Position and Load Independent DC to DC Wireless Power Transfer System for Moving Applications

PhD Project: Design of novel antenna systems for energy and data transfer

Alex Pacini
Supervisor: Prof. Alessandra Costanzo
Co-supervisors: Prof. Franco Mastri, Prof. Diego Masotti

DEI – Università di Bologna

Overview

- Tutorial
  - Introduction to Wireless Power Transfer (WPT)
  - Inductive Power Transfer (IPT)
  - Class E Resonant Inverter
  - Advantages of Wide Bandgap Semiconductors (WBG)
- Research Contribution
  - Geometry Optimization of Sliding Inductive Links for Position-Independent Wireless Power Transfer
  - Design of a Position-Independent End-to-End Inductive WPT Link for Industrial Dynamic Systems
- Conclusions

Tutorial

Introduction to Wireless Power Transfer (WPT)

Near Field and Far Field WPT

- Wireless Power Transfer (WPT) includes several technologies to transmit power without connecting wires
- "*The transmission of power without wires will very soon create an industrial revolution and such as the world has never seen before,*" – Tesla in a 1906 letter to George Westinghouse
- We focus on those based on electromagnetic fields

Near Field

- Non radiative region ($r << \lambda$)
- Short and medium range
- Good efficiencies
- Frequency is low (usually $f < 30\,\mathrm{MHz}$)
- Quasi-static
- Inductive or capacitive coupling

Far Field

- Radiative region
- Long range
- Efficiency is very low
- Very directional antennas
- Frequency is high (usually $f > 100\,\mathrm{MHz}$)
- Light waves are also an option

Mid Field?

Tutorial

Inductive Power Transfer (IPT)

Quiz 1!

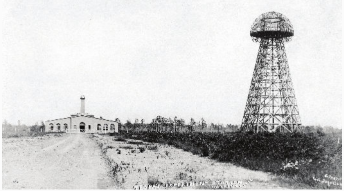
How to improve the maximum efficiency of two inductively coupled coils with a low coupling coefficient?

(A) Transmit more power, since the system is non linear
(B) Make the primary coil resonant
(C) Make the secondary coil resonant
(D) It cannot be improved, since it only depends on the geometries

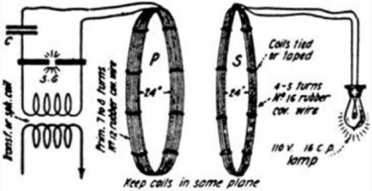
`qdle.net/44006612`

Introduction to Inductive Power Transfer

- Near-field inductive coupling was reported by Tesla [1] a century ago
- It relies on the near-field magnetic coupling of conductive loops
- In 2007, a MIT team lighted up a 60 W lamp using power transferred between two coils separated by 2 meters [2].
- The first to create a considerable buzz in the press, but there are also previous efforts, as [3]



Tesla Wardenclyffe Project [2]



Tesla's WPT experiment [4]

---

[1] Tesla, 1914.

[2] Schneider, 2010.

[3] Joung and Cho, 1996.

[4] Hui, Zhong, and Lee, 2014.

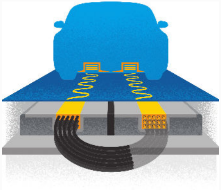
Applications of Inductive Power Transfer

- Medical implants ($\sim$ µW)
- Induction heaters
- Wireless charging systems for portable equipment or vehicles
- Continuous wireless powering for industrial movers or vehicles
- Endless possibilities...

WPT charger (Wikipedia)

Intel's system [2]

Bus in Genoa (60 kW) [2]



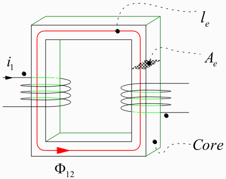
Electric car [5]

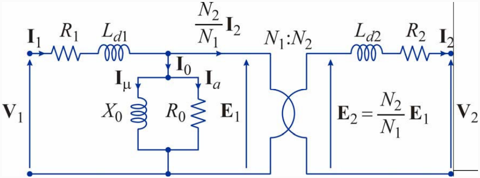
---

[2] Schneider, 2010.

[5] Ahn, Suh, and Cho, 2013.

Transformer

- In a regular transformer, the iron core allows almost the entire flux generated by current in one coil flow to the other
- 

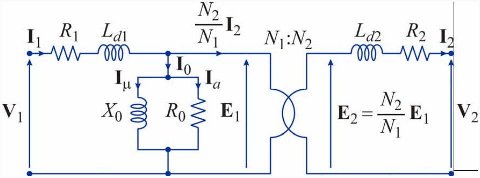


- The coupling coefficient k is defined as the fraction of flux from one coil that link with the other coil:

$$k = \frac{\Phi_{12}}{\Phi_1} \qquad k = \frac{M_{12}}{\sqrt{L_1 L_2}}$$

- In a iron core transformer, k is very high, typically 0.99, and therefore the leakage inductances (L_{d1} and L_{d2}) are small
- The magnetizing inductance (X_0) tends to be high
- If copper (R_1, R_2) and hysteresis (R_0) losses are low, the efficiency is very high (99% typical)

What if we remove the iron core?

- 

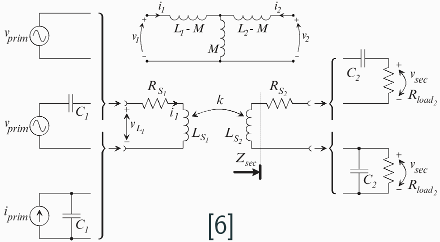
$$k = \frac{\Phi_{12}}{\Phi_1}$$

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

- Medium range IPT systems can not have the iron core for mobility reasons
- The leakage inductances become large
  - ωL_{d2} is much larger than the useful load at weak couplings and requires higher $\mathbf{E}_1$, which in turn requires higher primary currents
  - L_{d1} further reduces $\mathbf{E}_1$
- The magnetizing inductance falls dramatically, reducing again $\mathbf{E}_1$
- The efficiency is low (impractical for k below 5%)

Poor coupling = Poor efficiency? No!

- Without the iron core, the iron losses are zero ($R_0 = \infty$)
- Can be described by circuit theory for coupled circuits [6]
  - Resonance techniques can be employed
  - Secondary resonance sets the maximum efficiency with the optimum load ($\eta_{link_{max}}$)
  - Primary resonance lowers the required driver output voltage



[6]

Series or parallel secondary compensation, optimum load:

$$\eta_{link_{max}} = \frac{P_{out_{max}}}{P_{in}}$$

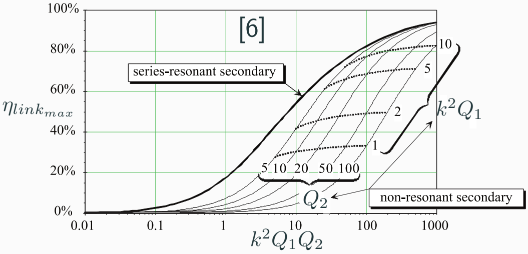
$$\eta_{link_{max}} = \frac{k^2 Q_1 Q_2}{\left(1 + \sqrt{1 + k^2 Q_1 Q_2}\right)^2}$$

---

[6] Schuylenbergh and Puers, 2009.

The kQ product as FoM

- The coupling coefficient k is not a good Figure of Merit (FoM)
- The maximum efficiency depends also on the quality factors of the coils (Q_1, Q_2)
- A good FoM is the kQ product [7]
  - As $Q = |Z_{11}| / ESR \rightarrow kQ = |Z_{12}| / ESR$
  - ESR, Equivalent Scalar Resistance (for two coils $ESR = \sqrt{R_{11}R_{22}}$)
  - $k^2Q_1Q_2 = (\omega M_{12})^2 / (R_{11}R_{22}) = k^2Q^2$



Uncompensated, optimum load:

$$\eta_{link_{max}} = \frac{k^2Q_1Q_2}{2 + k^2Q_1Q_2 + 2\sqrt{1 + Q_2^2 + k^2Q_1Q_2}}$$

Series or parallel secondary compensation, optimum load:

$$\eta_{link_{max}} = \frac{k^2Q_1Q_2}{2 + k^2Q_1Q_2 + 2\sqrt{1 + k^2Q_1Q_2}}$$

Good efficency is possible with low k and high Q!

---

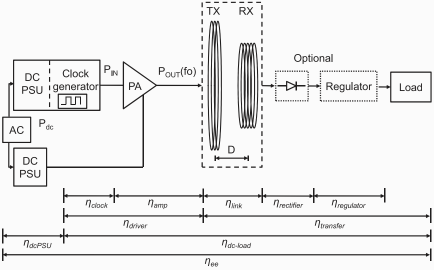
[7] Ohira, 2017.

[6] Schuylenbergh and Puers, 2009.

Maximizing kQ

- The coupling coefficient depends on coil geometry and distance only
    - Maximize the radius in the space available
    - Use specially shaped and optimized coils (i.e. Rx conformal to the magnetic field)
    - A bigger receiver coil at a fixed distance can have a lower k but higher kQ because of the increased inductance
- What about Q?
    - Choose an optimal frequency
    - Q is maximized when radiation begins to dominate losses for a certain size, but the coil is affected by parasitics (the reactance is not linear in frequency)
    - It is usually advised to use the highest frequency with a linear reactance
    - We are pushed in needing MHz power electronics
- k and Q are not mutually independent
- An EM optimization of the inductive link should be performed

IPT system blocks



$$\eta_{link_{max}} = \frac{k^2 Q_1 Q_2}{\left(1 + \sqrt{1 + k^2 Q_1 Q_2}\right)^2}$$

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

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

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

D [cm]	fo [kHz]	Driver Technology	Coil Technology	Magnetic Material	P_{load} [W]	$\eta_{transfer}$ [%]	$\eta_{dc\text{-}load}$ [%]	η_{ee} [%]	Ref.
0	134	Class-E	Litz wire	No	295	-	-	75.7	[12]
0	240	Class-E	Litz wire	No	3.7	71	-	66	[13]
10	20	H-bridge	Litz wire	Yes	2,000	85	-	-	[6]
10	-	-	-	Yes	3,300	-	-	90	[14]
15	6,700	HF transceiver	Loop + pancake coil	No	-	93	-	-	[15]
15	-	H-bridge	Litz wire	Yes	2,000	95	-	-	[16]
18	145	-	Litz wire	Yes	300-3,000	-	-	90	[17]–[19]
20	4,000	Class-E	Copper wire coil	No	2	-	50	-	[20]
20	20	H-bridge	Power lines	Yes	60,000	80	-	-	[21]
20	20	H-bridge	Power rail	Yes	27,000	-	-	74	[22]
30	3,700	HF transceiver	Surface spiral	No	220	95	-	-	[10]
30	**6,000**	**Class-E**	**Copper pipe coils**	**No**	**95**	-	**77**	**-**	**[our work]**
18-30, 40*	20	H-bridge	-	Yes	3,000	-	-	> 85	[23], [24]
70	7,650	Signal generator	Loop + pancake coil	No	30	75	-	-	[25]
50	13,560	Class-E	Loop + rectangle coil	No	70	85	70**	-	[11]
50	27,000	HF transceiver	Loop + spiral coil	No	40	47	-	-	[8]
100	508.5	Class-D	Litz wire	No	5-35	76	-	-	[26]
200	9,900	Colpitts oscillator	Litz wire	No	60	50	-	15	[9]

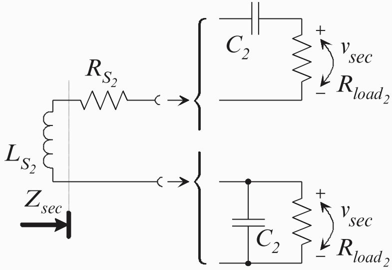
Kurs 2007

[8] Pinuela, Yates, Lucyszyn, and Mitcheson 2013

Receiver resonance choice

Optimum load:

$$R_{load_2} = \frac{\alpha}{\omega C_2}$$



Series Tuned – Current Source

- The current is sinusoidal
  $i_{sec} = I\sin(\omega t)$ (No DC path!)
- Optimal load resistance tends to be low
- Output voltage tends to be low
- $\alpha = \frac{\sqrt{1+k^2Q_1Q_2}}{Q_2}$

Parallel Tuned – Voltage Source

- The voltage is sinusoidal
  $v_{sec} = V\sin(\omega t)$
- Optimal load resistance tends to be high
- Output voltage tends to be high
- $\alpha = \frac{Q_2}{\sqrt{1+k^2Q_1Q_2}}$

Tutorial

Class E Resonant Inverter

Quiz 2!

Why is it advantageous to use soft-switching inverters?

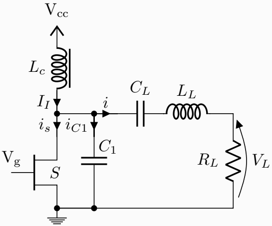
(A) They allow to turn on the switch at zero voltage, avoiding the switching losses
(B) They allow higher switching frequencies
(C) They allow to turn on the switch at zero voltage derivative, avoiding switching losses
(D) All of the above

`qdle.net/44006612`

Inverter and Losses

There are two types of losses in power devices

- Conduction losses, proportional to the square of current
- Switching losses, proportional to frequency
  - Can be eliminated using soft-switching techniques and enable high frequencies
- The need is to find a suitable soft-switching resonant inverter able to efficiently drive the primary coil



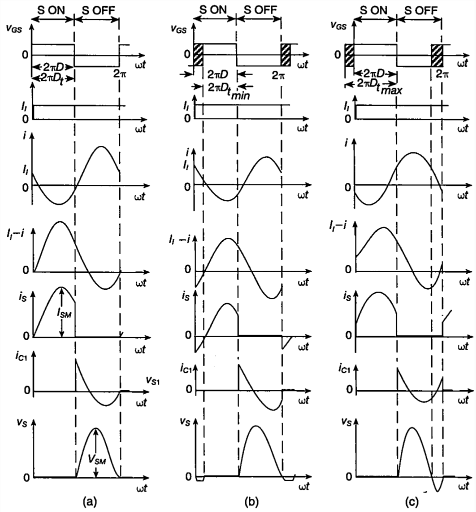
- The Class E Zero Voltage Switching (ZVS) inverter [9], [10]
  - Soft-switching resonant inverter
  - The most efficient inverters known so far

---

[9] Sokal and Sokal, 1975.

[10] Kazimierczuk, 2011.

Zero Voltage Switching (ZVS)



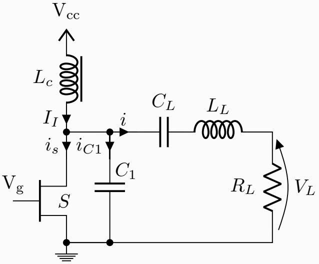
(a) (b) (c)

(a) optimum operation, (b) suboptimum operation with $dv_s(\omega t)/d(\omega t) < 0$, (c) $dv_s(\omega t)/d(\omega t) > 0$, at $\omega t = 2\pi$

- The current and voltage waveform of the switch are designed for high efficiency operation by turning on the switch at zero voltage
- Switch current and voltage waveforms do not overlap during the switching time intervals
- Switching losses are virtually zero, yielding high efficiency

Class E Inverter 1/2

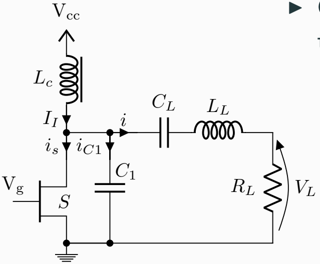
- The choke inductance L_C is assumed to be high enough to force a dc current I_I
- Switch is ON, the resonant circuit consists of L_L, C_L and R_L
- The series L_L-C_L has a slightly inductive reactance
- Switch is OFF, the resonant circuit consists of L_L, C_1, C_L and R_L connected in series
- The load network is characterized by two resonant frequencies and two loaded quality factors



- The turn on ZVS condition is expressed by $v_s(2\pi) = 0$
- ON $f_{o1} = \dfrac{1}{2\pi\sqrt{L_L C_L}}$, $Q_{L1} = \dfrac{\omega_{o1} L_L}{R_L} = \dfrac{1}{\omega_{o1} C_L R_L}$
- To achieve ZVS, $f > f_{o1}$
- OFF $f_{o2} = \dfrac{1}{2\pi\sqrt{\frac{L_L C_L C_1}{C_L + C_1}}}$, $Q_{L2} = \dfrac{\omega_{o2} L_L}{R_L} = \dfrac{1}{\frac{\omega_{o2} L_L C_L C_1}{C_L + C_1}}$
- However, $f < f_{o2}$

Class E Inverter 2/2

- If the loaded quality factor Q is high, i is approximately sinusoidal
- When the switch is ON, the current $I_I - i$ flows through the switch
- When the switch is OFF, the current $I_I - i$ flows through capacitor C_1
- C_1 shapes the voltage across the switch
- A second condition is the zero-derivative switching (ZDS) $\left.\frac{dv_s(\omega t)}{d(\omega t)}\right|_{\omega t=2\pi} = 0$
- With ZDS, Miller's effect is zero
  - The instantaneous voltage gain is zero, $C_{iss} = C_{gs} + C_{gd}$
  - The gate driver is less critical and ground referenced



- Optimum operation can be achieved only at the optimum load resistance $R_L = R_{L_{opt}}$
  - If $R_L > R_{L_{opt}}$, i is not sufficient to discharge C_1 and $v_s > 0$ at turn-on
  - If $R_L < R_{L_{opt}}$, $v_s < 0$ at turn-on
  - The energy in C_1 is dissipated in the transistor at turn-on

Tutorial

Advantages of Wide Bandgap (WBG) semiconductors

Quiz 3!

Why is it advantageous to use Wide Bandgap (WBG) semiconductors?

(A) They are less expensive than silicon

(B) They reduces the ON resistance of power switches

(C) They are more rugged and better support over-currents

(D) None of the above

`qdle.net/44006612`

The power switch

The ideal power switch should

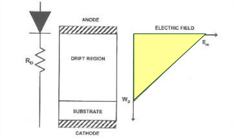
- be able to block high voltages without any leakage current when in the off state
- have zero resistance in the on state
- have an instantaneous switch on and switch off, without any charge storage

In real switches

- Switching losses can be eliminated using soft-switching techniques, i.e. Class E
- To reduce the conduction losses and increase the efficiency, the ON resistance of the switch (R_{on}) must be reduced
  - by using new device's structures (Super Junction, V-MOS, HEMT, ...)
  - by using WBG Semiconductors (GaN, SiC, Diamond, AlN, ...)

Reducing R_{on}: New device's structures

- 1D Abrupt Junction

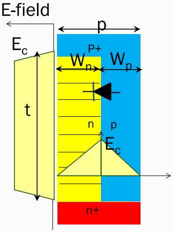


$$E(x) = \frac{-qN_D}{\varepsilon}(W_D - x)$$

$$V_{bd} = \frac{qN_D W_D^2}{2\varepsilon} \quad E_C = \frac{qN_D W_D}{\varepsilon}$$

$$R_{on} = \frac{W_D^2}{\mu_n \varepsilon E_C} = \frac{4V_{bd}^2}{\mu_n \varepsilon E_C^3}$$

- 2D Resurf Junction



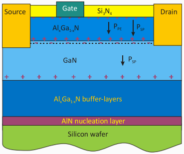
E_C is sum of two contributes

$$E_C = \frac{qN_n W_n}{\varepsilon} + \frac{qN_p W_p}{\varepsilon}$$

$$R_{on} = \frac{2pV_{bd}}{E_C^2 \varepsilon \mu_n}$$

The Resurf increases the breakdown voltage by shaping the electric field

- High Electron Mobility Transistor (HEMT)

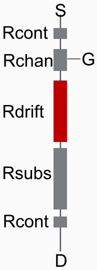


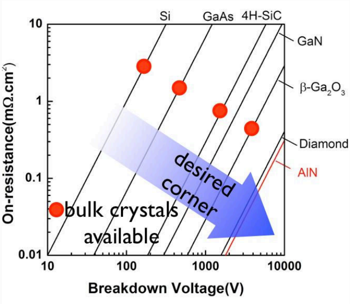
- 2DEG channel instead of a doped region
- 2DEG originates from an heterojunction between polar crystals with different electro-negativity (as GaN and AlGaN)
- Low C_{oss}, no junctions to be depleted
- High speed, majority carrier device
- High breakdown voltage, semiconductor is undoped and behaves as dielectric
- Low Ron, due to high 2DEG density

$$R_{on} = \frac{4}{qN_s\mu_N}\frac{V_{bd}^2}{E_C^2}$$

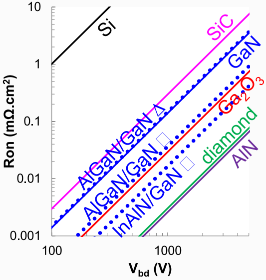
Reducing R_{on}: WBG Semiconductors

- R_{on} is reduced with an higher critical field E_C, which is obtained with high bandgap (3.4 eV for GaN)
- HEMT devices needs polar crystals (GaN and AlGaN)
- The market is currently governed by two materials, the Gallium Nitride (GaN) and the Silicon Carbide (SiC)
  - SiC is quite mature, especially for Schottky diodes (600 V to few kV)
  - GaN is less mature, uses HEMT transistors (100 V to 600 V)





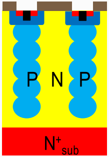
1D Abrupt Junction

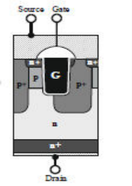


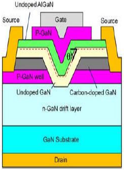
HEMT

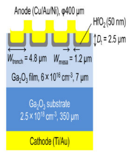
The modified Baliga's FoM with $

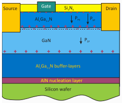
	Si SJ	SiC TrenchMOS	GaN V-MOS	Ga_2O_3	HEMT
Rcont	Very low	low	<5%	<5%	~10%
Rsubs	<3mΩ.cm	20mΩ.cm	10mΩ.cm	6mΩ.cm	NA
Rdrift	$Ron = \frac{2.V_{bd}}{{E_C}^2.\varepsilon.\mu_N}$	$Ron = \frac{4.{V_{bd}}^2}{{E_C}^3.\varepsilon.\mu_N}$	$Ron = \frac{4.{V_{bd}}^2}{{E_C}^3.\varepsilon.\mu_N}$	$Ron = \frac{4.{V_{bd}}^2}{{E_C}^3.\varepsilon.\mu_N}$	$Ron = \frac{1}{q.n_s.\mu_N} \cdot \frac{{V_{bd}}^2}{{E_c}^2}$
Rchannel	low	high	Medium	?	Very low
Wafer (mm)	200-300	100-150	75-100	50-100	150-200
Cost/wfr ($)	low	high	Very high	medium	low







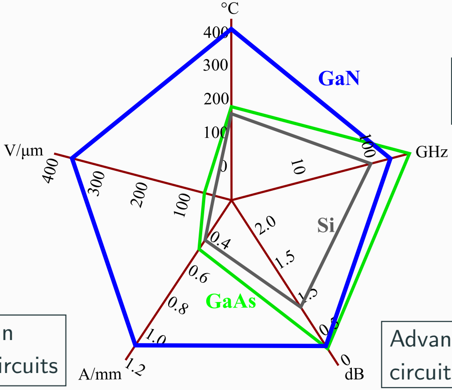




So, why do we need WBG semiconductors?

Advantageous in power supply circuits

High operating temperature
Due to large bandgap and high potential barrier



Advantageous in power supply circuits

High breakdown strength
and low R_{on}
Due to large bandgap

Advantageous in RF circuits

High maximum
oscillation frequency
Due to high electric field
saturation speed and low
parasitic capacity

Advantageous in power supply circuits

High maximum current
Due to high carrier density
and high electron mobility

Advantageous in RF circuits

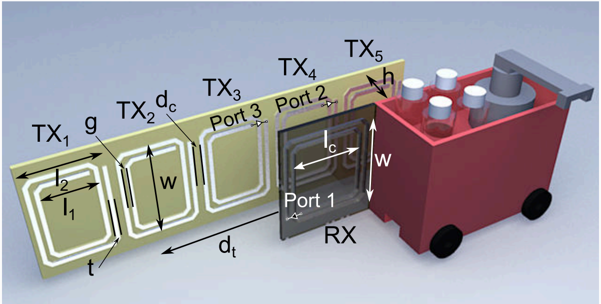
Superior noise factor
Due to low carrier scattering
and low RF losses

Research Contribution

Design of a Position-Independent End-to-End Inductive WPT Link for Industrial Dynamic Systems

Sliding carts in industrial plants

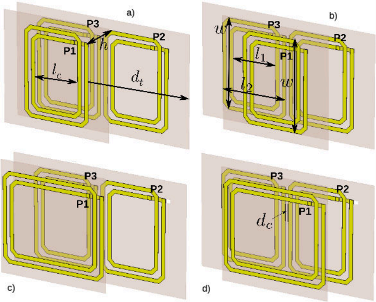
GOAL: to maintain a constant output voltage independently from position and load



Dimensions (cm):
$l_c = 17.2,\ l_1 = 12$
$l_2 = 18,\ d_c = 2$
$w = 24,\ g = 1,$
$t = 1,\ h = 6$

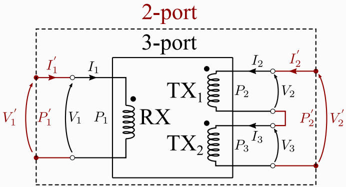
EM-based RX coil layout optimization: Series connection

- RX slides from a) to b) at a distance of 6 cm
- EM based optimization of the three-port network [11], [12]: P1 (RX), P2 (TX1), P3 (TX2)



$$l_c^{opt} \sim l_1 + \frac{l_2 - l_1}{2} + d_c$$

$$k_{RX_S} = \frac{1}{\sqrt{2}} \frac{k_{RX_1} + k_{RX_2}}{\sqrt{1 + k_{TX}}}$$

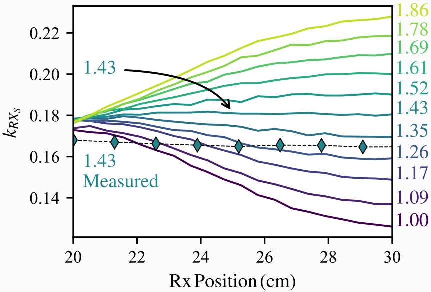


---

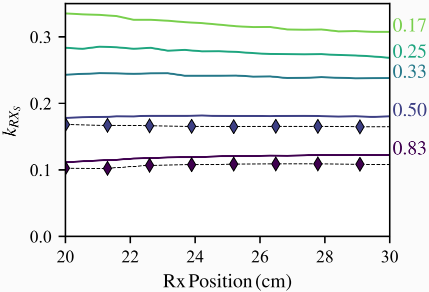
[11] Pacini, Mastri, Trevisan, Costanzo, and Masotti, 2016.

[12] Pacini, Mastri, Trevisan, Masotti, and Costanzo, 2016.

AC-AC link: two series connected TX and optimized RX

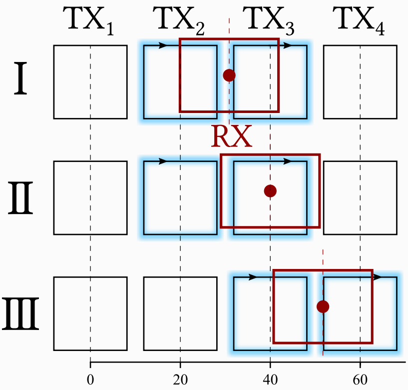


Predicted and measured coupling coefficient for the RX layout with different l_c (normalized to l_1)



Predicted and measured coupling coefficient for variable RX-TX distances h (normalized to l_1) with the optimum $l_c = 1.43$

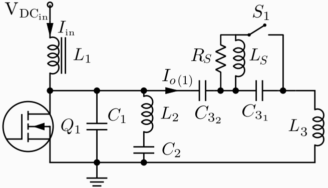
Sliding Positions



- The powered coils are highlighted
- The RX slides along the whole path (zero is RX/TX$_1$ centres aligned)
- When the RX aligns with a new TX coil, the previous is turned off while the next is turned on
- The behaviour is thus periodic and can be unlimited

Distributed Current Sources along the TX coils

- The series connection of two coils can be obtained *virtually* by forcing the same current
- A stand-alone Class EF Inverter [13] provides a constant current source with a dc-RF efficiency over 90% at 6.78 MHz
- The load can vary but must be resistive and $0 < R_L < R_{L_{\mathrm{MAX}}}$
- The inverter topology is modified to account for closely located coils when the RX is moving [14], [15] (the residual inductance must be the same)



$$L_{TX(n)} \simeq L_3\left(1+k_{TX}\right), \quad C_{3_2} = \beta C_{3_1}$$

$$C'_{3(n)} = \frac{C_3}{1+\left(\frac{\omega}{\omega_r}\right)^2 k_{TX}}, \text{ where } \omega_r = \frac{1}{\sqrt{C_3 L_3}}$$

$$C_{3_1} = C'_{3(n)}\left(\frac{\beta+1}{\beta}\right), \quad C_{3_2} = C'_{3(n)}\left(\beta+1\right)$$

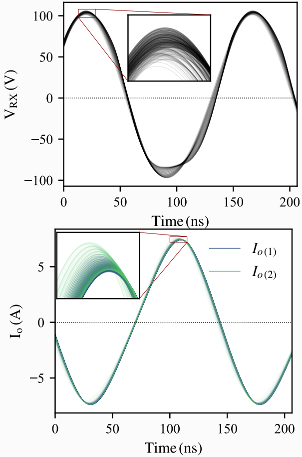
---

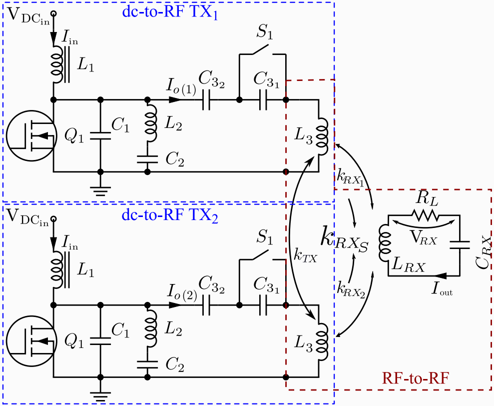
[13] Aldhaher, Mitcheson, and Yates, 2016.

[14] Pacini, Costanzo, Aldhaher, and Mitcheson, 2017.

[15] Pacini, Costanzo, Aldhaher, and Mitcheson, In Press.

Same RF current for all RX positions!

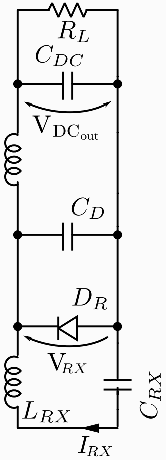




20 different Rx positions
(over 10 cm)
30 different Rx loads
$10\,\Omega < R_L < 1\,\mathrm{k}\Omega$

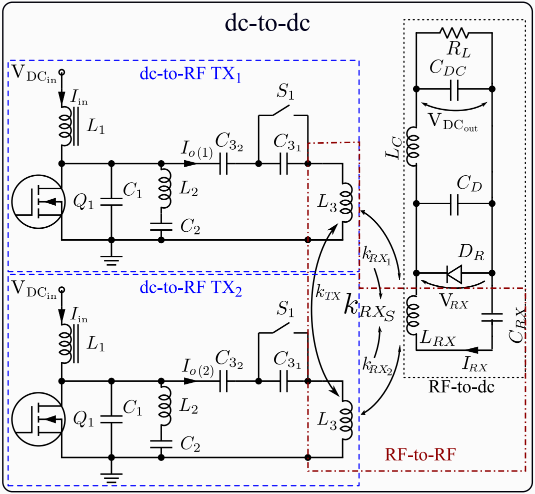
- One inverter for each TX coil
- Fully modular design
- Each line is a different load/position (600 in total)

Class E Rectifier design

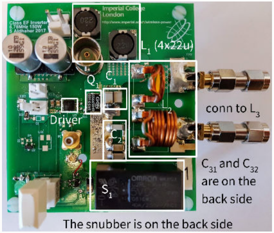


- Challenging RF-to-dc resonant rectifier specs
  - Efficient
  - Must provide a quasi-zero input reactance for any dc-load of interest, since the inverter requires a resistive load
  - To act as dc voltage source (constant $V_{DC_{out}}$)
- Non-ordinary class E design
  - The input reactance of the usual class E depends on the duty cycle which depends on the dc load
  - The rectifier must be optimised attached to the whole dc-to-RF link to account all the mutual effects
  - Optimization variables: C_D, C_{RX}
  - Optimization goals: constant $V_{DC_{out}}$, maximize dc-to-dc efficiency of the entire link
  - HB reduces simulation time by three orders

Overall DC-to-DC system design



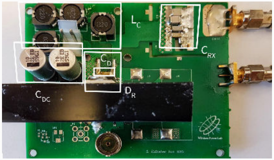
Inverter:



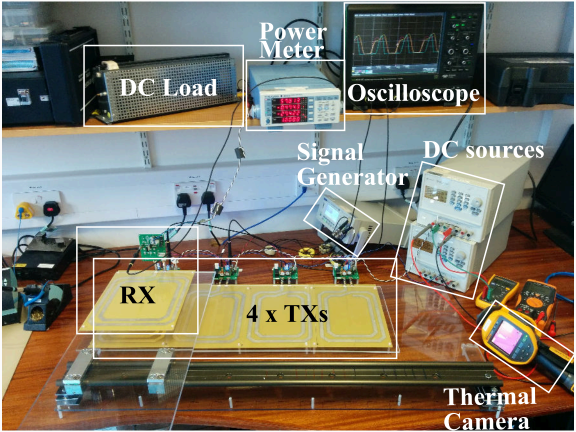
C_{31} and C_{32} are on the back side

The snubber is on the back side

Rectifier:



Measurement setup

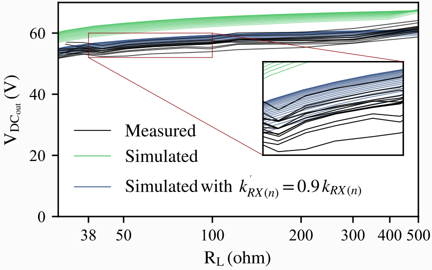


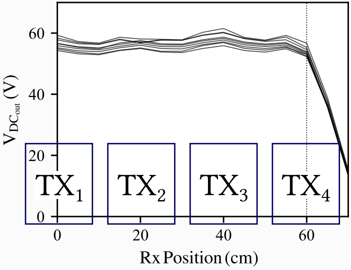
Inverter:	**Standalone [13]**	**Coupled [14], [15]**	
	Simulated	Simulated	Prototype
L_1	88 μH	88 μH	88 μH
L_2	270 nH	270 nH	283 nH
L_3	1.42 μH	1.42 μH	1.42 μH
C_1	830 pF	830 pF	660 pF
C_2	718 pF	718 pF	696 pF
C_3	480 pF	—	—
C_{3_1}	—	530 pF	526 pF
C_{3_2}	—	4.7 nF	4.7 nF
Q_1	50 mΩ (R_{on})	50 mΩ (R_{on})	GS66504B
R_S	—	10 kΩ	10 kΩ
L_S	—	250 nH	250 nH
k_{TX}	—	−0.0595	−0.0595
D	0.32	0.32	0.32
f	6.78 MHz	6.78 MHz	6.81 MHz
Rx load:	**Resistive**	**Rectifier**	
	Simulated	Simulated	Prototype
L_C	88 μH	88 μH	88 μH
L_{RX}	1.7 μH	1.7 μH	1.7 μH
C_D	—	33 pF	30 pF
C_{DC}	—	20 μF	20 μF
C_{RX}	324 pF	498 pF	498 pF
D_R	—	2 x C3D1P7060Q	C3D02060F

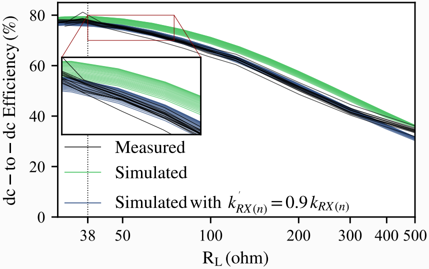
---

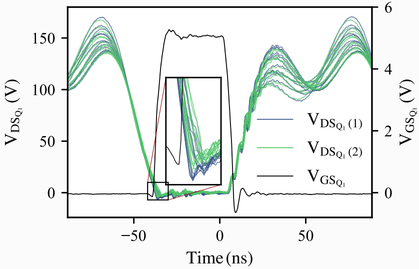
[13] Aldhaher, Mitcheson, and Yates, 2016.
[14] Pacini, Costanzo, Aldhaher, and Mitcheson, 2017.
[15] Pacini, Costanzo, Aldhaher, and Mitcheson, In Press.

Measurements









Conclusions

In these two years

- We developed a system capable of maintaining a constant output voltage, independent of the position and load
- The soft switching efficient operation is also maintained, independent of the position and load

In the next year, I plan to

- include the ability to transfer data with high data rates
- design a system with a different topology and lower frequency for transferring more power to industrial systems

Acknowledgments

I would like to thank Prof. Alessandra Costanzo, Prof. Franco Mastri and Prof. Diego Masotti for their invaluable help during these first two years.

I would also like to thank Prof. Paul Michelson and Samer Aldhaher for their support during the period spent at the Imperial College.

Part of the work was funded from the COST Action IC1301 WiPE and from the Imperial College.

Publications in journals i

- A. Pacini, A. Costanzo, S. Aldhaher, and P. D. Mitcheson, "Load- and Position- Independent Moving MHz WPT System Based on GaN Distributed Current Sources," *IEEE Transactions on Microwave Theory and Techniques*, In Press
- A. Pacini, A. Costanzo, and D. Masotti, "A theoretical and numerical approach for selecting miniaturized antenna topologies on magneto-dielectric substrates," *Int. J. Microw. Wireless Technol.*, vol. 7, no. 3-4, pp. 369–377, 2015

Publications at conferences i

- A. Pacini, A. Costanzo, S. Aldhaher, and P. D. Mitcheson, “Design of a Position-Independent End-to-End Inductive WPT Link for Industrial Dynamic Systems,” in *2017 IEEE MTT-S International Microwave Symposium (IMS)*, 2017, pp. 1053–1056
- A. Pacini, F. Mastri, R. Trevisan, D. Masotti, and A. Costanzo, “Geometry optimization of sliding inductive links for position-independent wireless power transfer,” in *IEEE MTT-S International Microwave Symposium (IMS)*, Institute of Electrical and Electronics Engineers (IEEE), 2016
- A. Pacini, F. Mastri, R. Trevisan, A. Costanzo, and D. Masotti, “Theoretical and Experimental Characterization of Moving Wireless Power Transfer Systems,” in *2016 10th European Conference on Antennas and Propagation (EuCAP)*, Institute of Electrical and Electronics Engineers (IEEE), 2016, pp. 1–4

Publications at conferences ii

- A. Pacini, A. Costanzo, and D. Masotti, "A theoretical and numerical approach for selecting miniaturized antenna topologies on magneto-dielectric substrates," in *2014 44th European Microwave Conference*, Institute of Electrical & Electronics Engineers (IEEE), 2014

References i

[1] N. Tesla, *Apparatus for transmitting electrical energy.* US Patent 1,119,732, 1914.

[2] D. Schneider, "Electrons Unplugged," *IEEE Spectrum*, vol. 47, no. 5, pp. 34–39, 2010.

[3] G. Joung and B. Cho, "An energy transmission system for an artificial heart using leakage inductance compensation of transcutaneous transformer," in *PESC Record. 27th Annual IEEE Power Electronics Specialists Conference*, IEEE, 1996.

[4] S. Y. R. Hui, W. Zhong, and C. K. Lee, "A critical review of recent progress in mid-range wireless power transfer," *IEEE Transactions on Power Electronics*, vol. 29, no. 9, pp. 4500–4511, 2014.

[5] S. Ahn, N. P. Suh, and D.-H. Cho, "Charging up the road," *IEEE Spectrum*, vol. 50, no. 4, pp. 48–54, 2013.

[6] K. V. Schuylenbergh and R. Puers, *Inductive Powering: Basic Theory and Application to Biomedical Systems*. Springer, 2009.

[7] T. Ohira, "The kQ product as viewed by an analog circuit engineer," *IEEE Circuits and Systems Magazine*, vol. 17, no. 1, pp. 27–32, 2017.

References ii

[8] M. Pinuela, D. C. Yates, S. Lucyszyn, and P. D. Mitcheson, "Maximizing DC-to-load efficiency for inductive power transfer," *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2437–2447, 2013.

[9] N. Sokal and A. Sokal, "Class e-a new class of high-efficiency tuned single-ended switching power amplifiers," *IEEE Journal of Solid-State Circuits*, vol. 10, no. 3, pp. 168–176, 1975.

[10] M. Kazimierczuk, *Resonant power converters*, 2nd ed. Hoboken, N.J: Wiley, 2011.

[11] A. Pacini, F. Mastri, R. Trevisan, A. Costanzo, and D. Masotti, "Theoretical and Experimental Characterization of Moving Wireless Power Transfer Systems," in *2016 10th European Conference on Antennas and Propagation (EuCAP)*, Institute of Electrical and Electronics Engineers (IEEE), 2016, pp. 1–4.

[12] A. Pacini, F. Mastri, R. Trevisan, D. Masotti, and A. Costanzo, "Geometry optimization of sliding inductive links for position-independent wireless power transfer," in *IEEE MTT-S International Microwave Symposium (IMS)*, Institute of Electrical and Electronics Engineers (IEEE), 2016.

References iii

[13] S. Aldhaher, P. D. Mitcheson, and D. C. Yates, "Load-independent Class EF inverters for inductive wireless power transfer," in *2016 IEEE Wireless Power Transfer Conference, WPTC 2016*, 2016, pp. 1–4.

[14] A. Pacini, A. Costanzo, S. Aldhaher, and P. D. Mitcheson, "Design of a Position-Independent End-to-End Inductive WPT Link for Industrial Dynamic Systems," in *2017 IEEE MTT-S International Microwave Symposium (IMS)*, 2017, pp. 1053–1056.

[15] A. Pacini, A. Costanzo, S. Aldhaher, and P. D. Mitcheson, "Load- and Position-Independent Moving MHz WPT System Based on GaN Distributed Current Sources," *IEEE Transactions on Microwave Theory and Techniques*, In Press.

[16] A. Pacini, A. Costanzo, and D. Masotti, "A theoretical and numerical approach for selecting miniaturized antenna topologies on magneto-dielectric substrates," *Int. J. Microw. Wireless Technol.*, vol. 7, no. 3-4, pp. 369–377, 2015.

[17] A. Pacini, A. Costanzo, and D. Masotti, "A theoretical and numerical approach for selecting miniaturized antenna topologies on magneto-dielectric substrates," in *2014 44th European Microwave Conference*, Institute of Electrical & Electronics Engineers (IEEE), 2014.

Thanks for your attention!

Any questions?