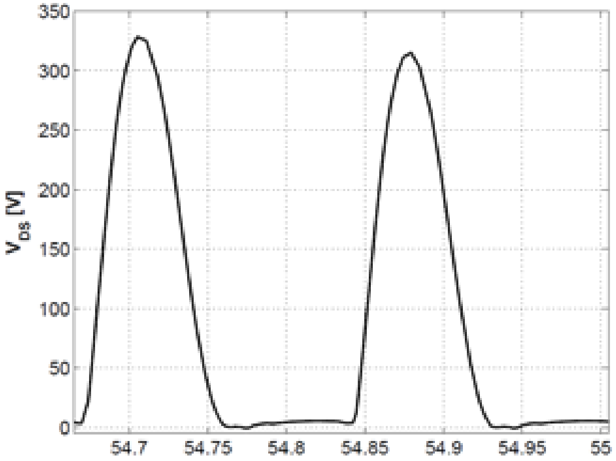
Inverters (2)

Semi-resonant Class-E inverter

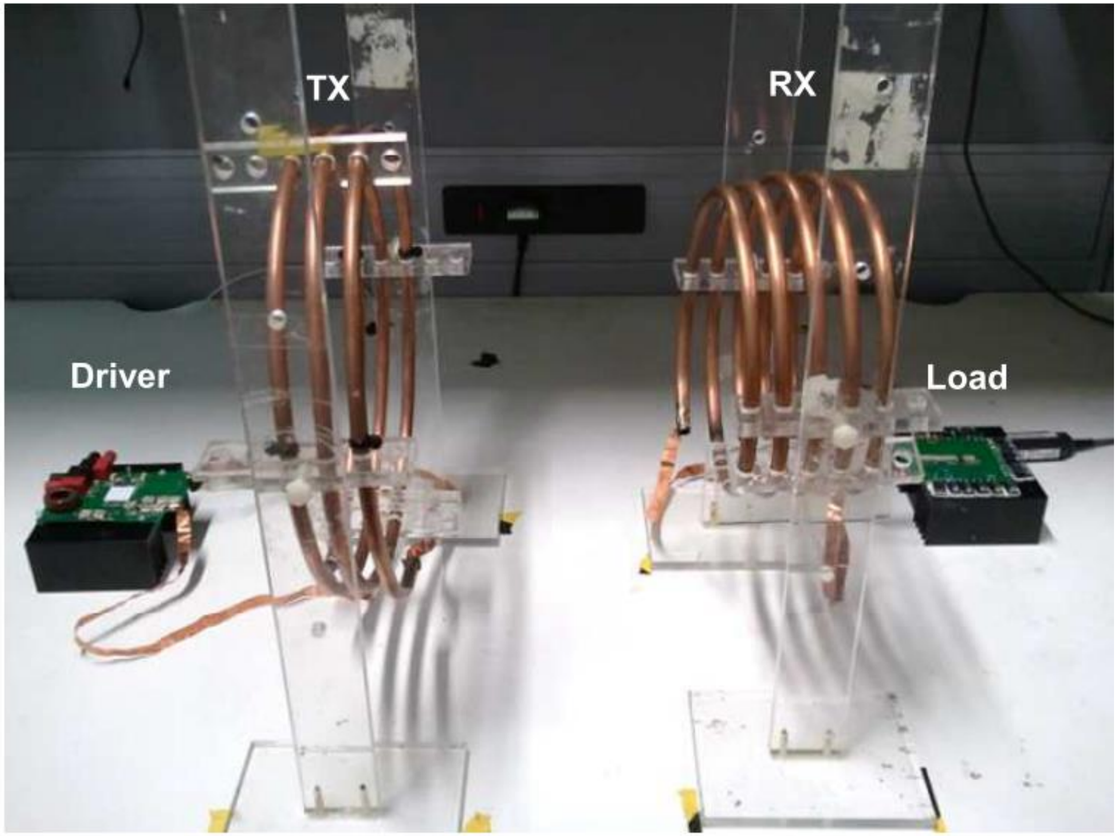
- Primary resonant tank tuned to slightly higher frequency than secondary resonant tank to keep primary tank impedance inductive
  - A requirement for Class-E operation

- Parallel combination of capacitor C_{res} and the transmitter coil forms impedance transformer
  - Load impedance appears larger
  - Increase in driver efficiency





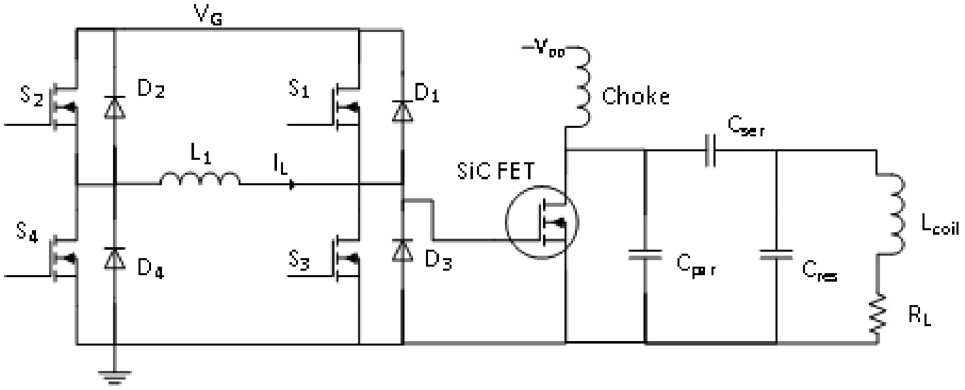
High Frequency Semi-resonant Class-E Driver



78% dc-load efficiency, 100 W, 6 MHz, IXYS Si module

What improvements can we make?

Resonant gate drive with class E



Class E primary IPT driver design:

- Cree C2M00800120D 1200 V SiC MOSFET

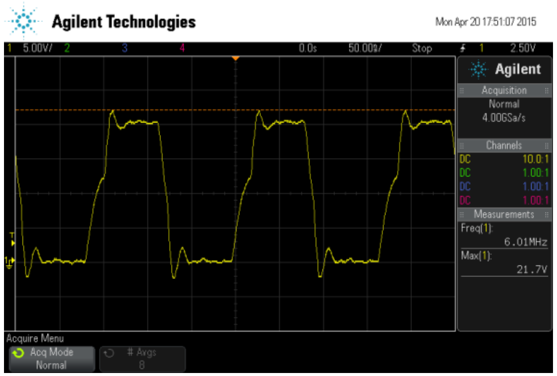
  (C_{iss} = 259pF, R_G = 11.4 Ohms, R_{DSon} = 280 Ohms)

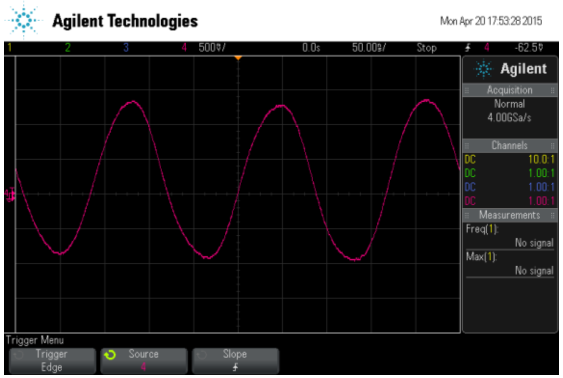
Resonant gate drive design:

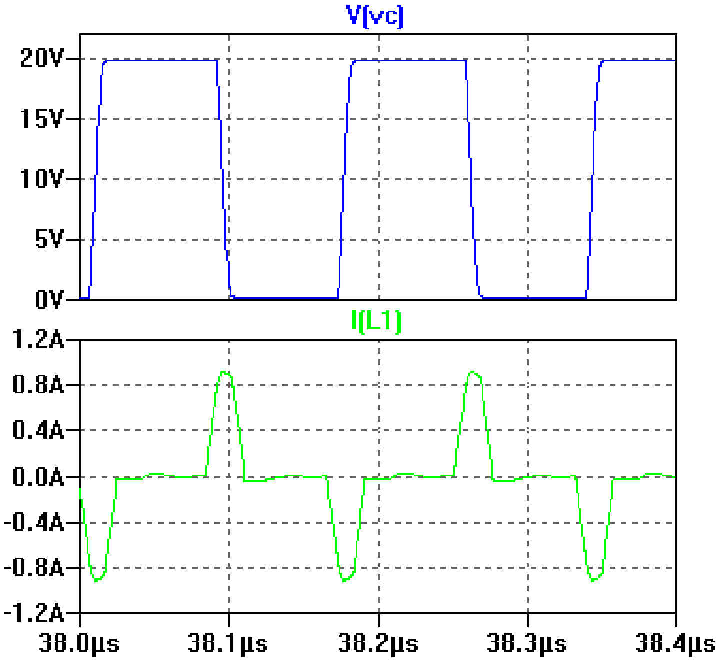
- New TI LMG5200 half bridge driver GaN modules integrated in one package as switches (~600mW power consumption for 2 modules at 6MHz)
- Body diode not good enough so use Vishay Schottky MSS1P3L

Resonant Gate Drive Results

Gate voltage (top), inductor current (bottom)





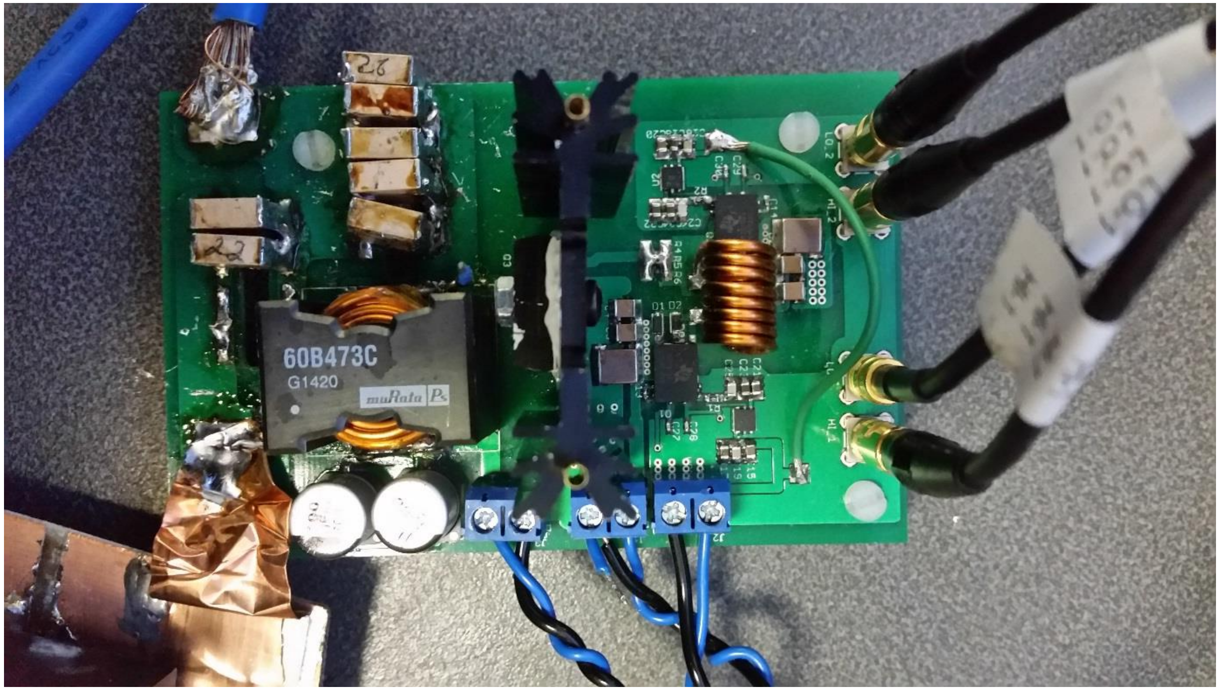


Measured current – fundamental only due to limited current probe bandwidth

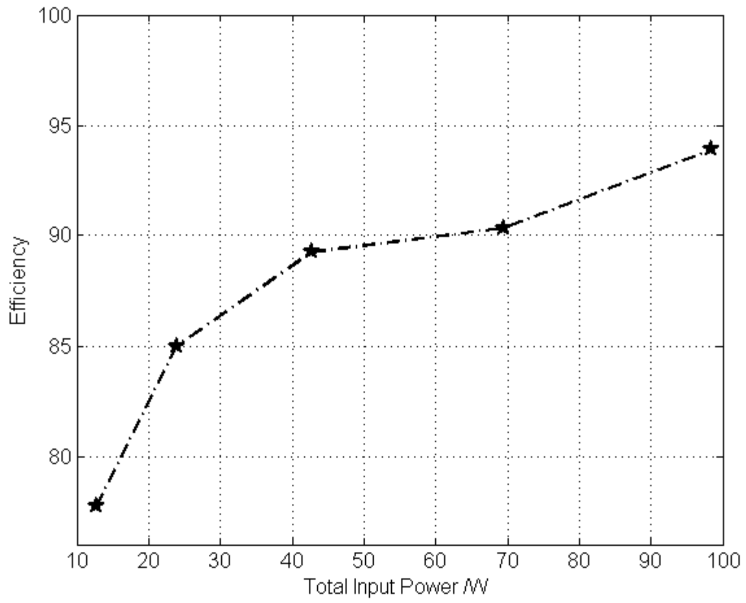
Class E board with Resonant Gate Drive

Output measured using Agilent current probe

Load resistance measured using Wayne Kerr Impedance Analyser at 3 MHz and at the temperature of operation



Measured Class E Efficiency



	Original	This work
Efficiency	~82%	~94%
Gate drive	~6 W	< 2 W

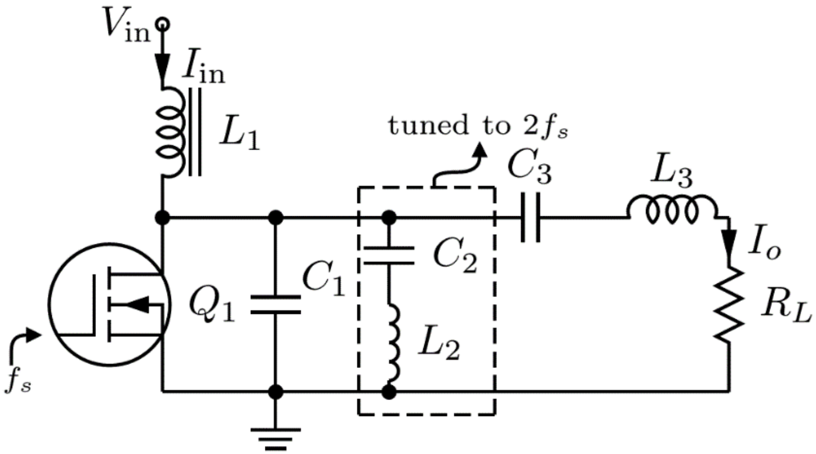
Measured Efficiency versus input power

Total efficiency of new SiC class E including resonant gate drive losses is ~94%, ~12 % better than original Si version with off-the shelf gate drive

Class EF Inverters

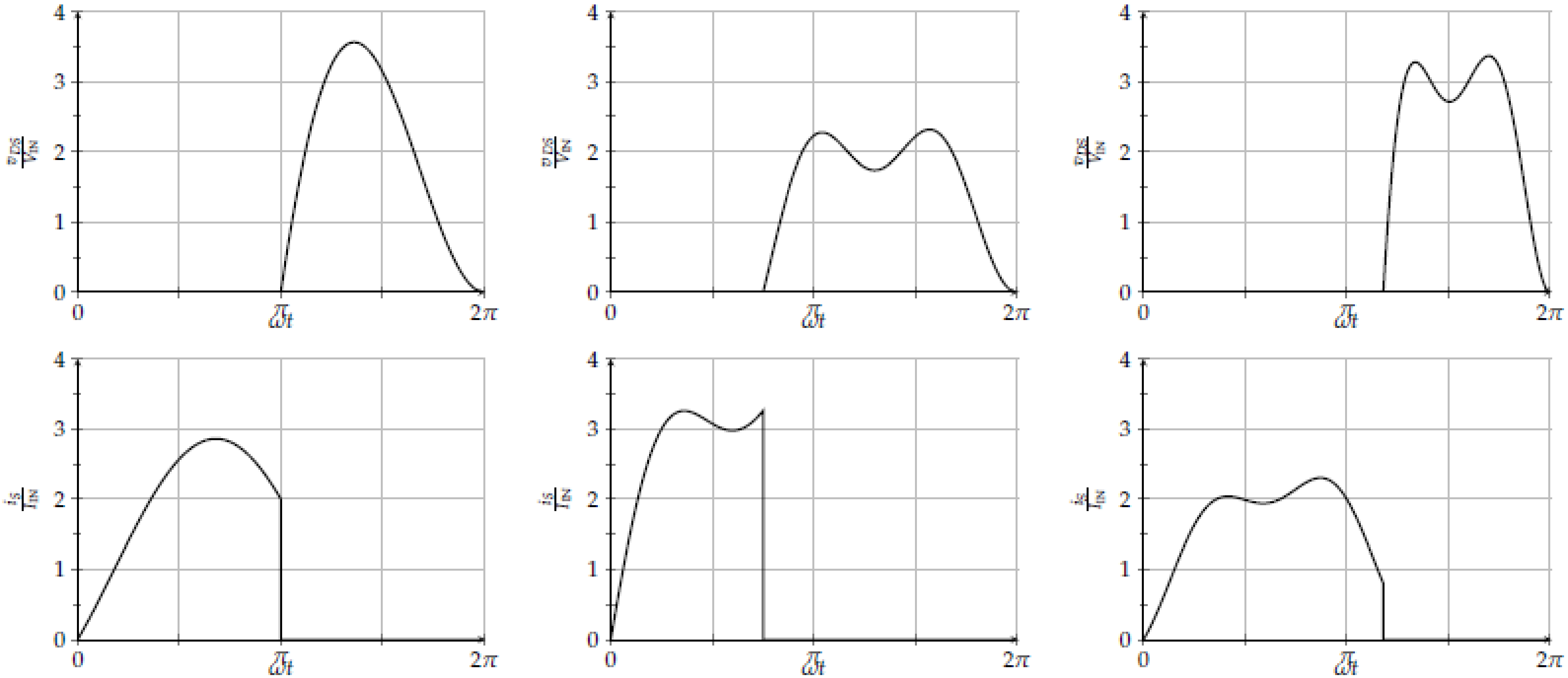
Class-EF$_2$ and Class-E/F$_3$ inverters

- 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
- Added network tuned to either 2nd harmonic (Class-EF$_2$) or 3rd harmonic (Class-E/F$_3$) of switching frequency.



Inverters (5)

- Class-EF$_2$ inverter: lower voltage stresses
- Class-E/F$_3$ inverter: lower current stresses

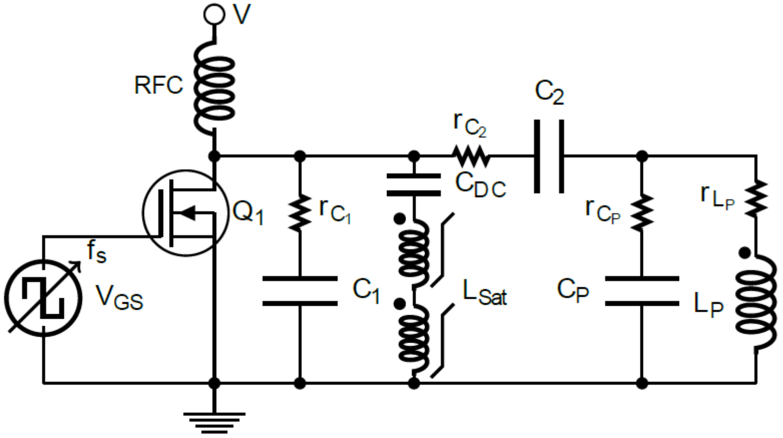


(a) Class-E (b) Class-EF2 (c) Class-E/F3

System level optimisation: saturable reactor

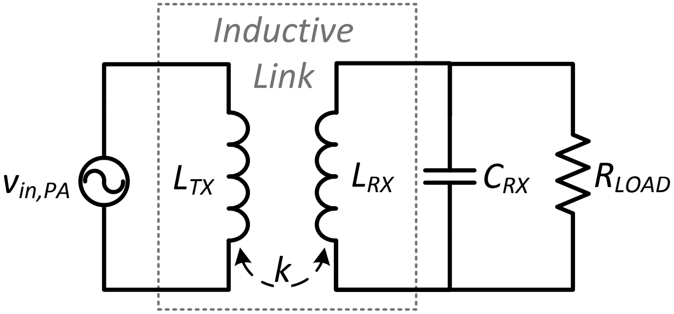
Class-E inverter with saturable reactor

- Tuning for optimum switching operation when load change occurs.
- Saturable reactor: AC-to-AC transformer
  - Primary and secondary winding wound on a single magnetic core.
- Applying low DC current in one winding causes magnetic core's permeability to decrease, which changes impedance of second winding.
- Tuning procedure: vary switching frequency, and effective reactance of capacitor C_1 via saturable reactor.



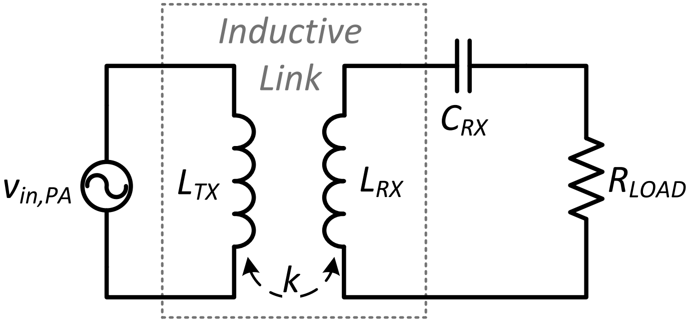
Rectifiers

Reminder - Receiver Resonance Choices



[a]

$$R_{LOAD} = \frac{\alpha}{\omega C_{RX}}$$



[b]

Parallel tuned – “voltage source”

Optimal Load resistance tends to be high

Output voltage tends to be high

$$\alpha = \frac{Q_{RX}}{\sqrt{1+k^2 Q_{TX} Q_{RX}}}$$

Series tuned – “current source”

Optimal Load resistance tends to be low

Output voltage tends to be low

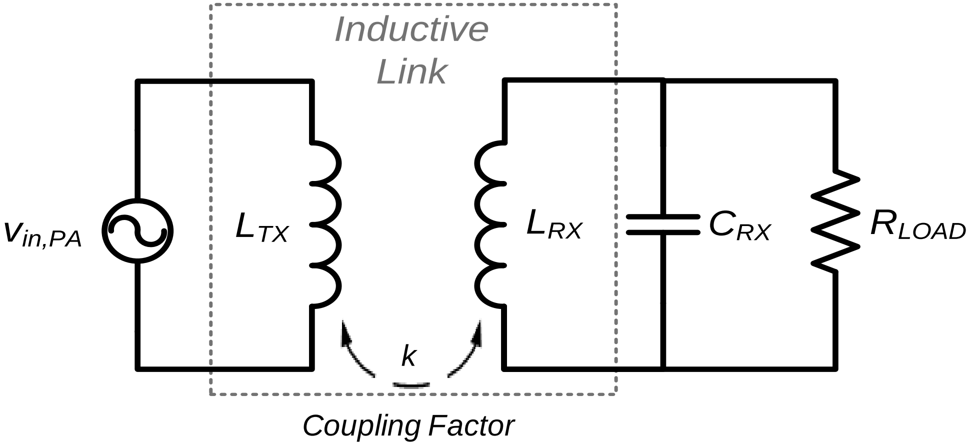
$$\alpha = \frac{\sqrt{1+k^2 Q_{TX} Q_{RX}}}{Q_{RX}}$$

Our rectifier needs to present an input impedance of R_{LOAD}

Wireless Power Transfer through Inductive Coupling

Rectifier Selection Criteria:

1. Operate with an input voltage source
2. Emulate an R_{LOAD} value according to the set of equations on the right-hand-side.



Equations describing the Link:

(1) $$\eta_{link} = \frac{k^2 Q_{TX} Q_{RX}}{\left(1+\sqrt{1+k^2 Q_{TX} Q_{RX}}\right)^2}$$

(2) $$R_{LOAD} = \frac{\alpha}{\omega C_{RX}}$$

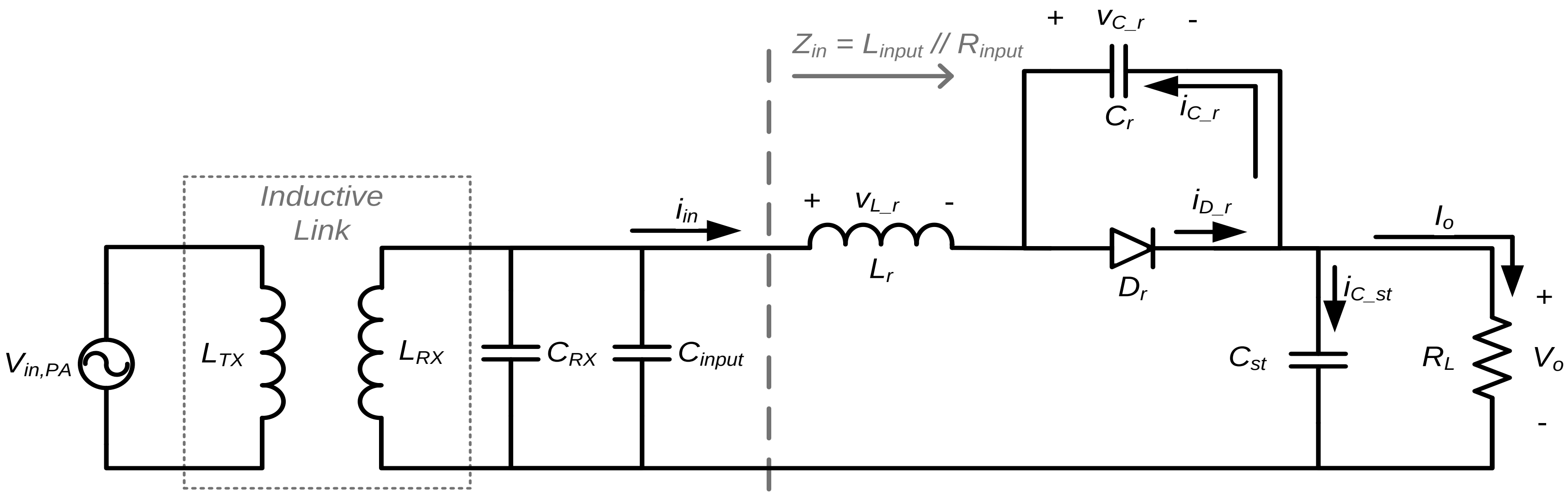
(3) $$\alpha = \frac{Q_{RX}}{\sqrt{1+k^2 Q_{TX} Q_{RX}}}$$

(4) $$Q = \frac{\omega L}{R}$$

Rectification through Selected Class-E Topology

Class-E Resonant Low dv/dt Rectifier:

- Any trace inductance form the wires is absorbed into the series inductance (L_r);
- The pn-junction capacitance of the diode (C_{pn}) is absorbed into the resonance capacitor (C_r). Thus $\mathbf{C_r = C_{r,add} + C_{pn}}$.



Rectification through Selected Class-E Topology

Equations*:

(5) $$\omega_r = \frac{1}{\sqrt{L_r C_r}}$$

(6) $$R_L = 2M^2 R_{input}$$

(7) $$L_r = \frac{R_L}{\omega_o Q_r}$$

(8) $$L_{input} = f_L\{L_r\}$$

(9) $$\omega_r = \frac{1}{\sqrt{L_{input} C_{input}}}$$

(10) $$V_o = M\hat{v}_{in}$$

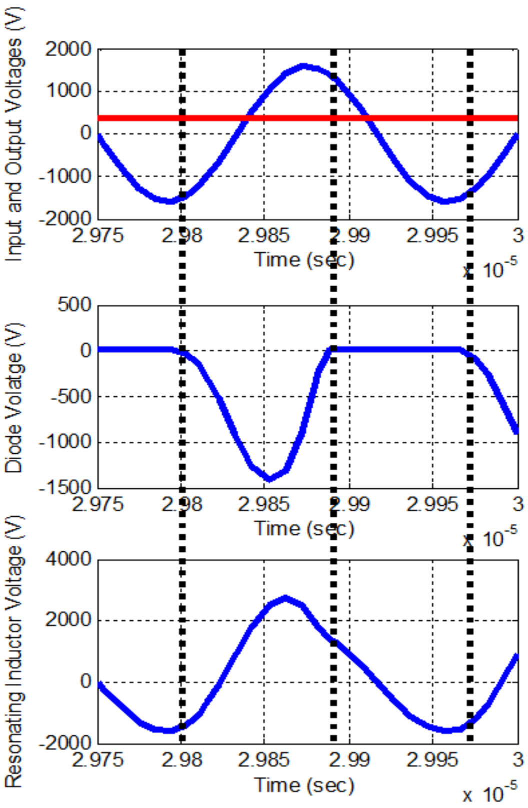
Design Process:

1. The operating frequency is equal to the resonance frequency and are both defined by the inductive link;
2. R_{input} is defined by the inductive link;
3. The duty cycle is chosen to be 50%, where the minimum stress (product of max voltage and current) of the diode occurs;
4. M, Q_r and $f_L\{L_r\}$ are evaluated by their explicit equations;
5. R_L, L_r and C_r are respectively defined by (6), (7) and (5);
6. C_{input} is defined by (8) and (9);
7. C_{pn} can be defined by (10) and $C_{r,add}$ is the difference of C_r and C_{pn}.

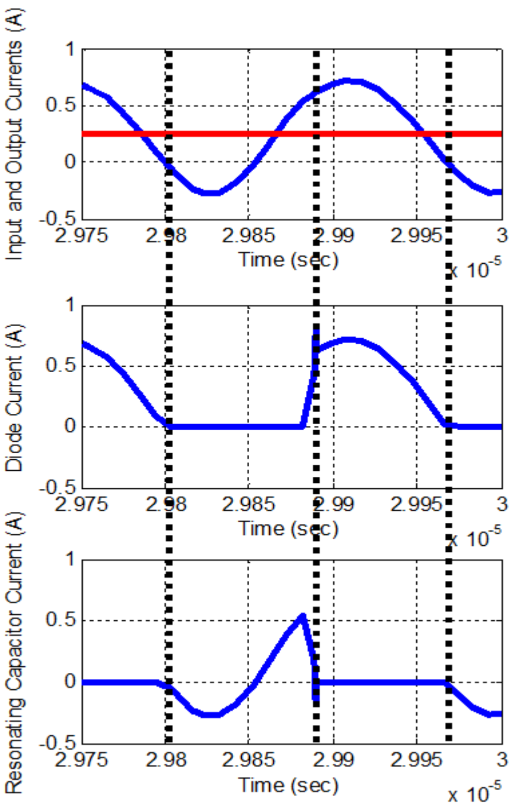
*Variables M, Q_r and $f_L\{L_r\}$ are explicitly dependent on the duty cycle. Refer to Ivascu, *et al.* "**Class E resonant low dv/dt rectifier**," *Circuits and Systems I: Fundamental Theory and Applications, IEEE Transactions on, vol. 39, pp. 604-613, 1992.*

Rectification through Selected Class-E Topology

Voltage Waveforms:



Current Waveforms:



Regulations

Electromagnetic Field Limits and Regulations

- Limits on EM field levels protecting humans from adverse effects of exposure.
  - Thermal and non-thermal effects

- EU Directive (2013/35/EU) – exposure of workers
  - Adopted on 26 June 2013, to be transposed into UK law by 1 July 2016
  - Based on ICNIRP 1998 and 2010

- Exclusion zones

- Design for minimal magnetic field
  - Increase link efficiency and overall efficiency

ICNIRP limits

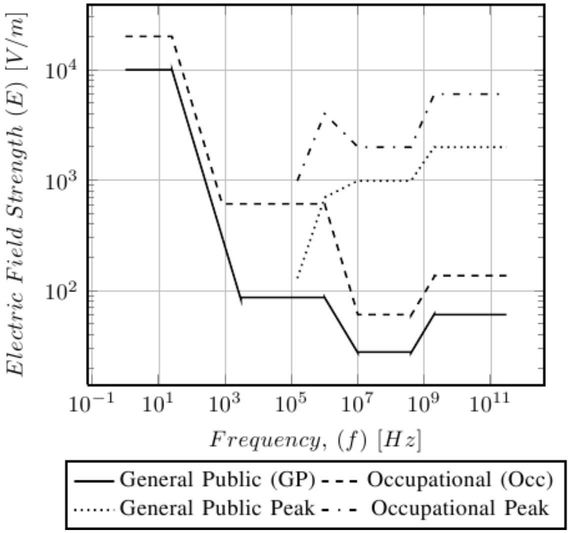


Fig.22 1998 ICNIRP E-field reference levels from [redrawn from ICNIRP1998]

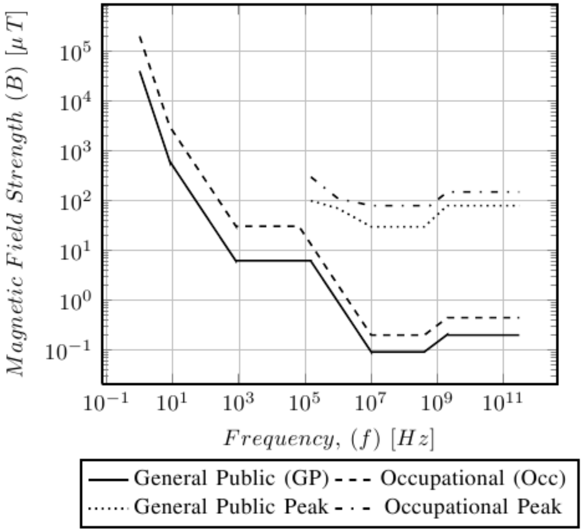


Fig.23 1998 ICNIRP B-field reference levels from [redrawn from ICNIRP1998]

- ICNIRP and the IEEE both set standards on safe magnetic and electric field levels for human exposure as a function of frequency

- Why are the occupational limits higher than the public limits?

Long Range IPT

Long Range System Operation

Imperial College
London

Wireless Power Lab

Long Range
Inductive Power Transfer

Long Range System outline

- Class-E inverter driving freewheeling Tx coil at 3 MHz
- Semi resonant operation
- Very large circulating current in Tx coil generates magnetic field throughout room
- Coupling is primarily magnetic
- Magnetic energy harvesting approach. Magnetic field transmitter and harvester.
- Can we have freedom of operation within a room?

High-Q coils (2)

- *2 cm x 2 cm coil Q(3 MHz) = 97*
  - *3 times greater Q factor than PCB coil with the same outside diameter*

- *17 x 17 cm coil Q(3 MHz) = 280*

- *1 x 1 m coil Q(3 MHz) = 2890*

Long Range Inductive Power Transfer System, J. Lawson et al, Proceedings of PowerMEMS 2013, Dec 2013.

Predicting Performance

- Environments contain conducting objects that have circulating currents within them due to the magnetic field generated by the Tx coil. Circulating currents generate their own magnetic field.

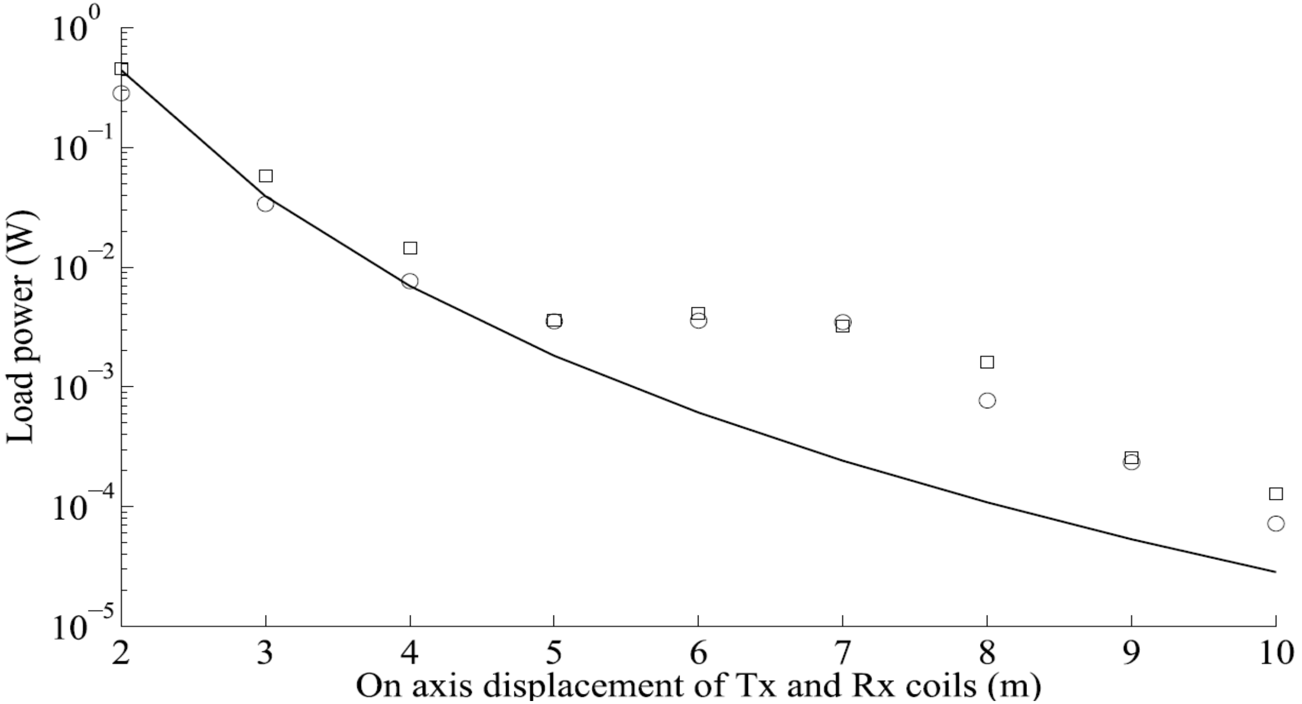
- Superposition results in magnetic field strength anomalies

- Calculate mutual coupling of Rx and Tx using actual magnetic field measurements and effective loop area of Rx coil. With on axis aligned coils this simplifies to [6]:

$$M_{TxRx} = \frac{A_{rx}B}{I_{Tx}}$$

- I_{Tx} can be found by close to Tx coil magnetic field measurement and using Biot-Savart law to calculate the circulating current. A Matlab script was created to find the vector field created by the Tx coil from the filamentary currents.

System performance



Load power for 98 W DC power input to Class-E inverter. Simulation using round loops approximation —, Prediction using local magnetic field strength □, Measured power at Rx coil ○.

246 W input, 10.9mW at the load at 6m

Conclusions

- An IPT link is a poorly coupled transformer
- To operate efficiently it has to be driven at high frequency
- It has a very poor power factor
- So we need an efficiency power electronics topology that can drive a poor PF at high frequency, efficiently
- Class E approach can work very well in MHz region
- Several improvements are possible (energy recycling gate drives, tenability, waveform shaping
- The rectifier must present the correct impedance to the system to maintain optimum link efficiency and can also be soft switched
- ICNIRP regulations (or local regulations) must be adhered to
- IPT can be used for both high power short range and low power long range transfer

References

- Modeling and Analysis of Class EF and Class E/F Inverters With Series-Tuned Resonant Networks, S Aldhaher, DC Yates, PD Mitcheson, Power Electronics, IEEE Transactions on 31 (5), 3415-3430

- Link efficiency-led design of mid-range inductive power transfer systems, CH Kwan, G Kkelis, S Aldhaher, J Lawson, DC Yates, PCK Luk, Emerging Technologies: Wireless Power (WoW), 2015 IEEE PELS Workshop on, 1-7

- Maximizing DC-to-load efficiency for inductive power transfer, M Pinuela, DC Yates, S Lucyszyn, PD Mitcheson, Power Electronics, IEEE Transactions on 28 (5), 2437-2447

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