UNIVERSITY OF MINNESOTA

Towards a wireless future: Next-generation power electronics

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Wireless charging

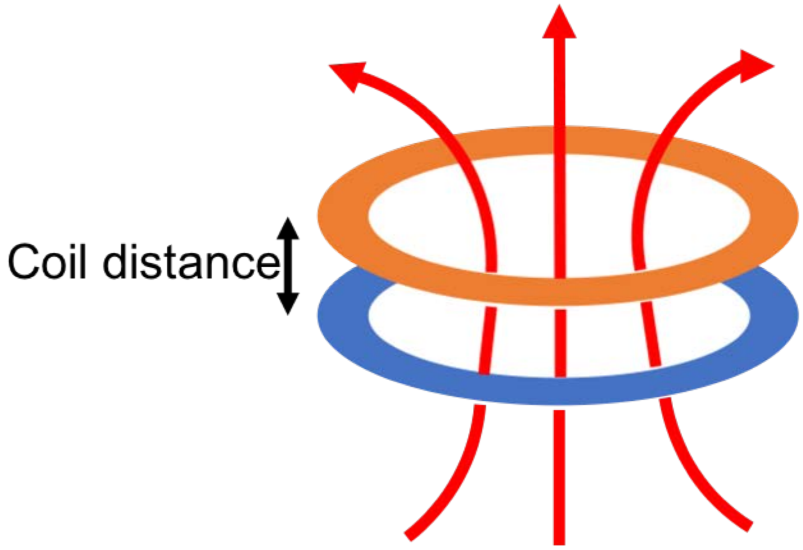
Short-range distance/ Small-power applications

Photo by Engadget

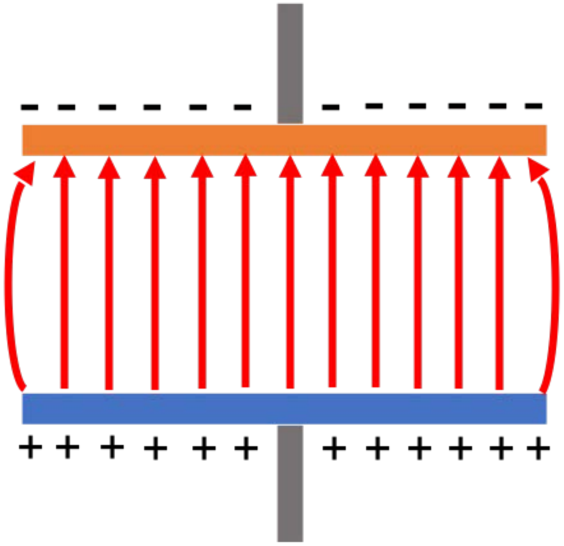
Mid-range distance/ High-power applications

Photo by Qualcomm

Wireless power transfer:
Transmission of electrical energy without wires

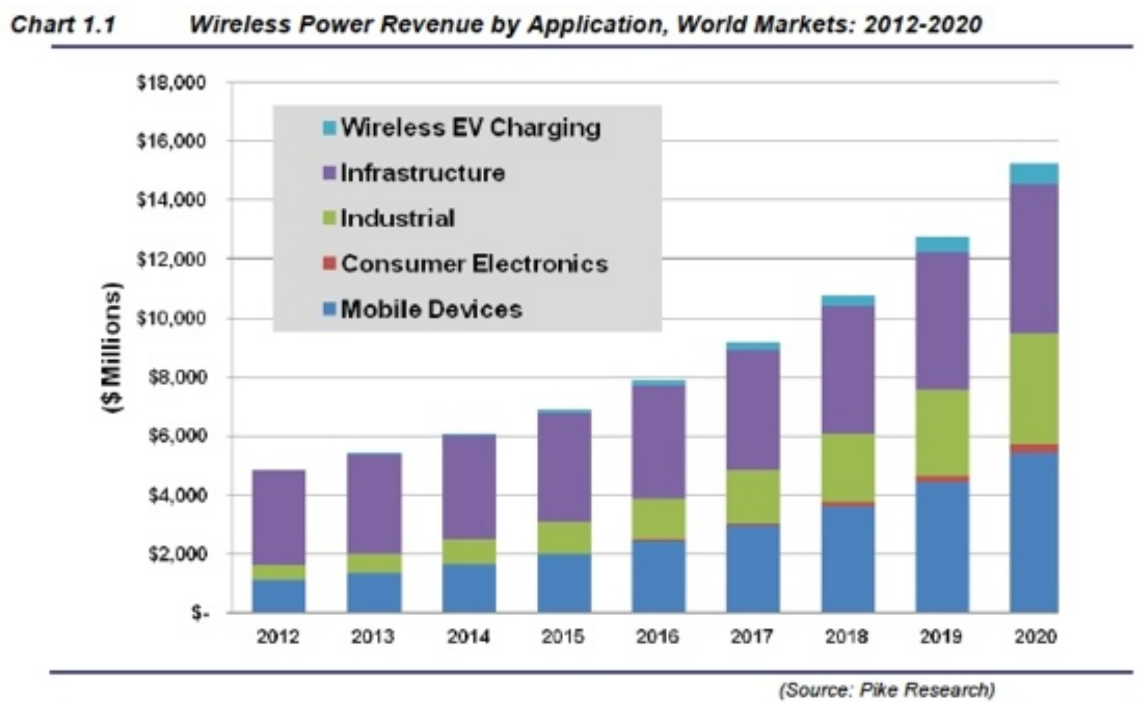


Inductive coupling



Capacitive coupling

Wireless Power Transfer Revenue by Application



http://www.navigantresearch.com/wp-content/uploads/2012/07/WPOW-12-Executive-Summary.pdf

Automation in factory/warehouse

Photo by Business insider

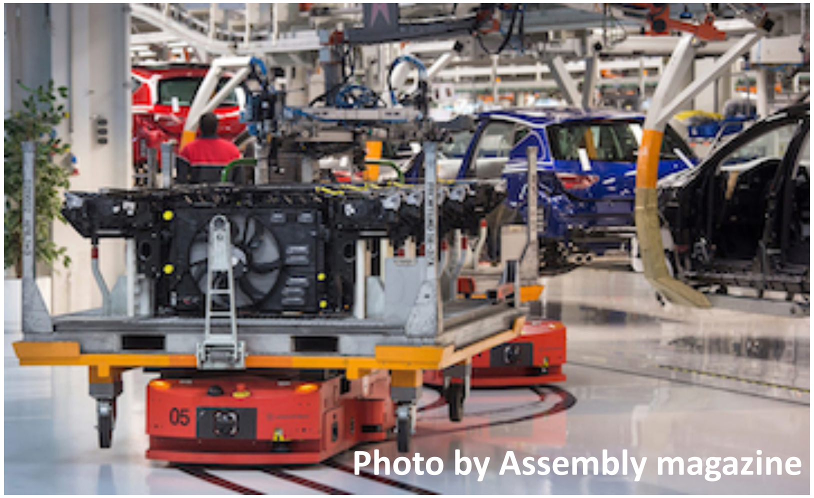


Photo by Assembly magazine

Photo by Amazon

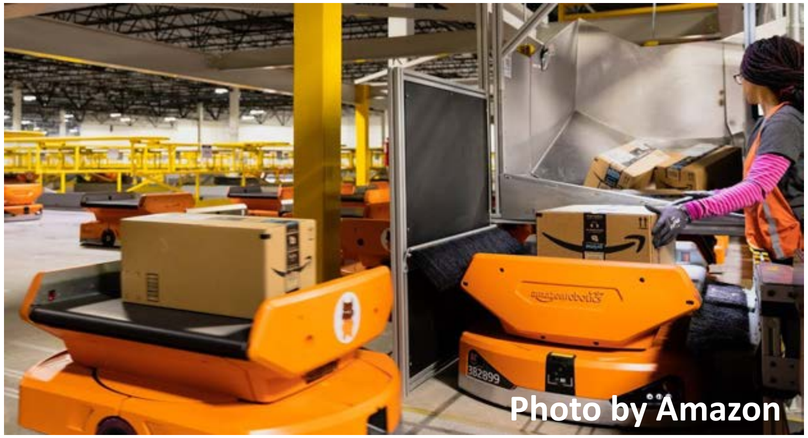
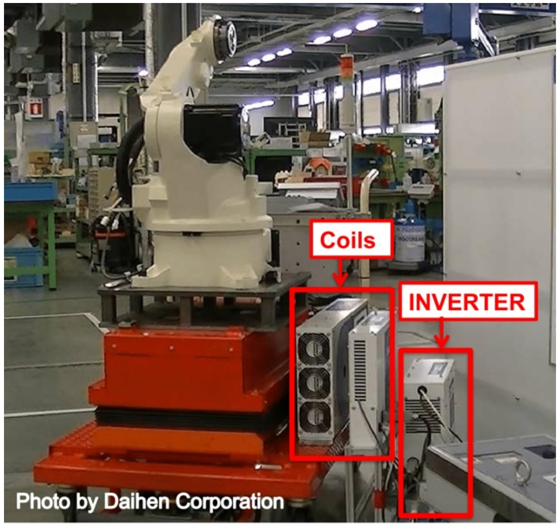


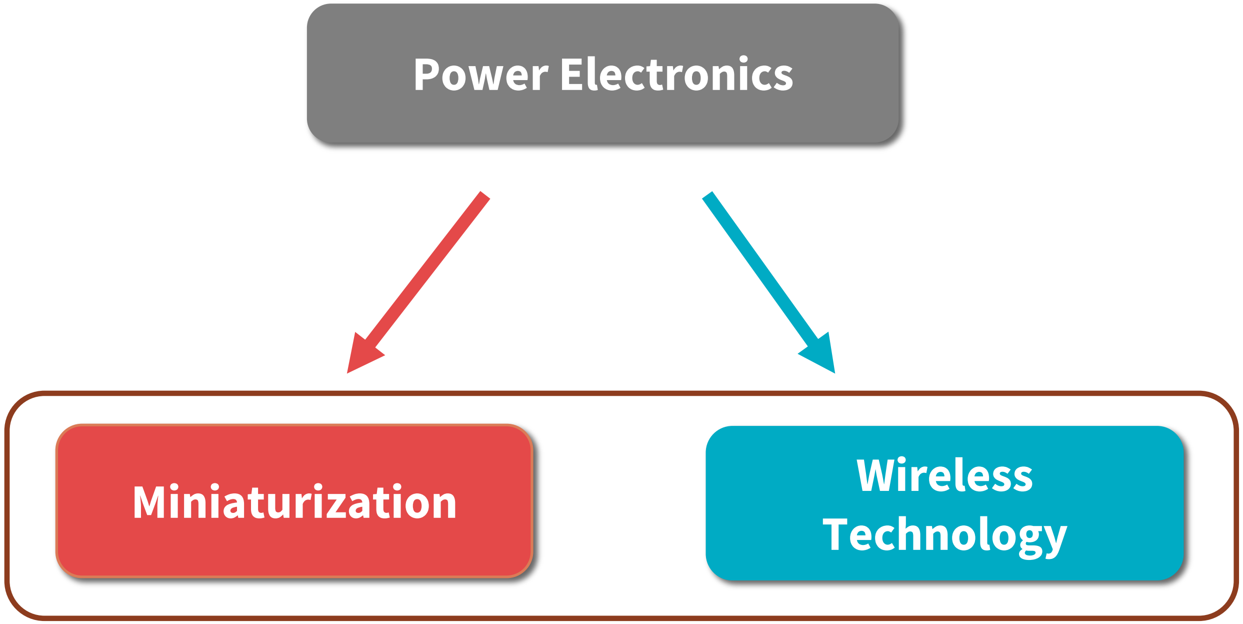
Photo by Amazon

WPT in AGV



- Developing WPT system for automated guided vehicles (AGVs).
- The WPT charging battery for these applications: up to 2 kW.
- We need to reduce the volume and weight of WPT systems for AGVs while maintaining high efficiency.

Towards a wireless future:
Bridging between power electronics and needs of modern technology



How to miniaturize power converter

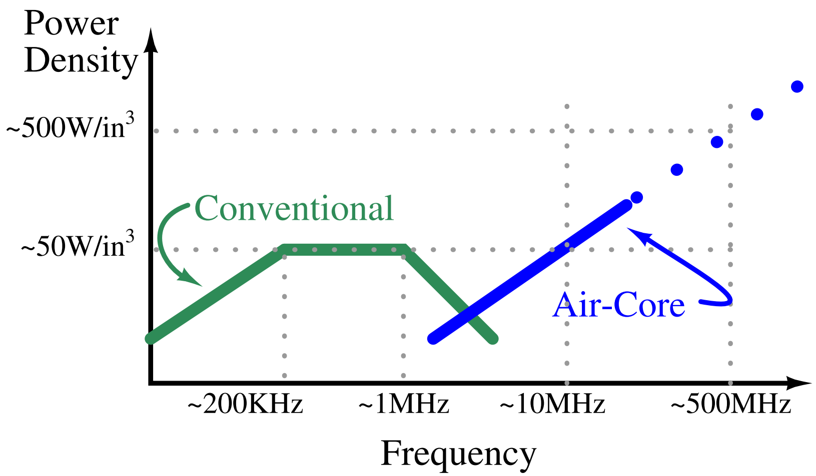
Foot print: 12 x 12 mm^2

Foot print: 7 x 7 mm^2

Increasing switching frequency

- Increasing switching frequency
  - Reducing energy storage requirements
  - Fast response

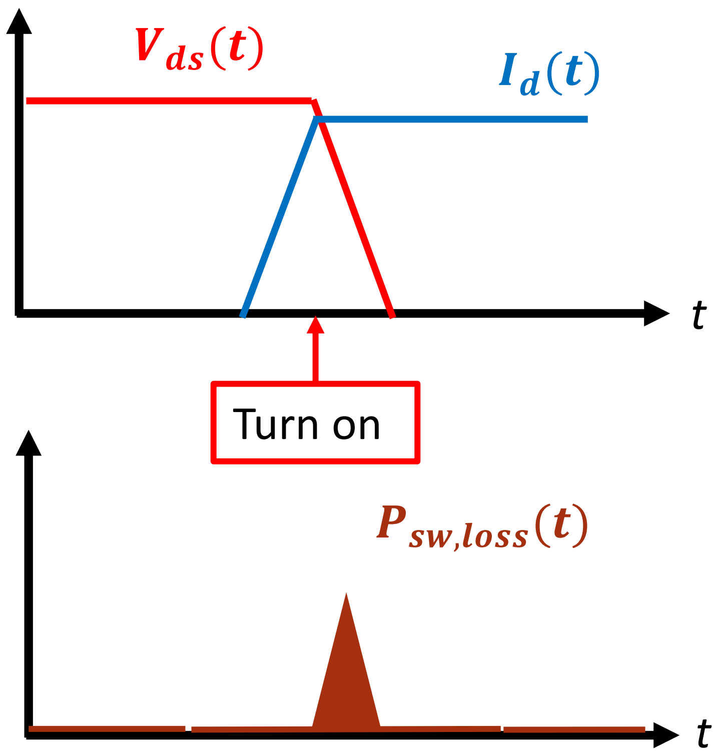
Advantage of 10's of MHz operation



- Increasing power density
- **Air-core inductors:** No core losses

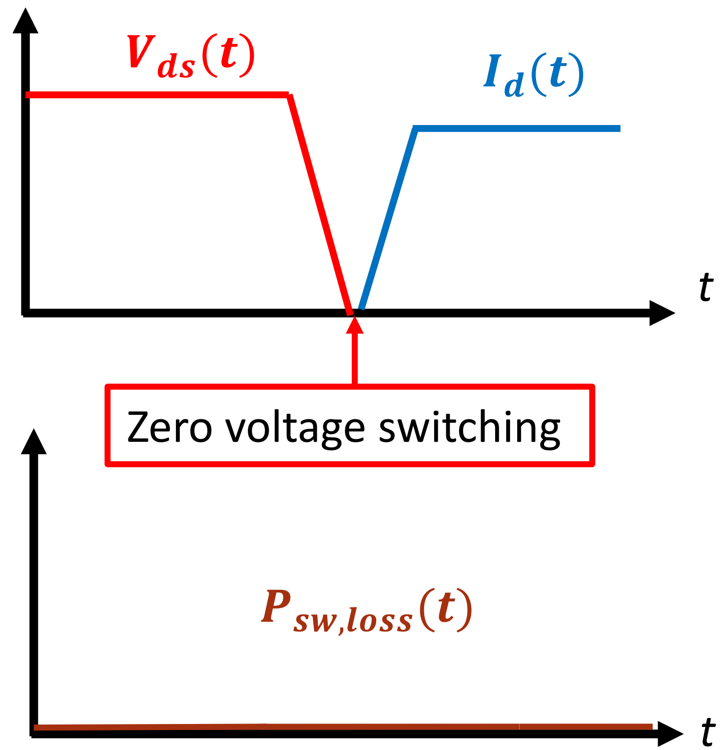
Switching losses at 10's of MHz

Hard switching operation



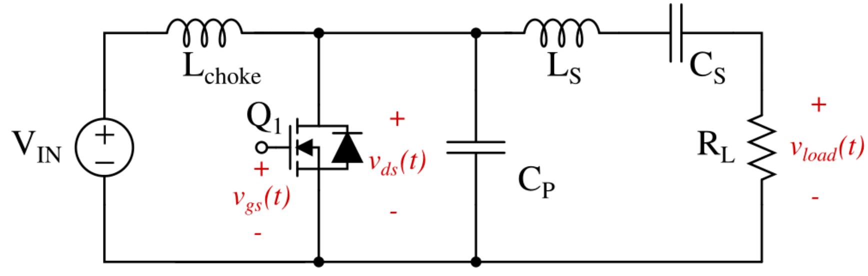
Conventional converter

Soft switching operation

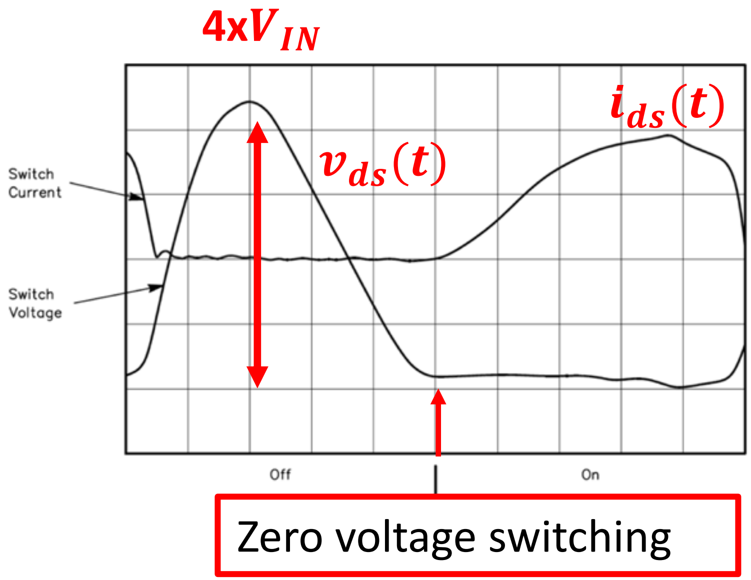


Resonant converter

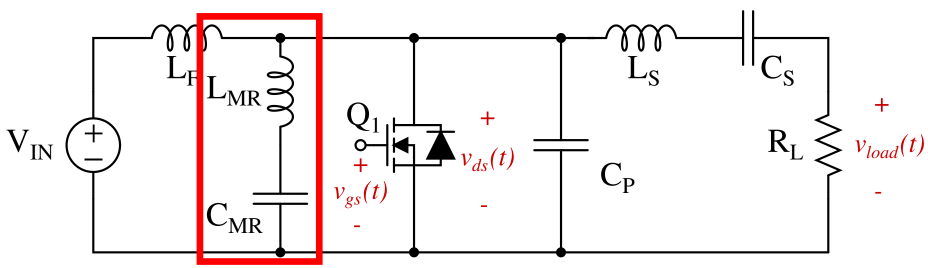
Single-ended resonant inverter



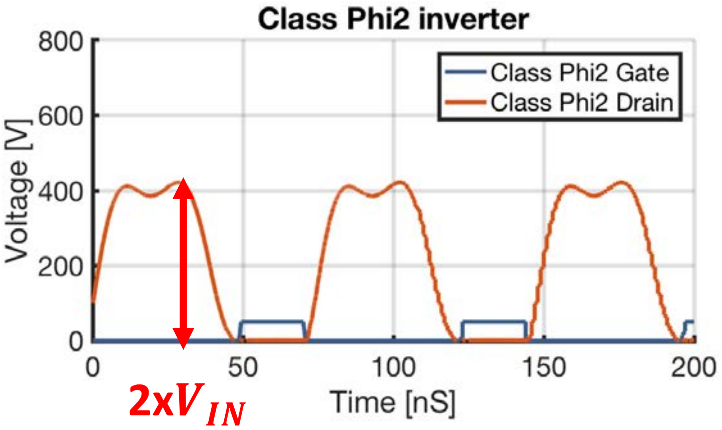
Class E inverter



G D Ewing, ” High-efficiency radio-frequency power amplifiers," In 1965.

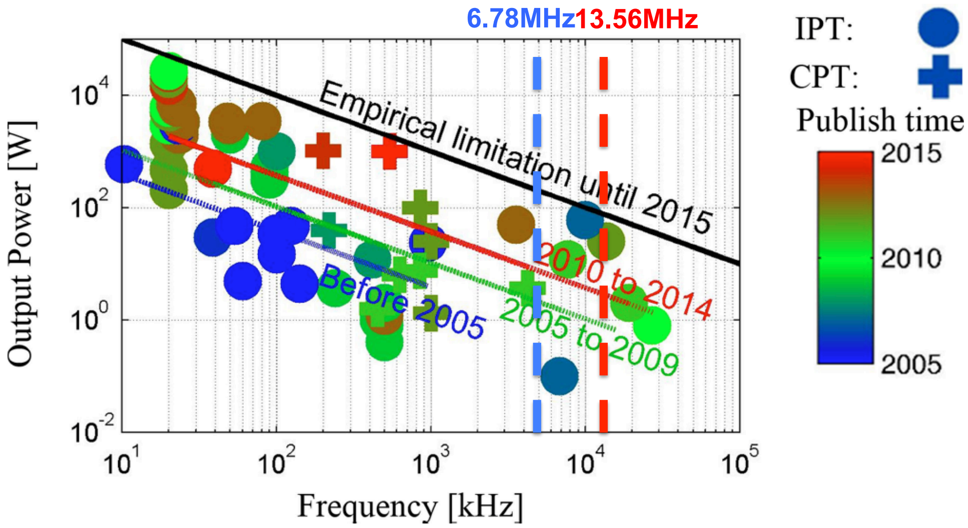


Class Φ_2 inverter



J M Rivas, ” A High-Frequency Resonant Inverter Topology With Low-Voltage Stress," In TPEL, 2018.

Output power vs switching frequency in WPT



- P_{OUT} in WPT decreases in a linear trend with frequency.
- This limitation is primarily determined by power electronics limitations.
- Thanks to **wide band gap devices**, P_{OUT} and F_S increased 10 times in the last 10 years.

J. Dai, "A Survey of Wireless Power Transfer and a Critical Comparison of Inductive and Capacitive Coupling for Small Gap Applications," In IEEE Transactions on Power Electronics}, vol. 30, pp. 6017-6029, 2015.

Wide band gap materials

Parameters	Si	4H-SiC	GaN	Diamond
Energy bandgap, E_g(eV)	1.1	**3.3**	**3.4**	**5.5**
Critical Electric field, E_C(MV/cm)	0.25	**2.2**	**3**	**10**
Electron drift velocity, v_{sat}(cm/s)	$1{\times}10^7$	$\mathbf{2{\times}10^7}$	$\mathbf{2.2{\times}10^7}$	$\mathbf{2.7{\times}10^7}$
Thermal conductivity, λ(W/cm-K)	1.5	**4.9**	1.3	**22**

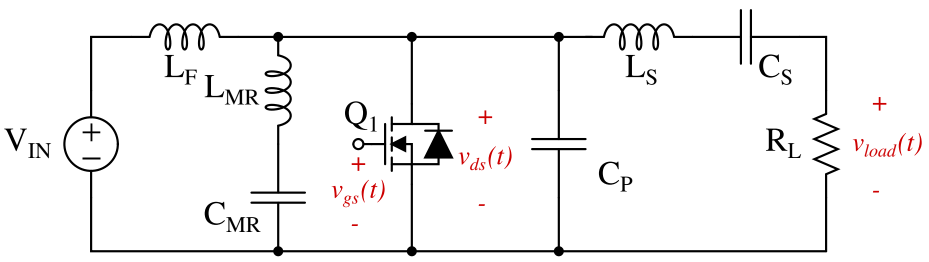
- The advent of wide band gap materials
  - Wider energy bandgap and larger E-field: higher breakdown voltage
  - Higher electron saturation velocity: higher switching frequencies
  - Higher thermal conductivity (e.g., SiC and diamond): improving heat spreading

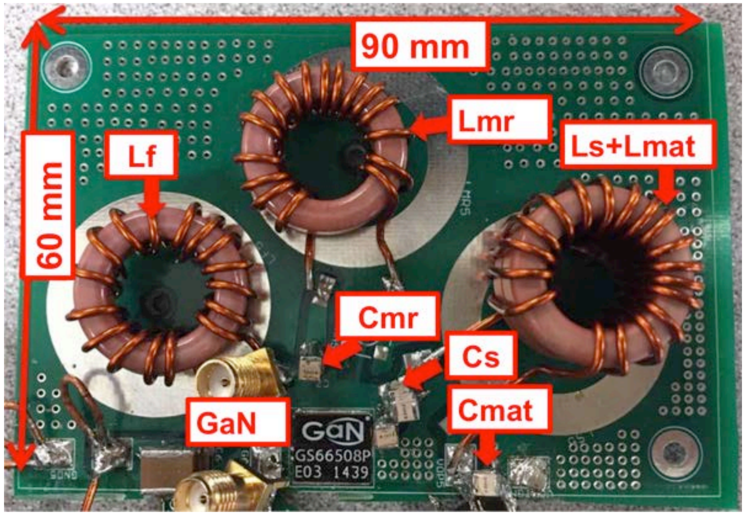
Enhancement-mode GaN FET

Parameters	Si MOSFET ARF 521	eGAN FET GS66508P
V_{BR}	500 V	**650 V**
$R_{DS,ON}$ @ $25^{o}C$	560 $m\Omega$	**52 $m\Omega$**
$R_{DS,ON}$ @ $150^{o}C$	-	140 $m\Omega$
$C_{ISS} = C_{gs} + C_{gd}$	780 pF	**200 pF**
$C_{OSS} = C_{ds} + C_{gd}$	125 pF	67 pF
$C_{RSS} = C_{gd}$	7 pF	2 pF
R_G	0.56 Ω	1.5 Ω

- eGaN FET characteristics
  - Low drain-source on-resistance at room temperature
  - Low gate capacitance

Class Φ_2 Inverter with eGaN FET



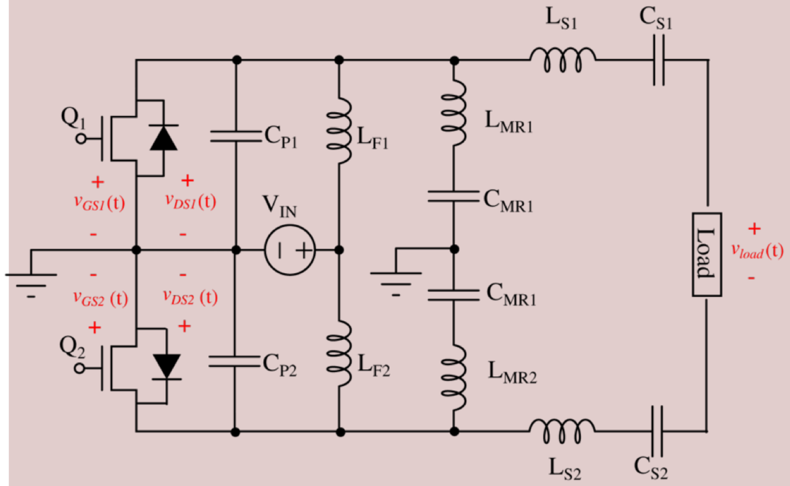


- Class $\Phi_2$inverter topology: reducing $V_{DS,MAX}$ and using single device.
- Inductors : air core inductors.
- With 50 Ω load, $P_{IN} = 1450\,W, P_{OUT} = 1371\,W$ with efficiency of 94% at $V_{IN} = 280\,V, F_s = 13.56\,MHz$.
- Power density: 105 W/in^3

How to increase output power to 2 kW?

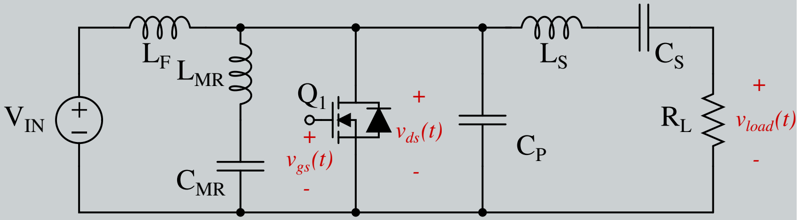
Approach 1

- eGaN FET (650 V rating)
- Push-pull class Φ_2 inverter



Approach 2

- SiC MOSFET (1200 V rating)
- Single-ended class Φ_2 inverter



J Choi, et al, "Comparison of SiC and eGaN devices in a 6.78 MHz 2.2 kW resonant inverter for wireless power transfer," 2016 IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, 2016, pp. 1-6

Comparison of eGaN FETs and SiC MOSFETs

	Approach 1	Approach 2
Parameters	**eGaN FET**	**GE SiC MOSFET**
Package	GaNpx 	DE-150 
V_{BR}	650 V	**1200 V**
I_D	30 A	60 A
$R_{DS,ON}$ @ $25^o C$	55 $m\Omega$	**25 $m\Omega$**
$R_{DS,ON}$ @ $150^o C$	140 $m\Omega$	-
$R_{DS,ON}$ @ $175^o C$	-	**42 $m\Omega$**
C_{ISS}	**260 pF**	**3164 pF**
C_{OSS}	**65 pF**	199 pF
R_G	1.5 Ω	1 Ω

Gate losses in WBG devices

- Hard switching: $P_{GATE} = \boldsymbol{C_{iss}} \cdot {V_G}^2 \cdot f_s$
- Sinusoidal switching: $P_{GATE} = 2\pi^2 \cdot \boldsymbol{C_{iss}}^{\boldsymbol{2}} \cdot {V_G}^2 \cdot {f_s}^2 \cdot R_G$
- Trapezoidal switching: $P_{GATE} = \boldsymbol{C_{iss}}^{\boldsymbol{2}} \cdot {V_G}^2 \cdot f_s \cdot R_G \cdot (\frac{1}{t_r} + \frac{1}{t_f})$

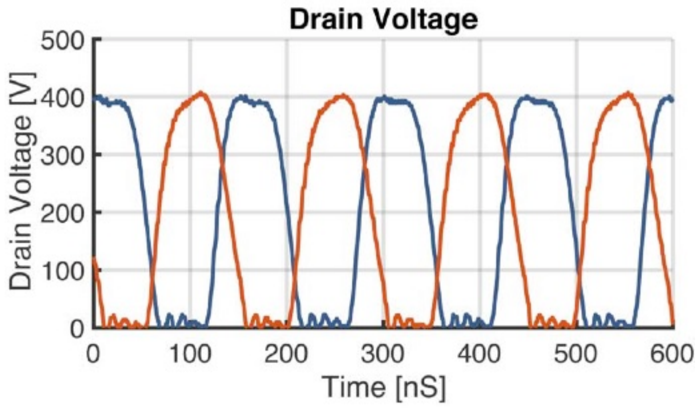
$\boldsymbol{F_S = 13.56\ MHz}$

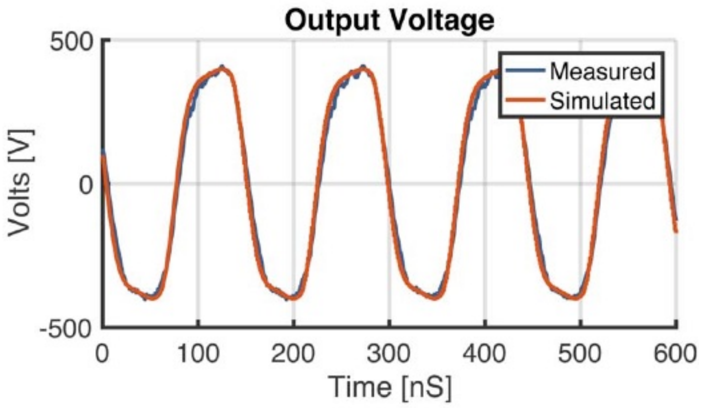
Device	GE SiC MOSFET	eGaN FET
V_{GS}	20 V	10 V
Hard switching	**17.2 W**	0.27 W
Sinusoidal switching	**14.53 W**	0.03 W
Trapezoidal switching	**12.1 W**	0.02 W

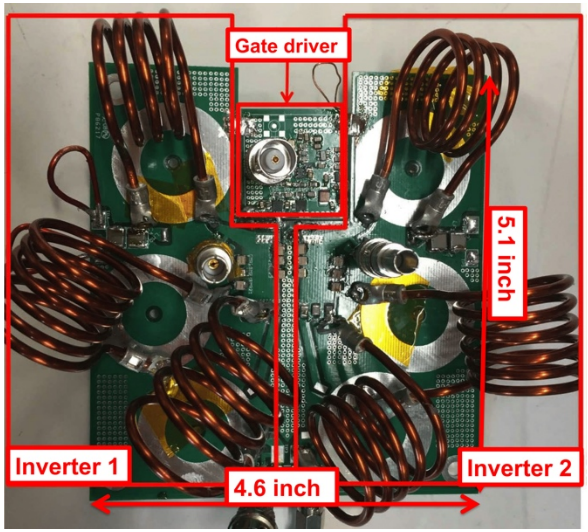
$\boldsymbol{F_S = 6.78\ MHz}$

Device	GE SiC MOSFET	eGaN FET
V_{GS}	20 V	10 V
Hard switching	8.6 W	0.18 W
Sinusoidal switching	5.7 W	0.03 W
Trapezoidal switching	6 W	0.02 W

Push-pull inverter performance at $V_{IN} = 200\ V$

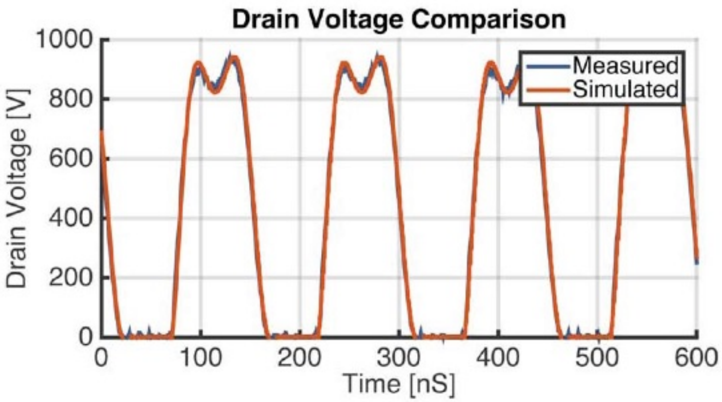


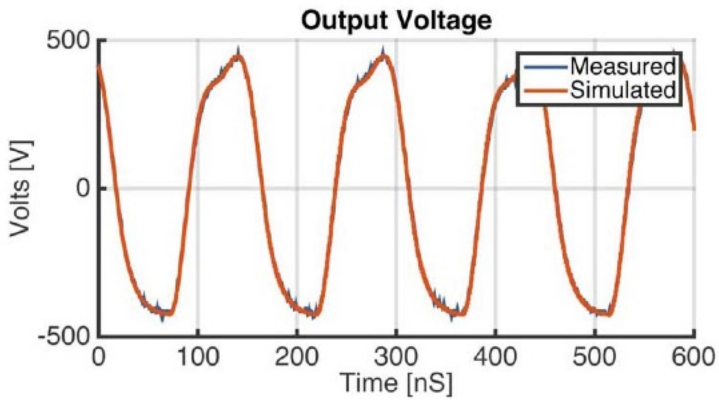


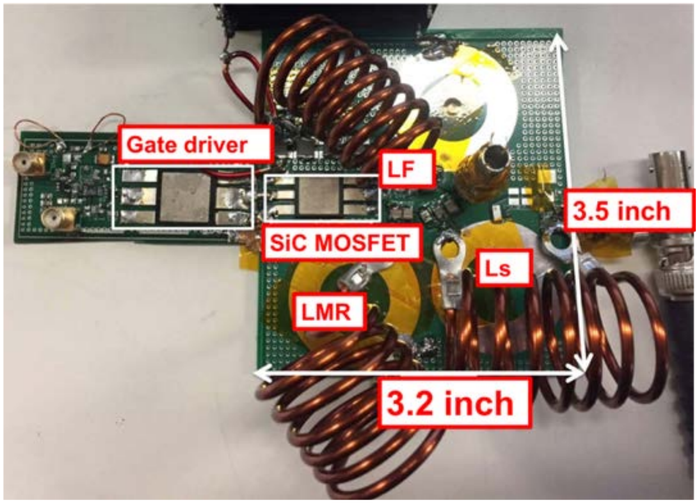


Parameter	Measured	Simulated
$V_{DS,MAX}$	407 V	414 V
$V_{OUT,RMS}$	310 V	320 V
P_{OUT}	1927 W	2120 W
Efficiency	96%	96%

Single inverter performance at $V_{IN} = 440\ V$



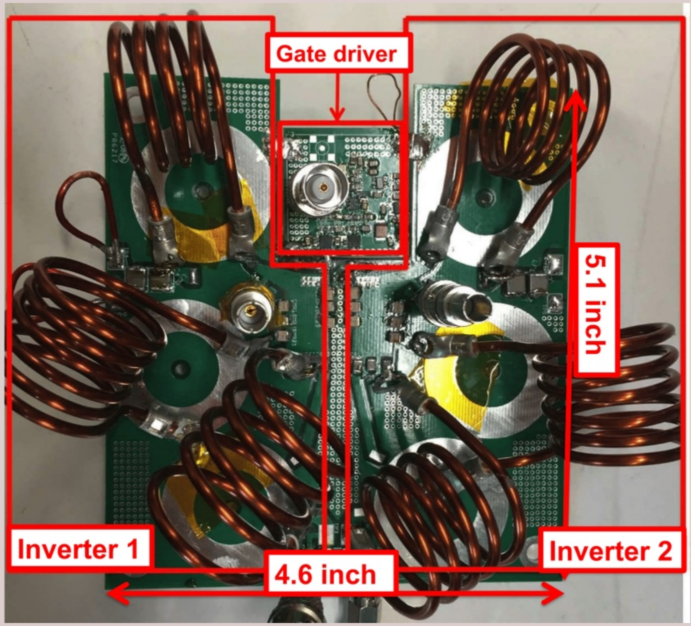


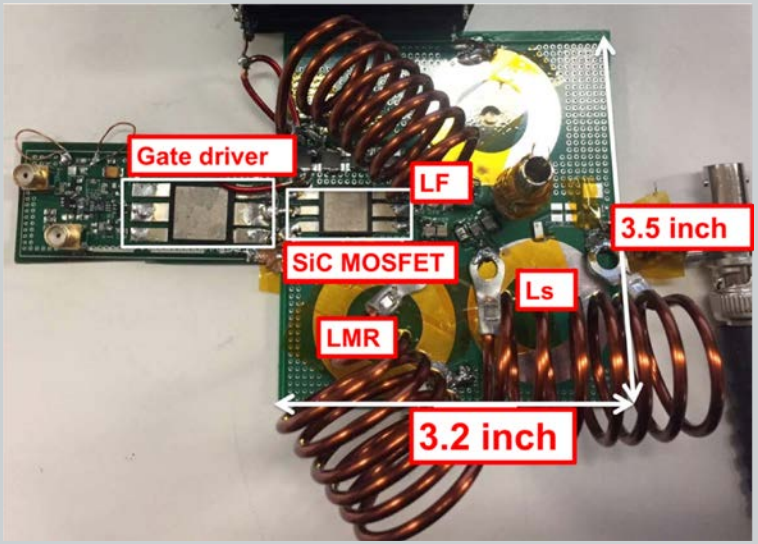


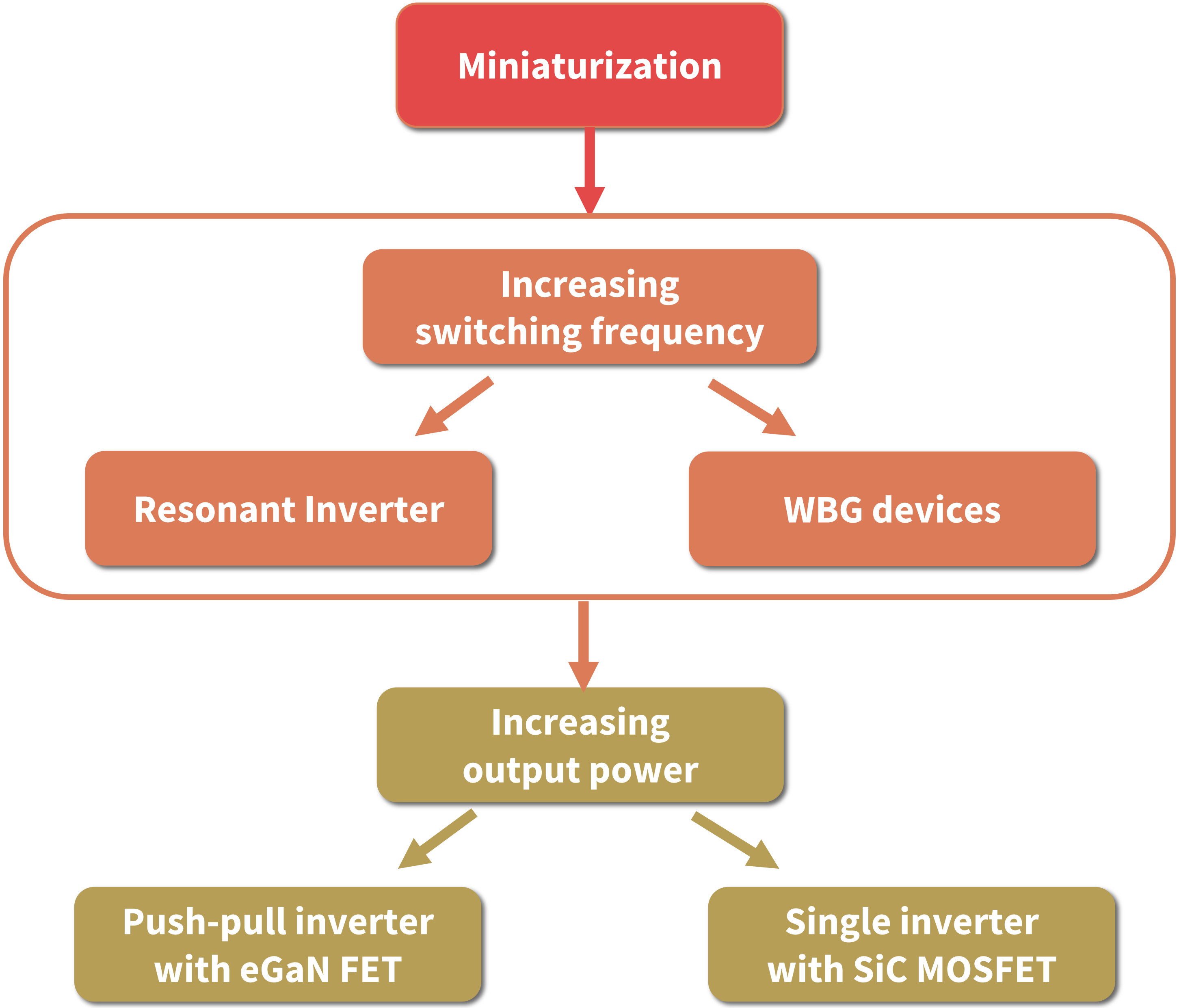
Parameter	Measured	Simulated
$V_{DS,MAX}$	940 V	942 V
$V_{OUT,RMS}$	332 V	333 V
P_{OUT}	2204 W	2224 W
Efficiency	93%	96%

Performance comparison

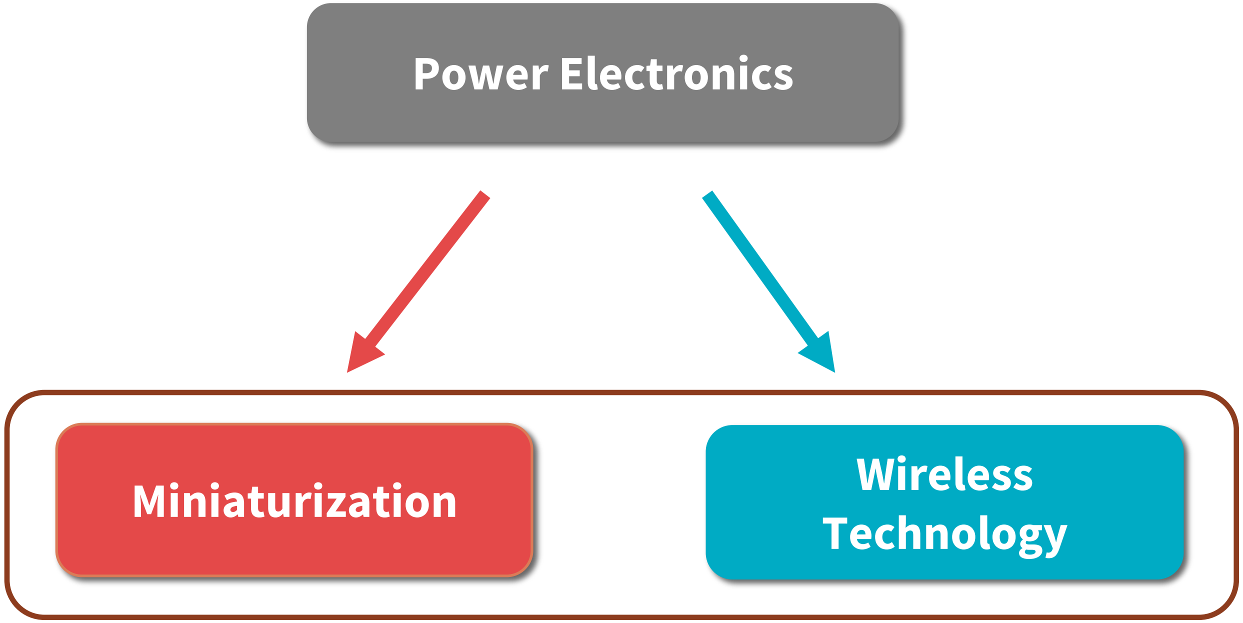
eGaN FETs in push-pull inverter	SiC MOSFET in single inverter
❑ Higher efficiency, small input current ripple ❑ Lower power density, complicated gate driver	❑ Simple topology, easier gate driving, higher power density ❑ Lower efficiency, higher input current ripple



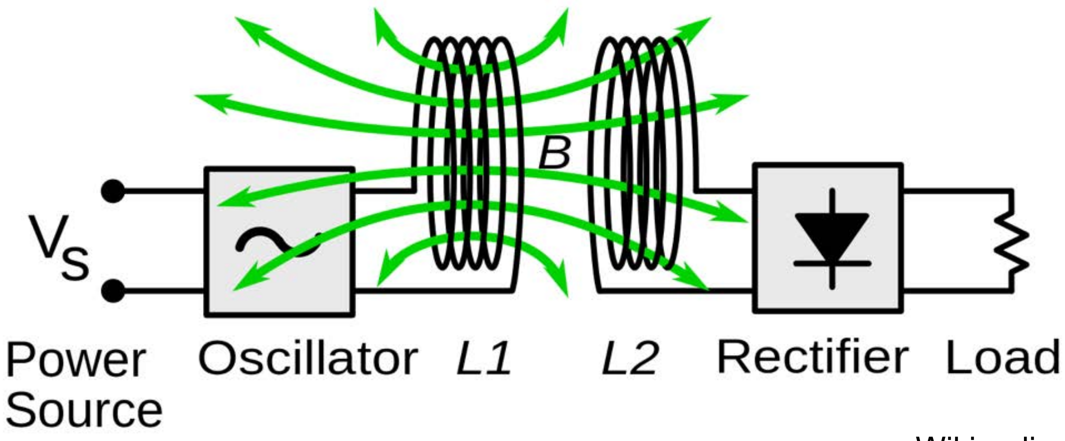



Miniaturization
Increasing switching frequency
Resonant Inverter
WBG devices
Increasing output power
Push-pull inverter with eGaN FET
Single inverter with SiC MOSFET

Towards a wireless future: Bridging between power electronics and needs of modern technology



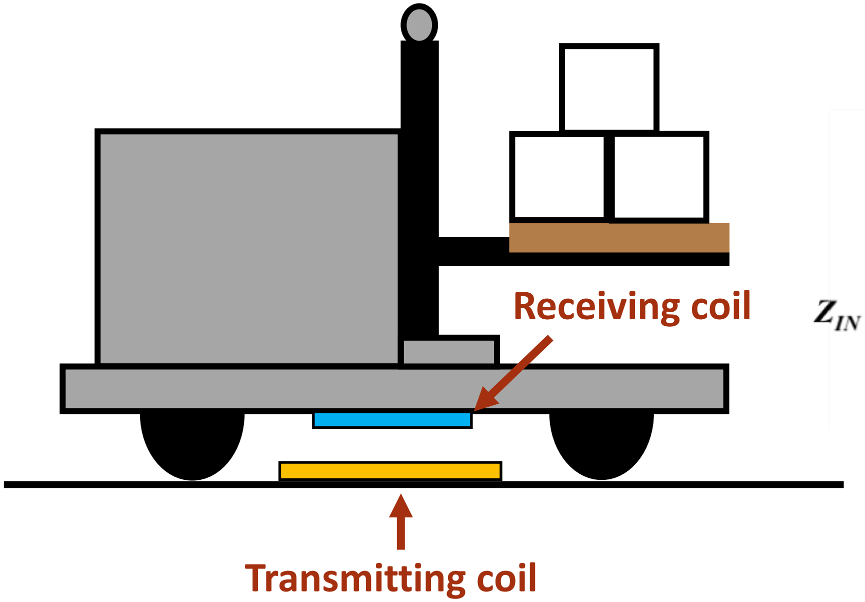
Inductive coupling

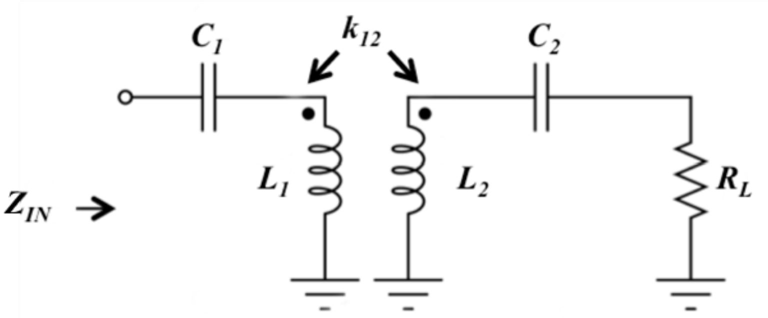


Wikipedia

Using Magnetic field to transmit power

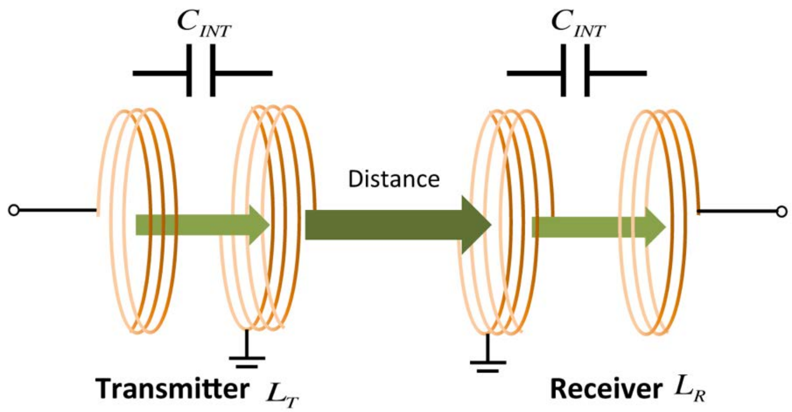
Mid-range distance, high-power WPT

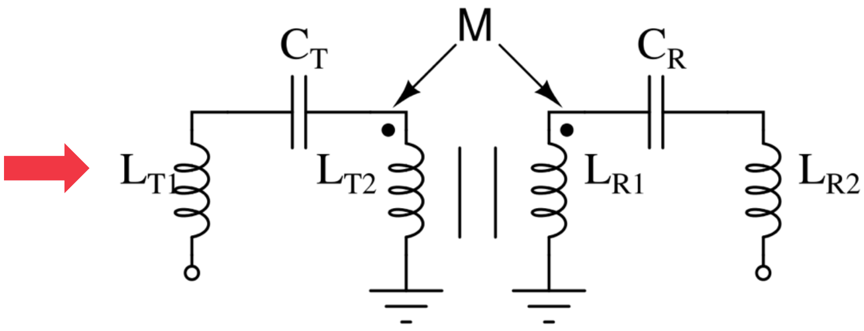




- **Magnetic resonant coupling (MRC):** Magnetic field + resonance
- Efficiency: above 90%, delivering power over a wide range of air gaps.
- High-power applications: Breakdown voltage of capacitor is important.

Open-type MRC coils

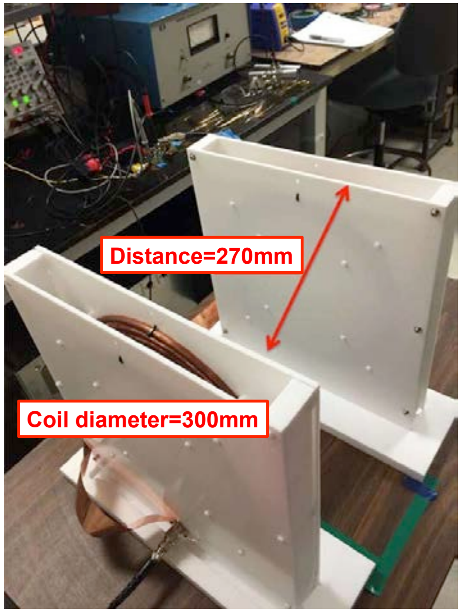


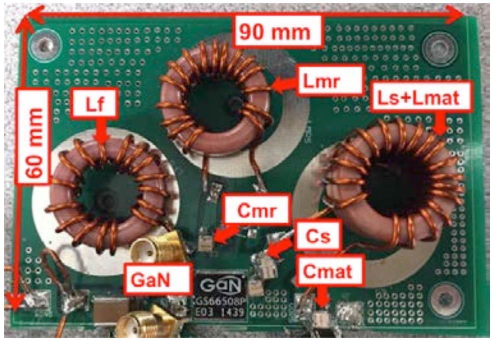


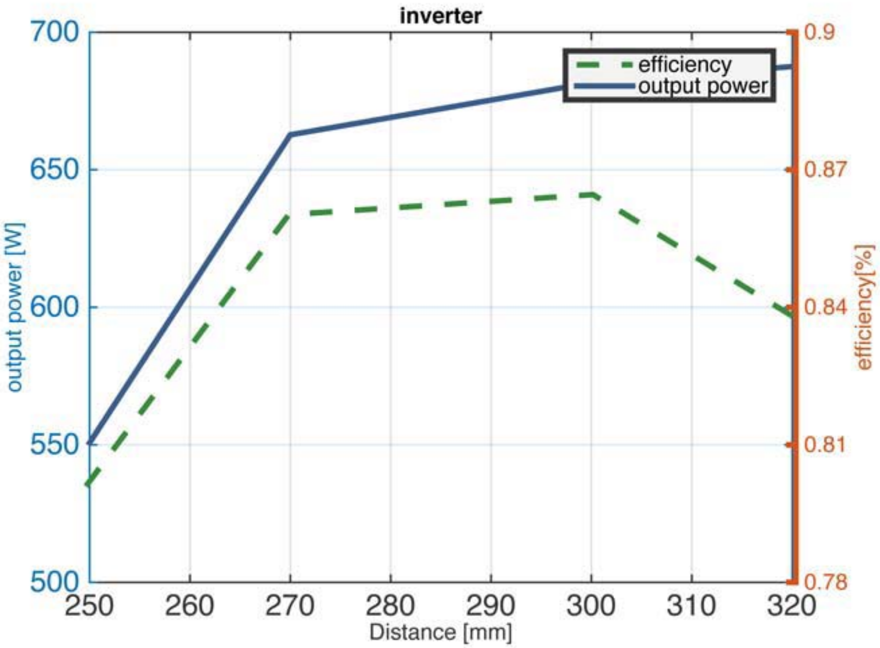
- Each consists of two coils having a resonant inter-coil capacitance.
- We can adjust a coil resonant frequency by changing conductor size and/or separation between coils.

J. Choi, "13.56 MHz 1.3 kW resonant converter with GaN FET for wireless power transfer," In Wireless Power Transfer Conference (WPTC), IEEE, 2015.

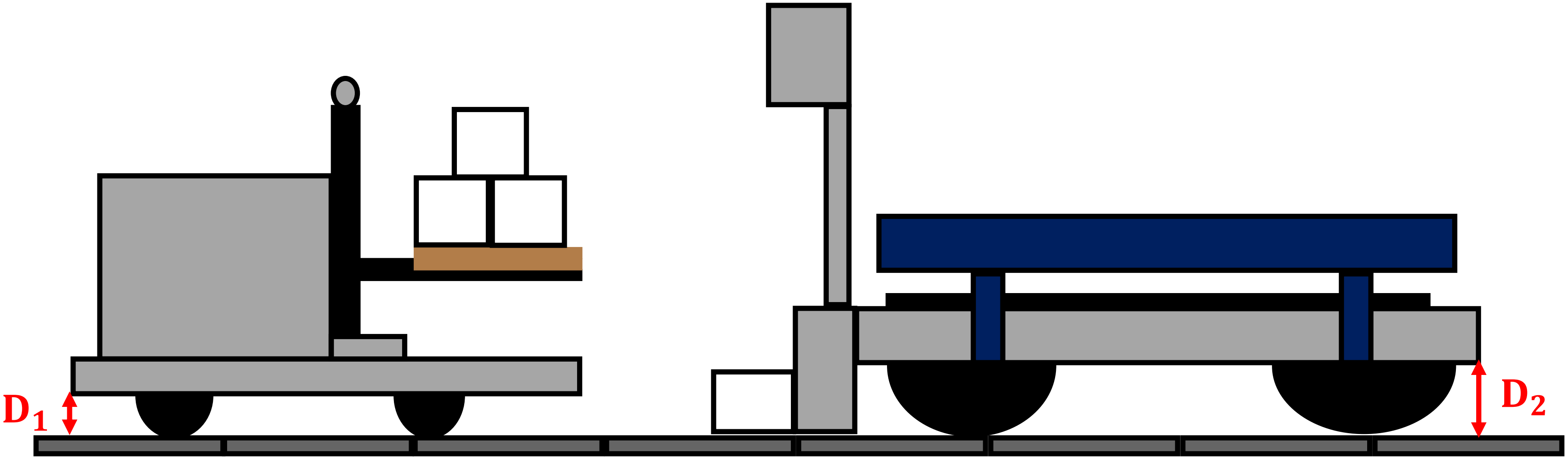
MRC coils with class Φ_2 inverter



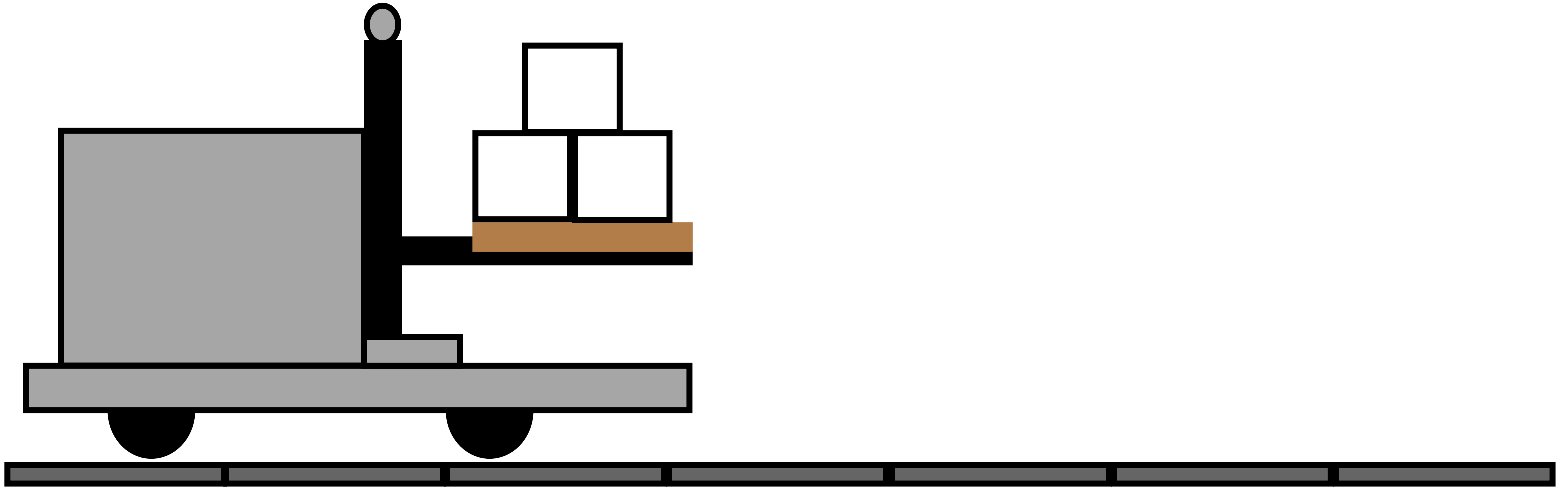




Distance variations in different AGVs

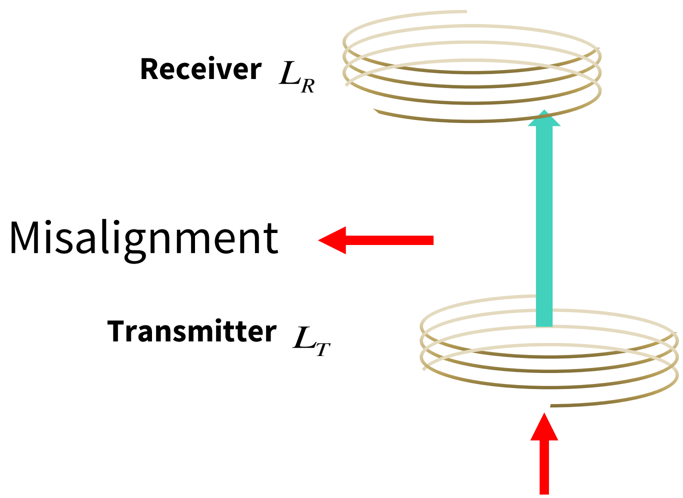


Alignment variations in dynamic charging



Misalignment between transmitting and receiving coils while driving

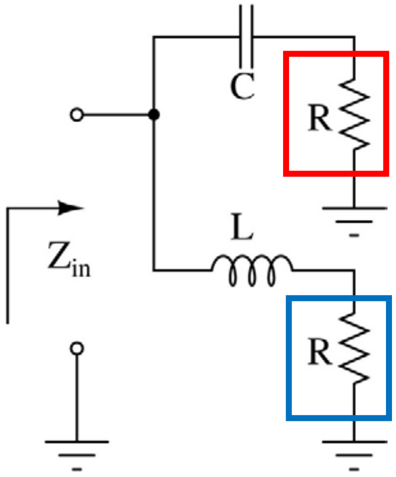
Alignment variations in MRC coils

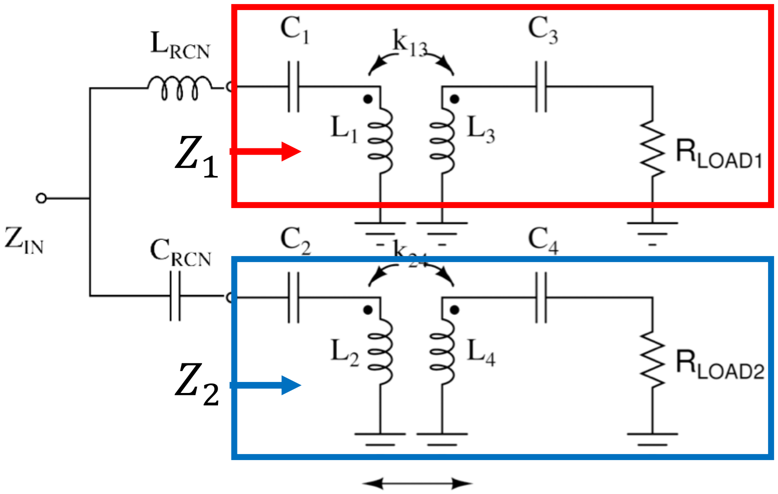


$$Z_{IN}' = R_{in}' + j \cdot X_{IN}'$$

- Distance or alignment variations → Coil impedance (Z_{IN}) variations
- Resonant inverters are designed for a specific load value and sensitive to the load variations.

Resistance compression network (RCN)

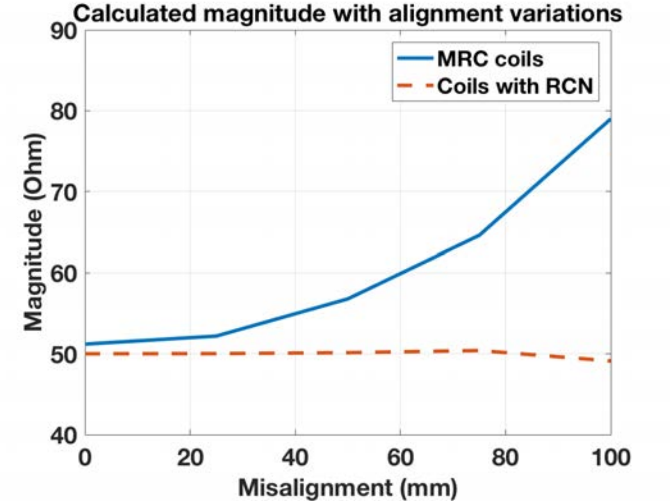


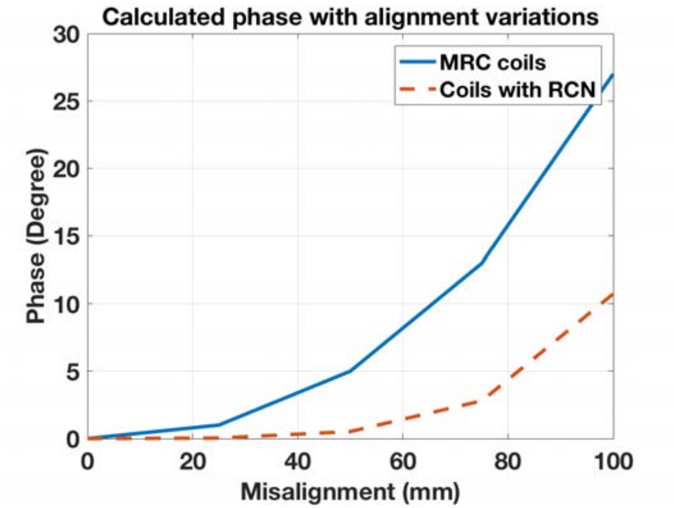


- Compression network can transform and transfer all provided energy from input to the resistive load without losses.
- Example
  - A 100:1 variation in R around the center → 5.05:1 variation in Z_{IN}.
- $Z_1 = R_1 + jX_1 = |Z_1|\angle\theta_1,\ Z_2 = R_2 + jX_2 = |Z_2|\angle\theta_2$

Y. Han, O. Leitermann, D. A. Jackson, J. M. Rivas and D. J. Perreault, "Resistance Compression Networks for Radio-Frequency Power Conversion," in *IEEE Transactions on Power Electronics*, vol. 22, no. 1, pp. 41-53, Jan. 2007.

RCN with MRC coils



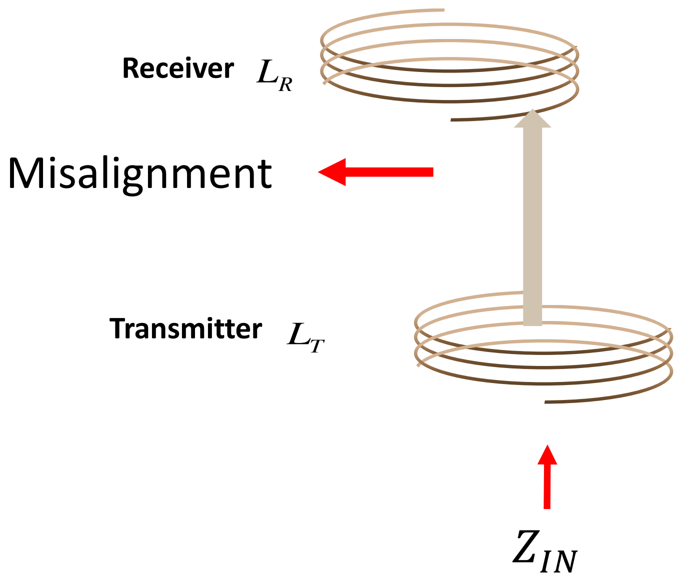


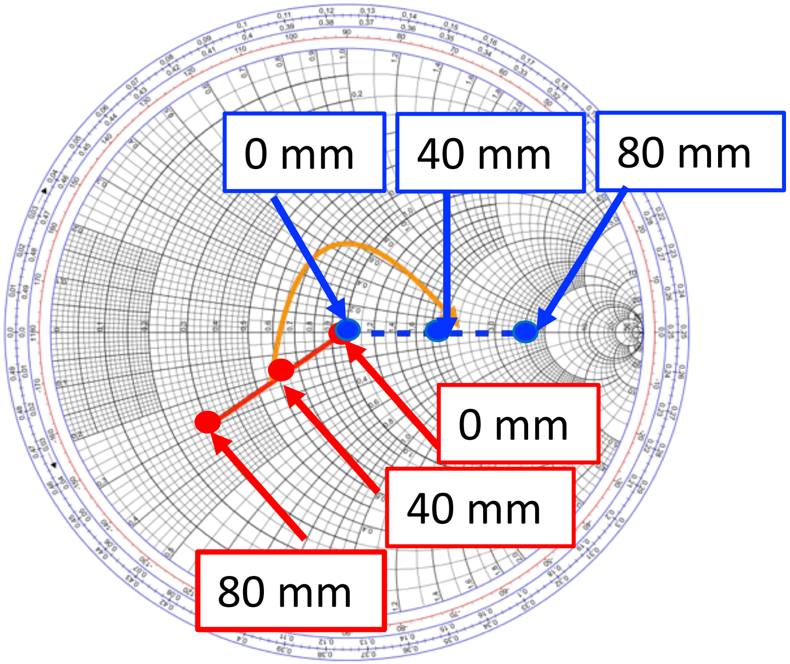
- Assuming that two coil impedances are the same.

$$Z_1 = Z_2 = Z_L = R_L + jX_L = |Z_L|\angle\theta_L$$

$$Z_{IN} = Z_{1,RCN} \parallel Z_{2,RCN} = (jwL_{RCN} + Z_L) \parallel \left(\frac{1}{jwC_{RCN}} + Z_L\right) = |Z_{in}|\angle\theta_{IN}$$

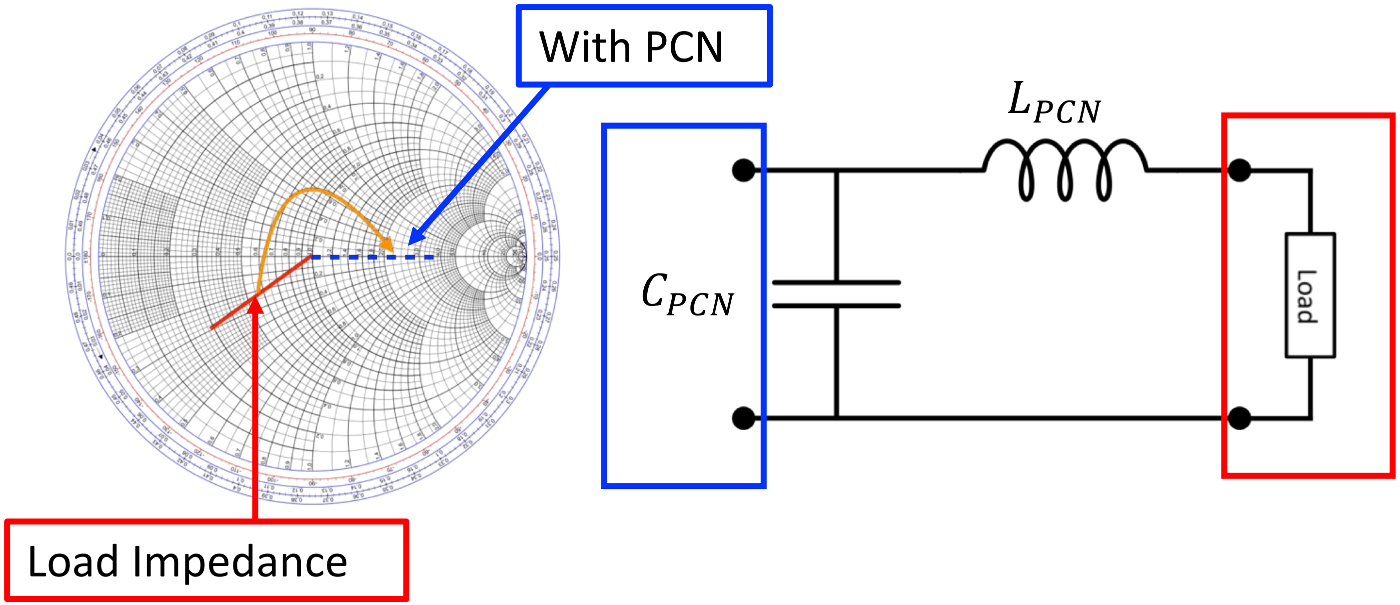
Phase compression network (PCN)





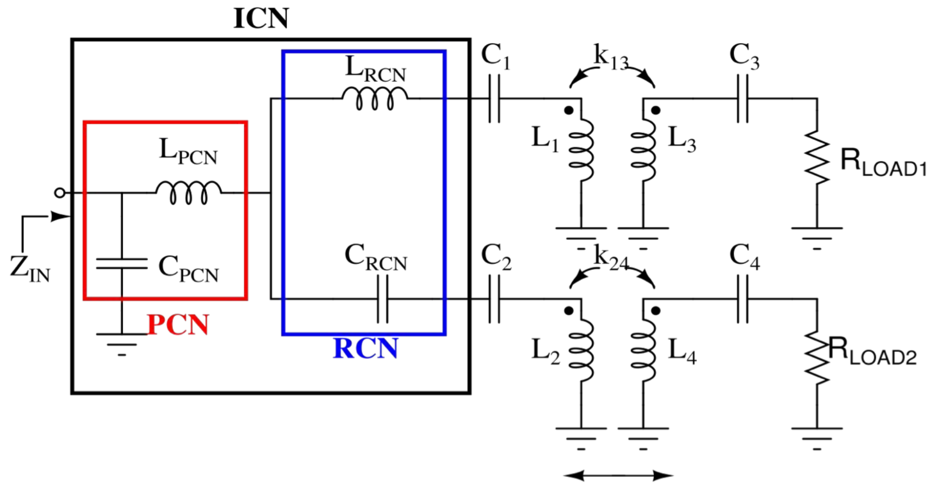
- PCN compresses phase shifts in the coil impedance.
- The load line is marked on the Smith chart.

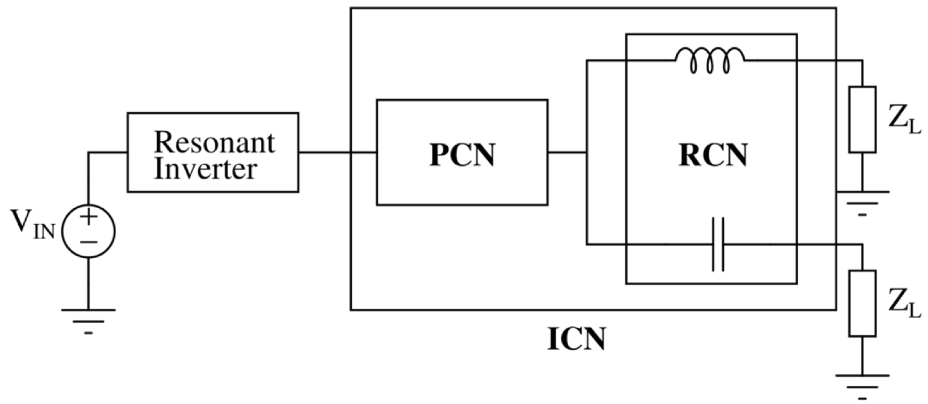
Phase compression network (PCN)



- By adding the passive components in series or parallel, the load line can be rotated to the real axis on the Smith chart.

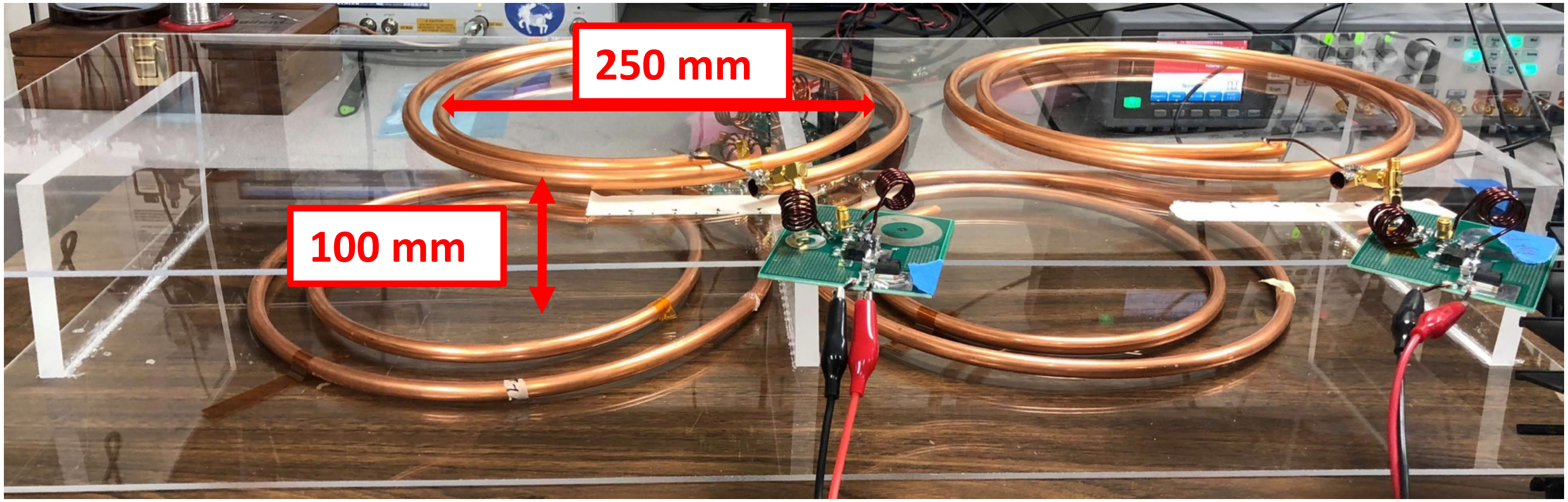
Impedance compression network (ICN)





J. Choi and J. Rivas, "Implementing an impedance compression network to correct misalignment in a wireless power transfer system," *2017 IEEE 18th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Stanford, CA, 2017, pp. 1-8.

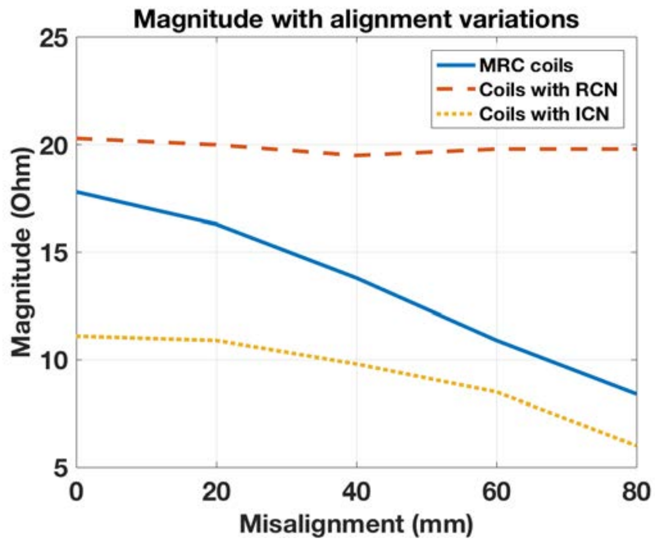
Experimental results of MRC coils with ICN

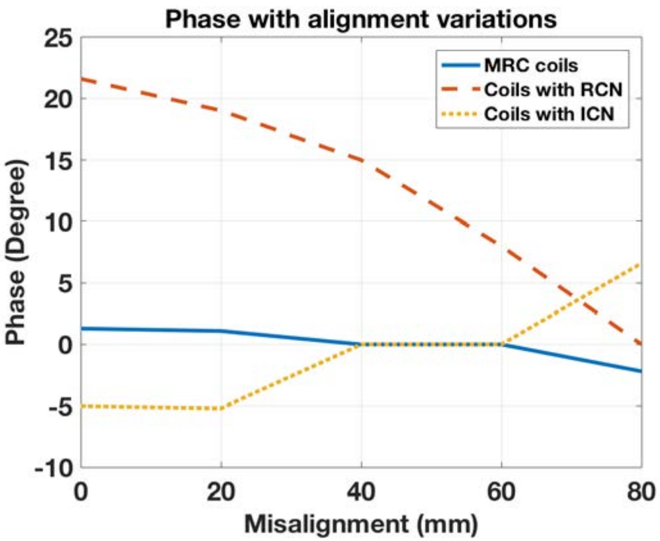


Parameter	Value	Parameter	Value
L_1	1.68 μH	C_1	82 pF
L_2	1.68 μH	C_2	83 pF
L_3	2.02 μH	C_3	71 pF
L_4	2.02 μH	C_4	73 pF

- Horizontal alignment varies from 0 mm to 80mm.
- Distance: 100 mm
- Resonant frequency: 13.56MHz
- Copper tube

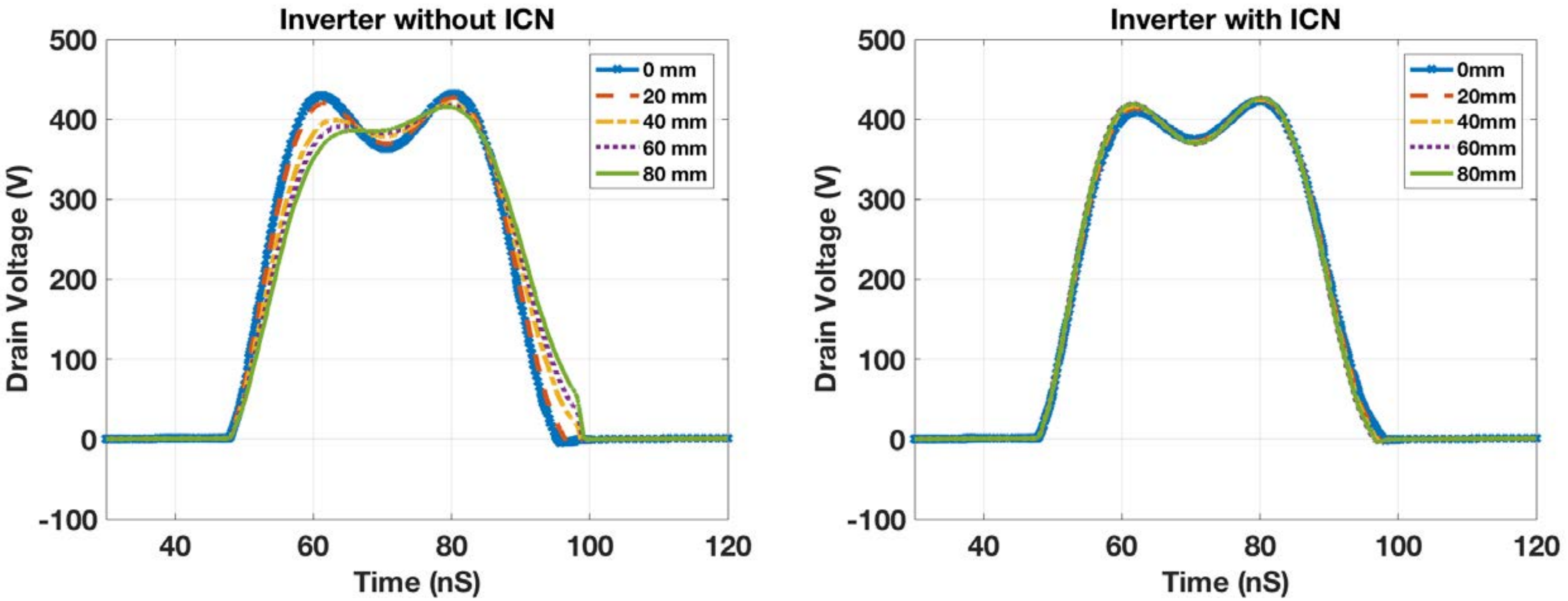
Measured coil impedance with horizontal misalignments





- The horizontal alignment between coils varies from 0 mm to 80 mm.
- $\frac{|Z_{IN}|\ @0\ mm}{|Z_{IN}|\ @80\ mm} = 3.07\ without\ ICN,\quad \frac{|Z_{IN}|\ @0\ mm}{|Z_{IN}|\ @80\ mm} = 1.85\ with\ ICN$
- The phase of the coil impedance is well-compressed with the ICN.

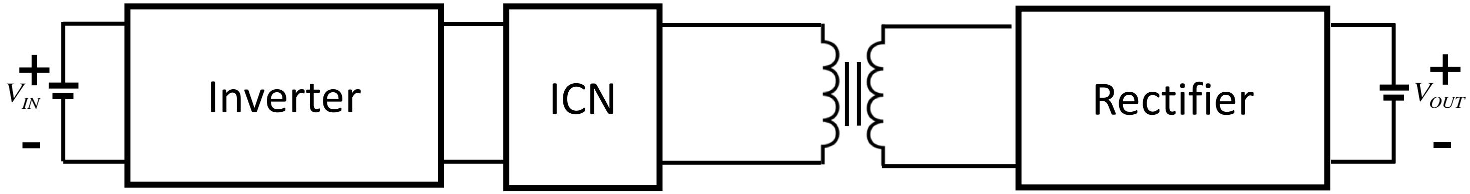
Simulated results of ICN with class Φ_2 inverter

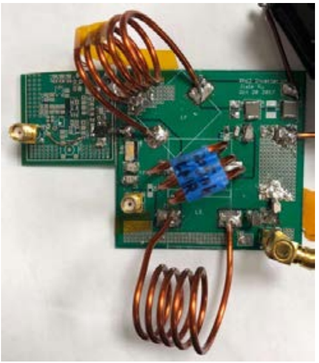


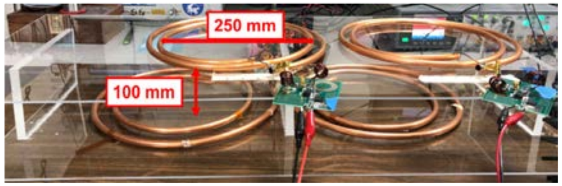
- Cannot maintain ZVS
- Efficiency decreases from 95% to 88%.

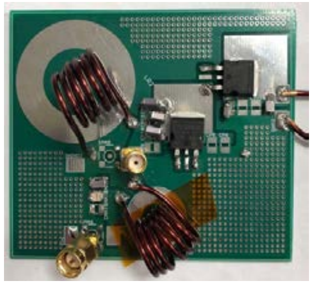
- Maintain ZVS
- Efficiency: constant at 95%

Dc-to-dc resonant converter with MRC coils and ICN





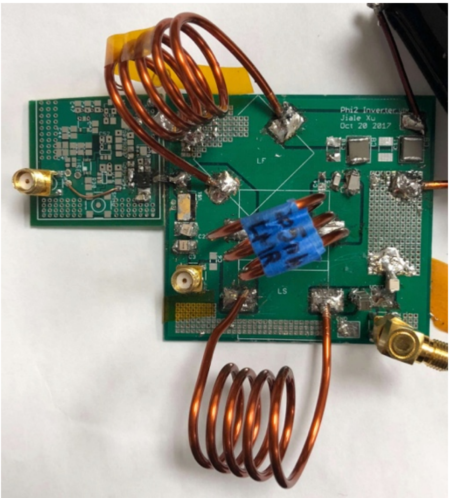


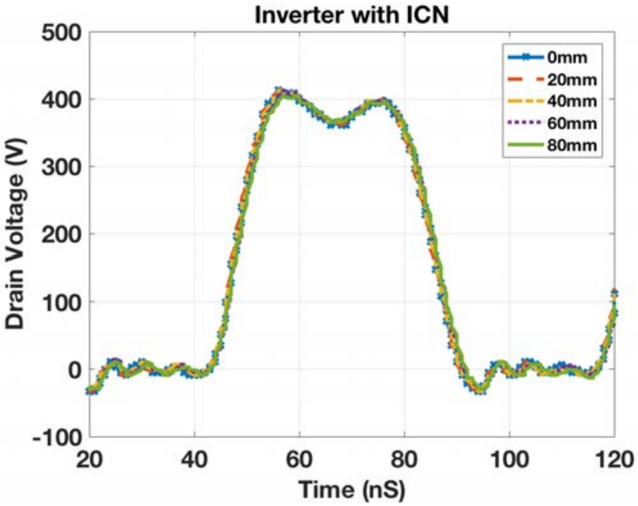


Dc-to-dc resonant converter

- Class Φ_2 inverter with eGaN FET
- Impedance compression network
- Magnetic resonant coupling coils
- Class DE rectifier

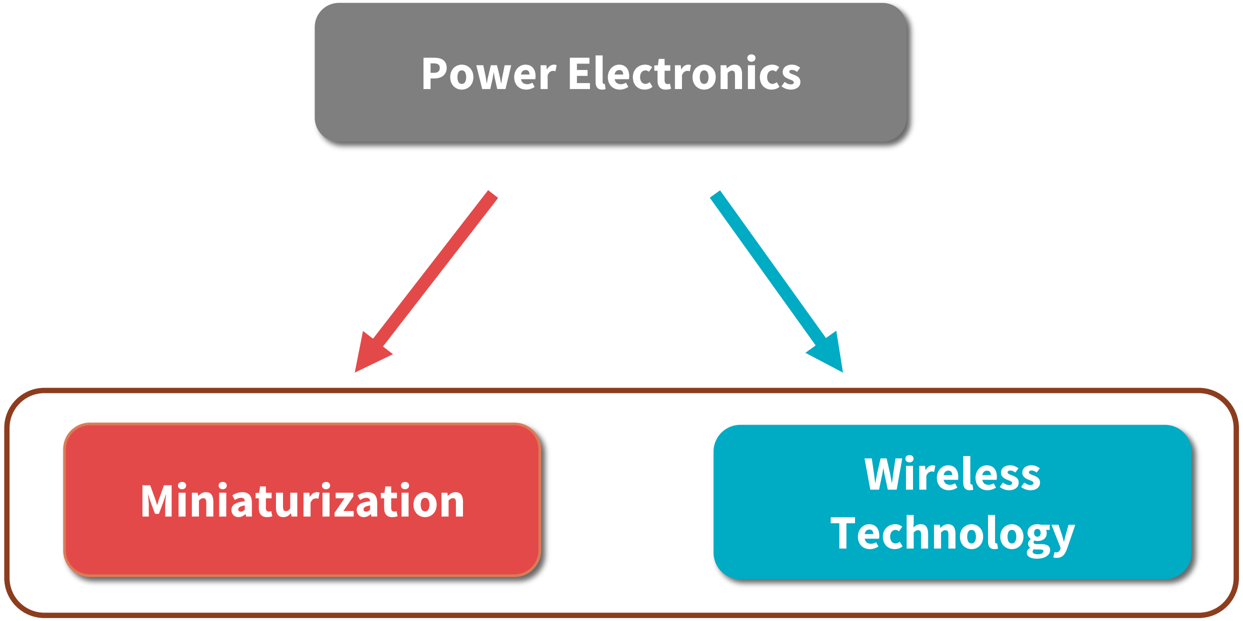
Experimental results of dc-to-dc converter with ICN



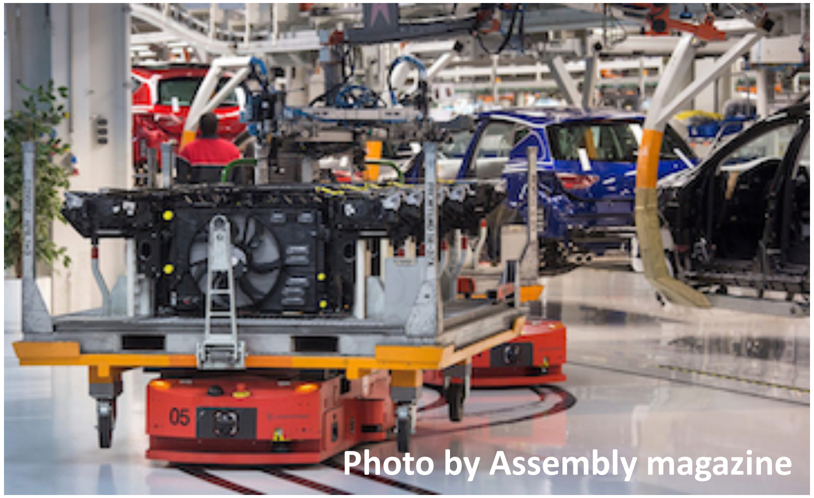


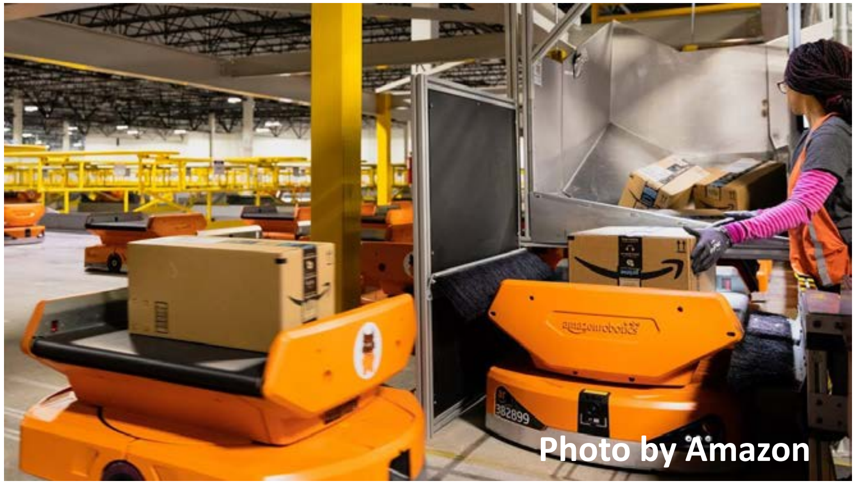
- With the ICN, the class Φ_2 inverter maintain ZVS and the drain waveforms are identical each other.
- Dc-to-dc system efficiency ≈ 76%.
- Inverter efficiency ≈ 95%.

Towards a wireless future: Bridging between power electronics and needs of modern technology



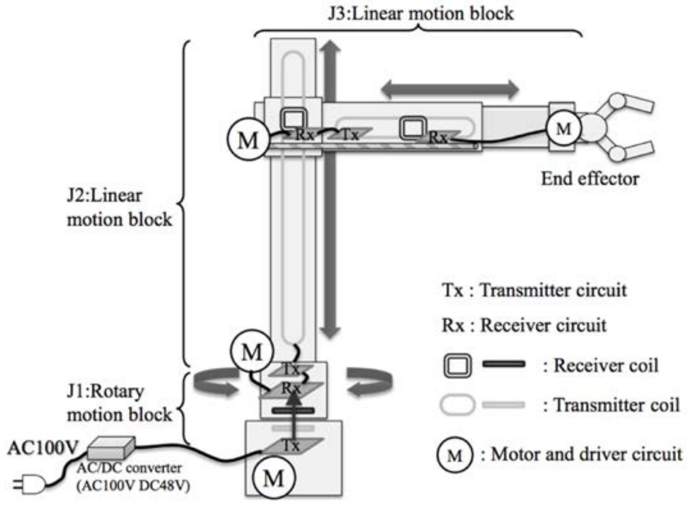
WPT in AGV

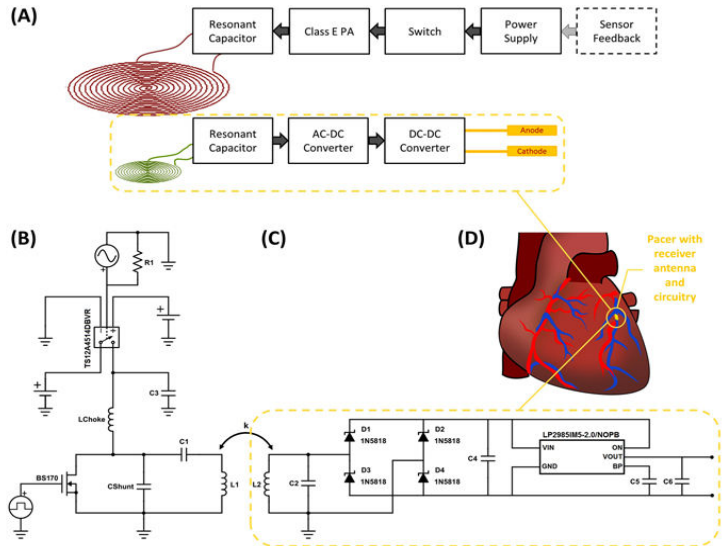




- Optimizing WPT system for automated guided vehicles (AGV) and automated guided forklift (AGF).
- Dynamic charging: EVs to charge themselves during driving.

WPT in small-power applications



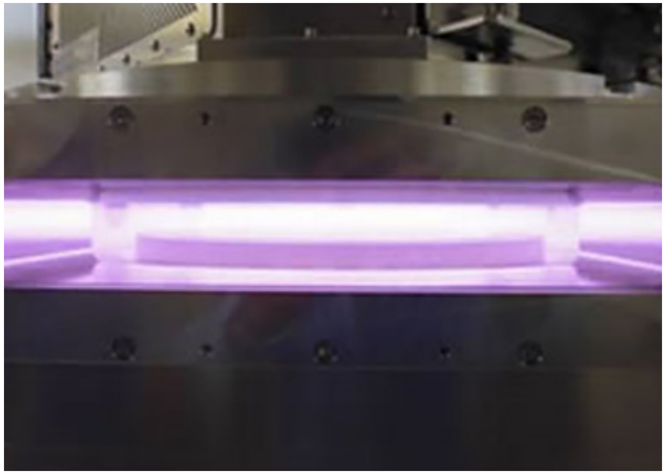


- ❑ Replace wires to coils to deliver power in joints or any rotational components in robots
- ❑ Many biomedical devices require miniaturized WPT technology.
  - Pace maker, Stimulators
  - Blood clot prevention

S. Kikuchi, T. Sakata, E. Takahashi and H. Kanno, "Development of wireless power transfer system for robot arm with rotary and linear movement," *2016 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, Banff, AB, 2016, pp. 1616-1621.

P. Abiri, A. Abiri, R. Packard, Y. Ding, A. Yousefi, J. Ma, M. Bershon, K. Nguyen, D. Markovic, S. Moloudi and T. Hsiai, " Inductively powered wireless pacing via a miniature pacemaker and remote stimulation control system," *Scientific Reports volume 7, Article number: 6180 (2017)*.

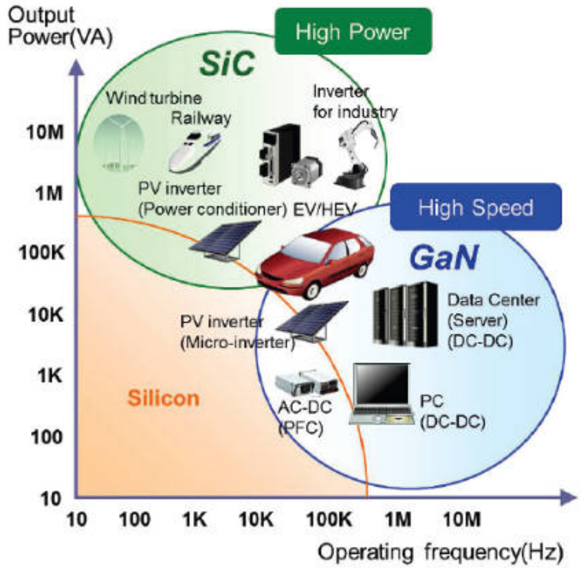
Plasma generation



- Semiconductor thin-film processes for etching, chemical vapor deposition (CVD) and physical vapor deposition (PVD).
- The size and efficiency of RF power generator has to improved.
- Very high frequency operation (above 30 MHz) and the impedance matching with variable loads are required.

http://www.daihen.co.jp/en/products/fineplasma/

Switching device study

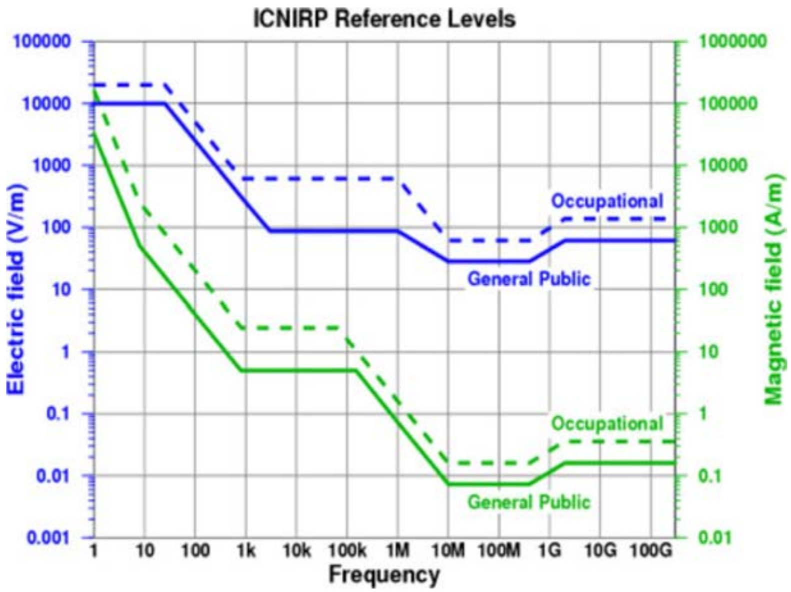


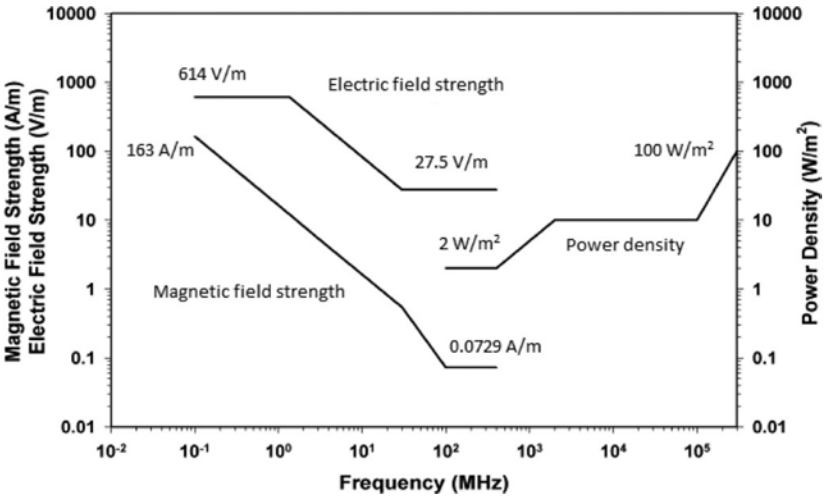
SiC for high power voltages (>1kV) with high current = niche market

GaN on Si for high frequency at midrange voltages (<1kV, up to 100A) = mass market

- Wide band gap devices such as eGaN FETs or SiC MOSFETs have a lot of potential to improve performance of high-frequency, high-power converters.
- However, performance of these devices have not been well proved yet to operate at VHF.
- Developing Ga_2O_3 devices, ultra wide-bandgap (UWBG) devices.

Safety issues in wireless power transfer





- Human exposure issue is one of the major concerns in WPT systems.
- Left: ICNIRP reference levels for exposure to time-varying electric and magnetic fields.
- Right: IEEE Reference levels for exposure to time-varying electric and magnetic fields.
- Need to study the maximum limits of output power at MHz frequency.

Summary

- Overcoming technical limitations of dc-to-ac inverters by designing high-power (above 2 kW) and high-efficiency (above 90%) systems to operate at 10's of MHz switching frequency.
- Using Wideband gap devices such as SiC MOSFETs or eGaN FETs to reduce the size and weight of the entire WPT systems and improve system performance.
- Designing an open-type 4-coil unit to eliminate need for external capacitors in high-power operation.
- Implementing an impedance compression network (ICN) to compensate for distance and alignment variations between coils in a WPT system without controlling or tracking systems.
- Extending this approach to various industrial applications such as EVs, plasma generation, robotics and biomedical devices

Thank you!