Wireless Power:
a Path Toward Core-Less Transformers

Chathan M. Cooke
MIT: RLE, High Voltage Lab.; Sea Grant Development Lab.
Tuesday, January 19, 2016
at: National Grid, Waltham, MA

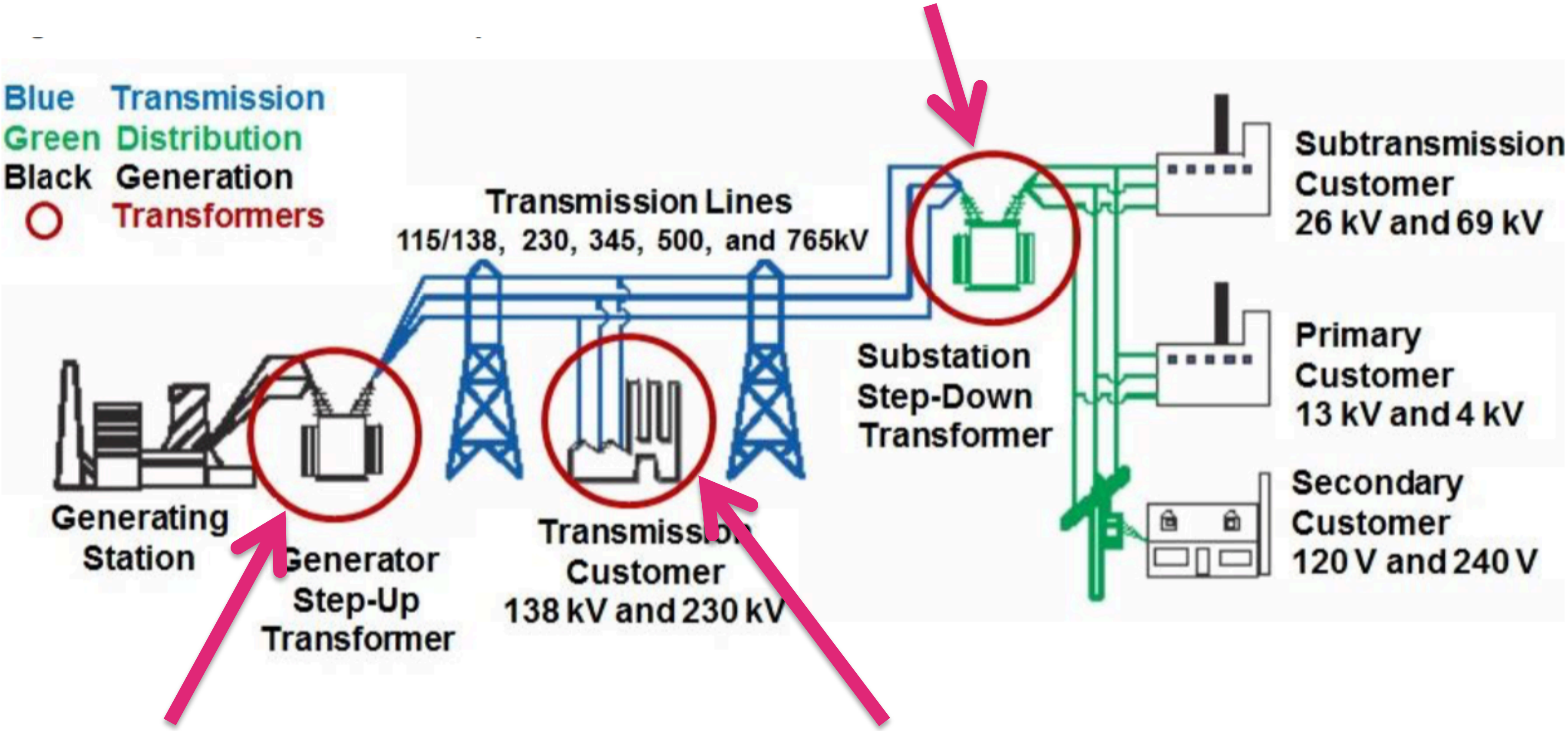
IEEE - PES
Presentation

7d
Cites: Feb2016

Presentation Outline

- Transformers:
  - Necessary Classical Device
  - Construction, Size, Core Basics
- An Alternate Approach:
  - Wireless Power: “Resonance”
- Resonant Coupling
- Scaling:
  - Resonant Coupling to High Power
- Key Limits, Future Prospects

Transformers: A Necessary Component In Electric Utility Systems



via: DOE 2012

"U.S. DOE report on large power transformers and the U.S. electric grid"

Transformers: A Classical Magnetic Device

- Transformer Basics
  - Magnetics: The coupling of 2 windings
  - Use of steel core, tight magnetic coupling

- Structure and Internals

- Costs, Weight (especially of steel core)
  - Worldwide manufacture and shipping

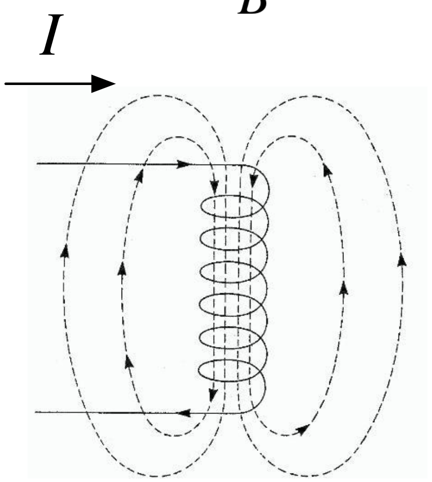
- Size and Scaling Relations
  - Steel core

Transformers: Linked Magnetic Flux

$$V_2 = -N_2 \frac{d\Phi_{B2}}{dt}$$ Faraday's Law

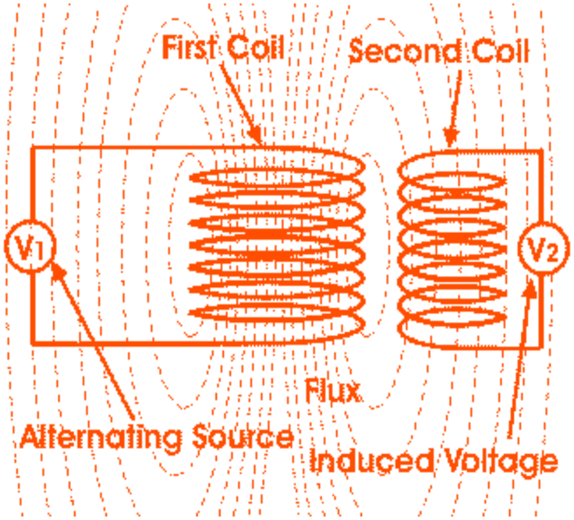
Magnetic Flux

Φ_B



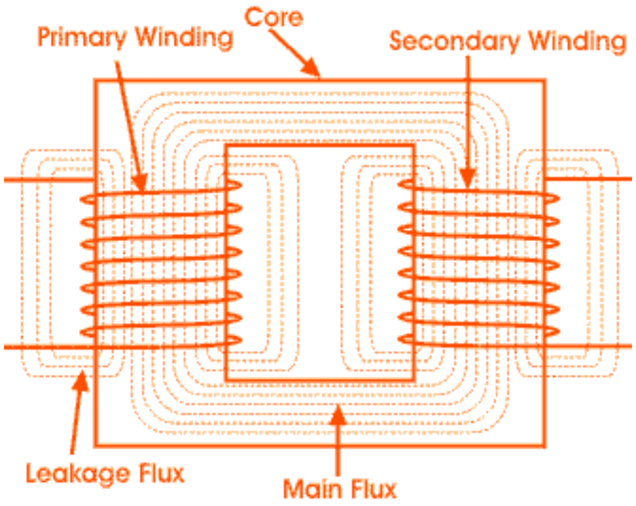
Single Coil

Φ_{B1} Φ_{B2}



Coupled Coils

$\Phi_{B2} \cong \Phi_{B1}$



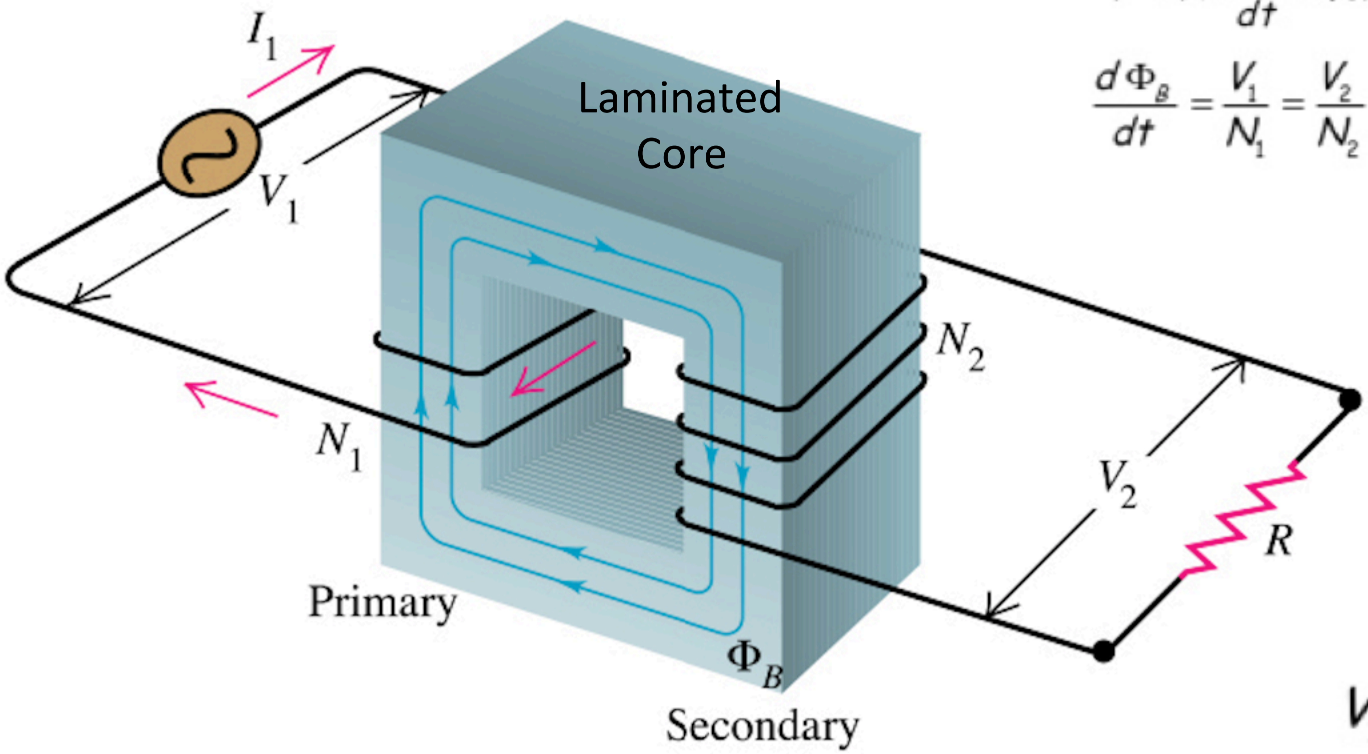
Tightly Coupled Coils

via: quora.com

Basic Transformer Structure

$$V = N\frac{d\Phi_B}{dt} \quad \text{for both coils}$$

$$\frac{d\Phi_B}{dt} = \frac{V_1}{N_1} = \frac{V_2}{N_2} \qquad \frac{V_1}{N_1} = \frac{V_2}{N_2}$$



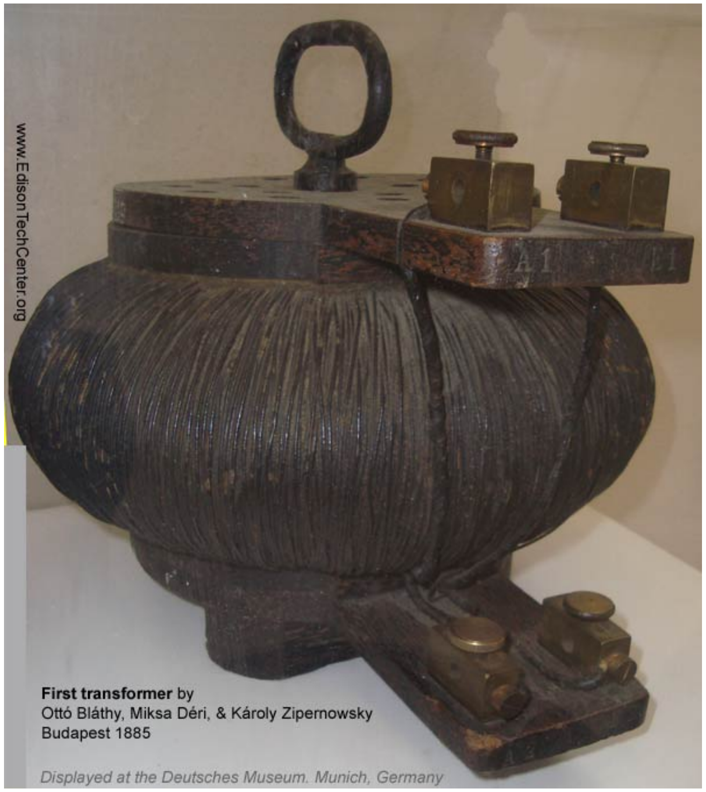
$$V_1 I_1 = V_2 I_2$$

via: www.indiastudychannel.com

In The Beginning

Stanley: 1886 ‘E’-core transformer

BDZ: 1885 toroid-core transformer

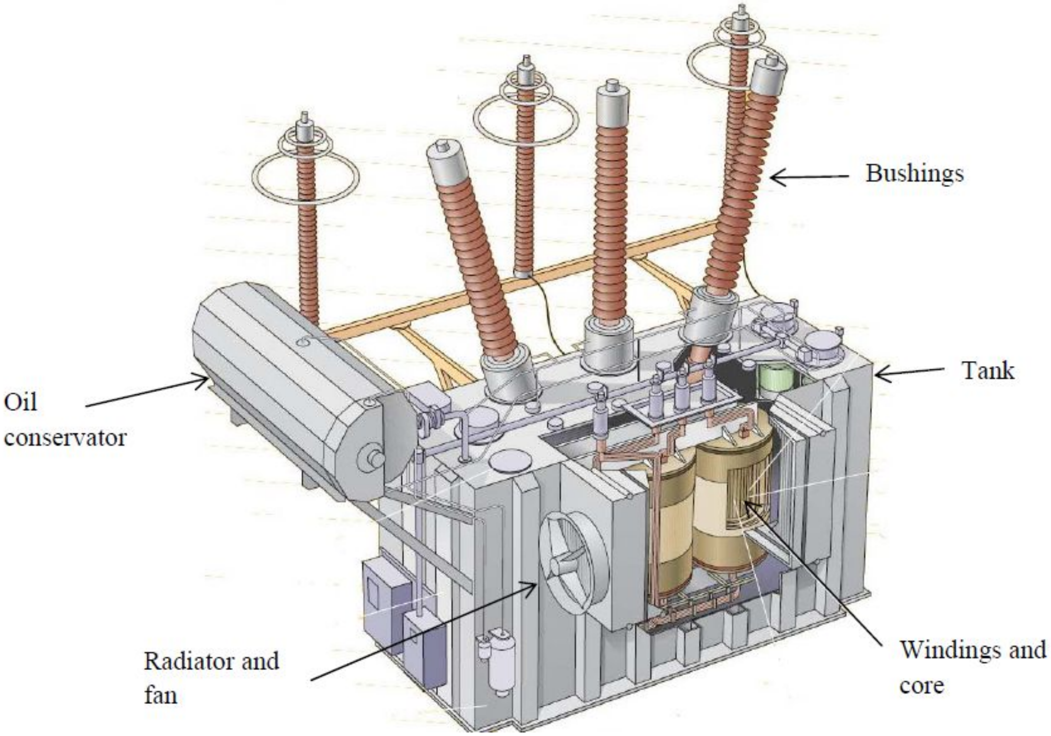


via: www.edisontechcenter.org/Transformers.html

Typical Transformer Coils On Core

http://www.transformerindia.com/photos/cb04.jpg

Power Transformer Structure



112 MVA

via: www.cbsa-asfc.gc.ca

via: www.meppi.com/Products/Transformers/

Transformer Steel Cores

Steel Sheet Rolls

http://siliconsteel.com/

Cut and Stacked

via: www.tehenergo.ee/en/item/36-distribution_transformers.html

Steel Core Assemblies

via: www.lagor.it

Steel Core Assemblies

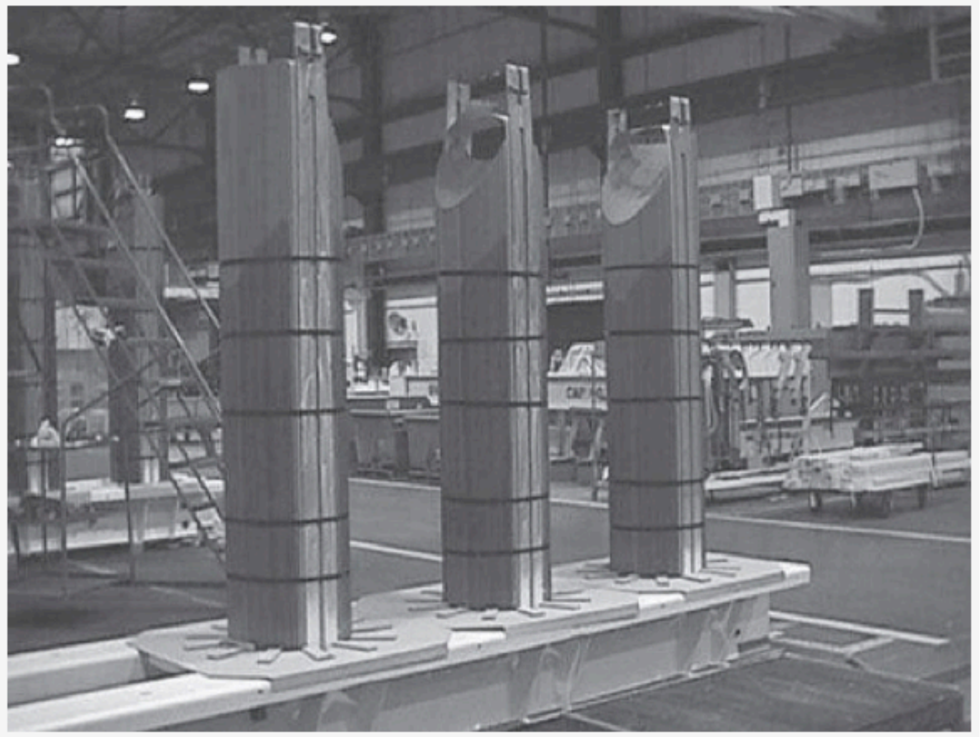
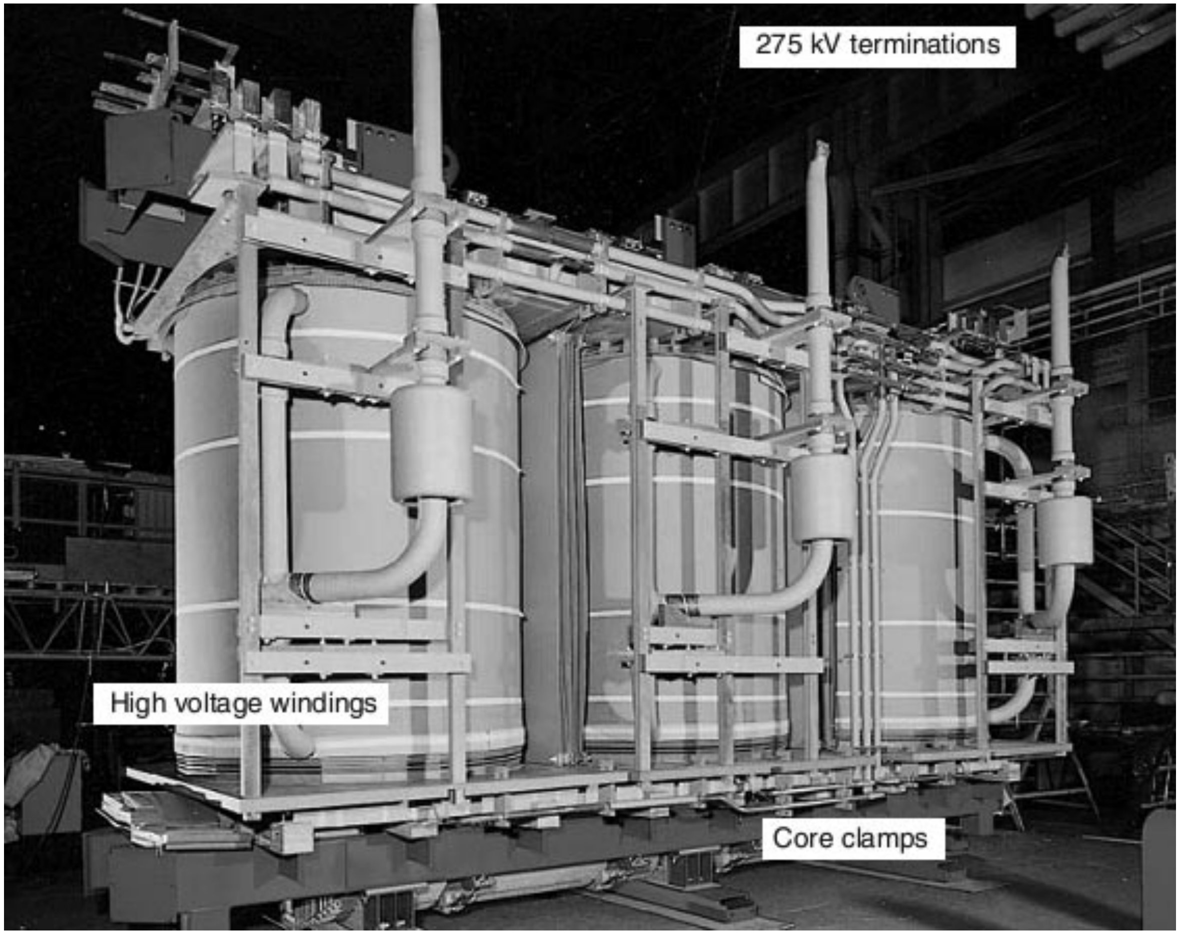


Figure 3 – 'E'-assembly, prior to addition of coils and insertion of top yoke

via: electrical-engineering-portal.com/power-transformer-construction-core

via: www.copper.org/

Full Construction Over Steel Core



via: electrical-engineering-portal.com/what-are-the-main-classes-of-transformer

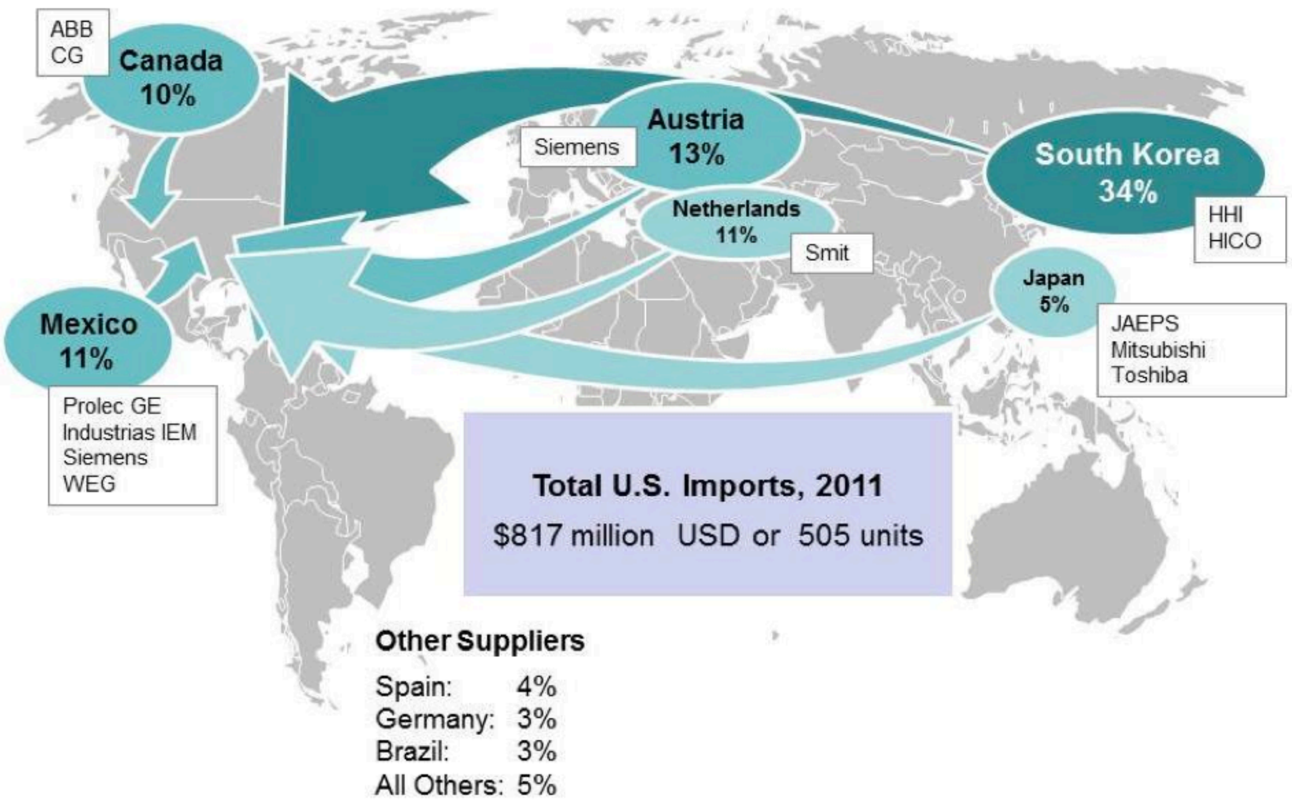
Transformer Costs: 100-500 MVA

- Total Cost: 2 to 5 $million [~ $10/lb]
- Total Weight: 200,000 to 600,000 lbs
- Cost Breakout:
  - – Raw Materials: ~60%
    - Copper: ~25%
    - Core Steel: ~25%
- Weight Breakout
  - – Core Steel: ~200,000 lb (larger MVA)

via: 2011 Data, DOE 2012

Transformers Travel to US

Figure 16. Global Suppliers of Large Power Transformers to the United States in 2011
(Power transformers with a capacity rating greater than or equal to 100 MVA)



Note: CG stands for Crompton Greaves; HHI stands for Hyundai Heavy Industries; HICO stands for Hyosung Power and Industrial Systems; JAPES stands for Japan AE Power Systems Corporation.

Source: USITC, ICF International Analysis.

via: DOE 2012

Transformer Size Relationships

- Basic Magnetics Theory: Faraday and Ampere
- Two Specific 'Areas' related to Power Capacity
- Power vs Size: Scaling relations
- Frequency effects
- Permeability effects (linear like frequency)
- Cooling more severe at higher powers

Transformer Equations

Voltage:

$$E = \frac{d\Phi}{dt} = \frac{1}{\sqrt{2}}\,\omega\,N\,B\,A_C = \frac{2\pi}{\sqrt{2}}\,N\,f\,B\,A_C \quad \text{(volts)}$$

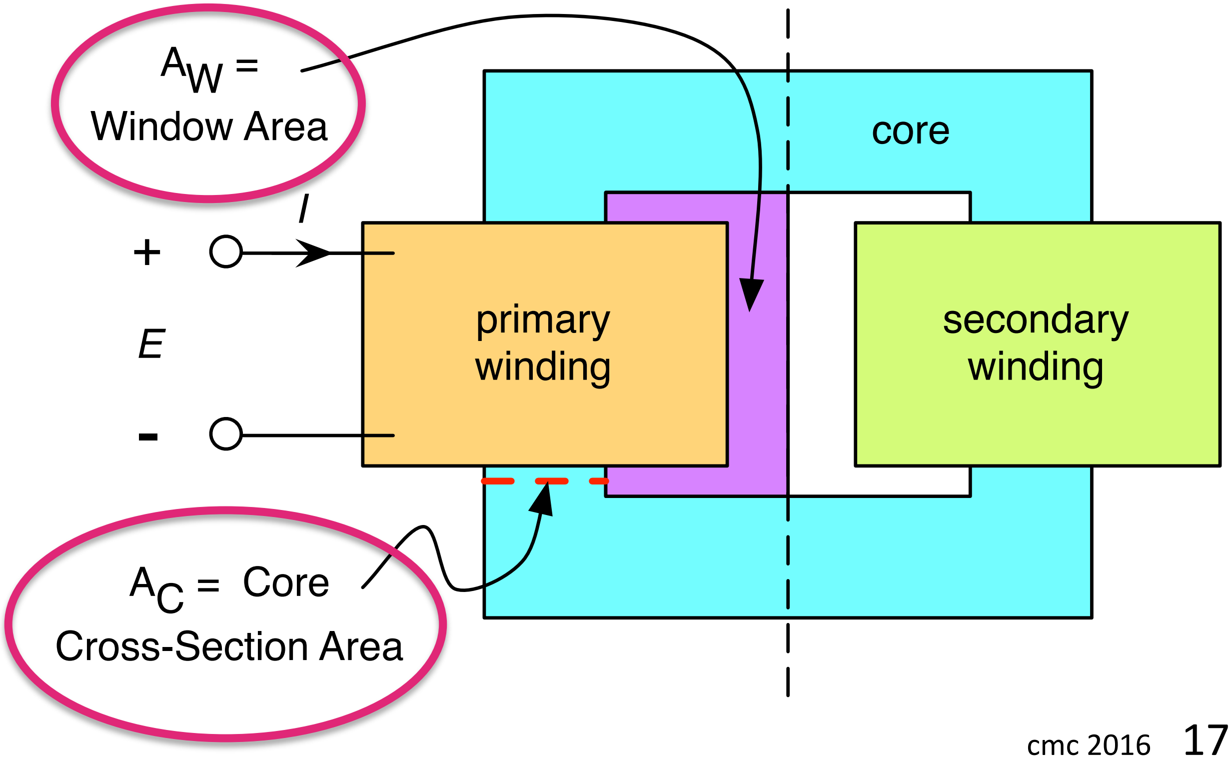
Core Area

Flux Density

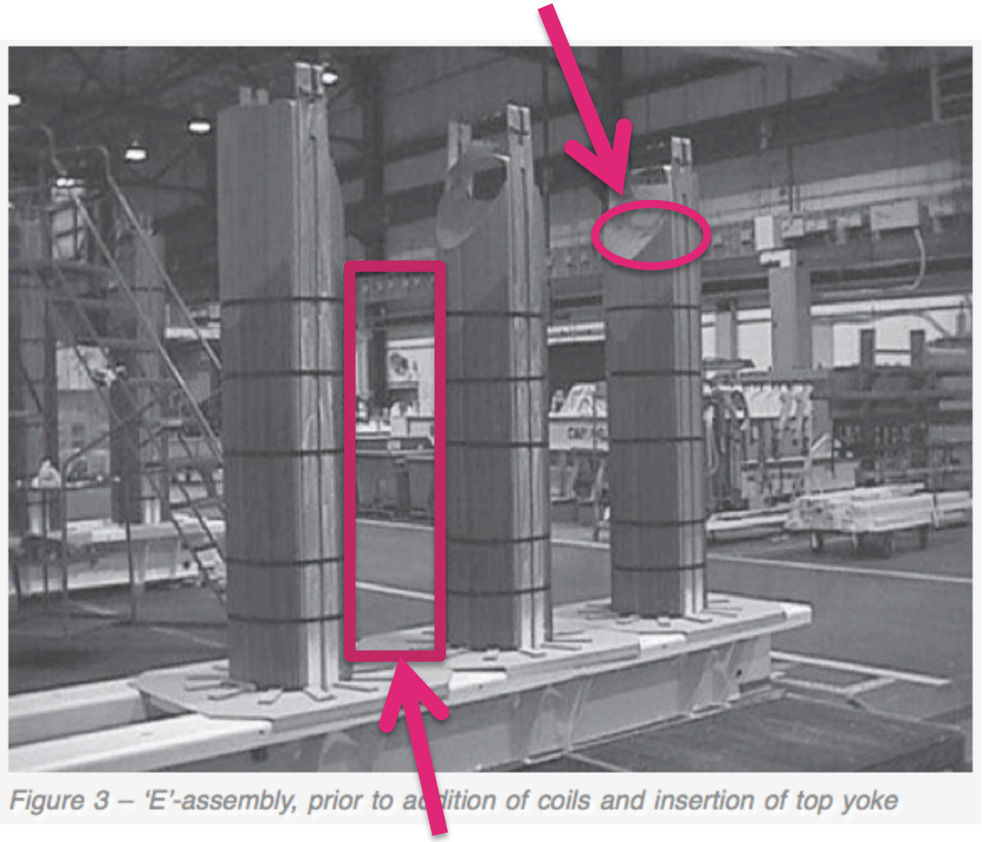
Current:

$$I = J_{wire} A_W \quad \text{(amp)}$$

$$P = E\,I$$



Key Specific ‘Areas’ for Power Capability



Core Cross-Section Area, A_C

Figure 3 – ‘E’-assembly, prior to addition of coils and insertion of top yoke

‘Winding Window’ Area, A_W

via: electrical-engineering-portal.com

Transformer Power, P (watts)

Window Area

Core Area

$$P = E\,I = K f \mathrm{B}\,\mathrm{J}_{wire} \mathrm{A}_W \mathrm{A}_C \quad \text{(watts)}$$

But: $\mathrm{A}_W = \mathrm{K}_U \mathrm{A}_C$

with:

B_{max} = 1.1 Tesla, J_{wire} = 500 Amp/cm2, 40% winding fill factor

f = frequency

A_C = Core Area

Power: $$P = 0.56 f \left(\mathrm{A}_C\right)^2 \quad \text{(watts)}$$

f in hertz,
A_C in in^2

Examples: Transformer Size - Power

$$P = 0.56 f \left(A_C\right)^2 \quad \text{(watts)}$$

At 60 Hz:

Core Area = 100 in^2 → → 336 kW

Core Area = 1000 in^2 → → 33.6 MW

Core Area = 3000 in^2 → → 302 MW

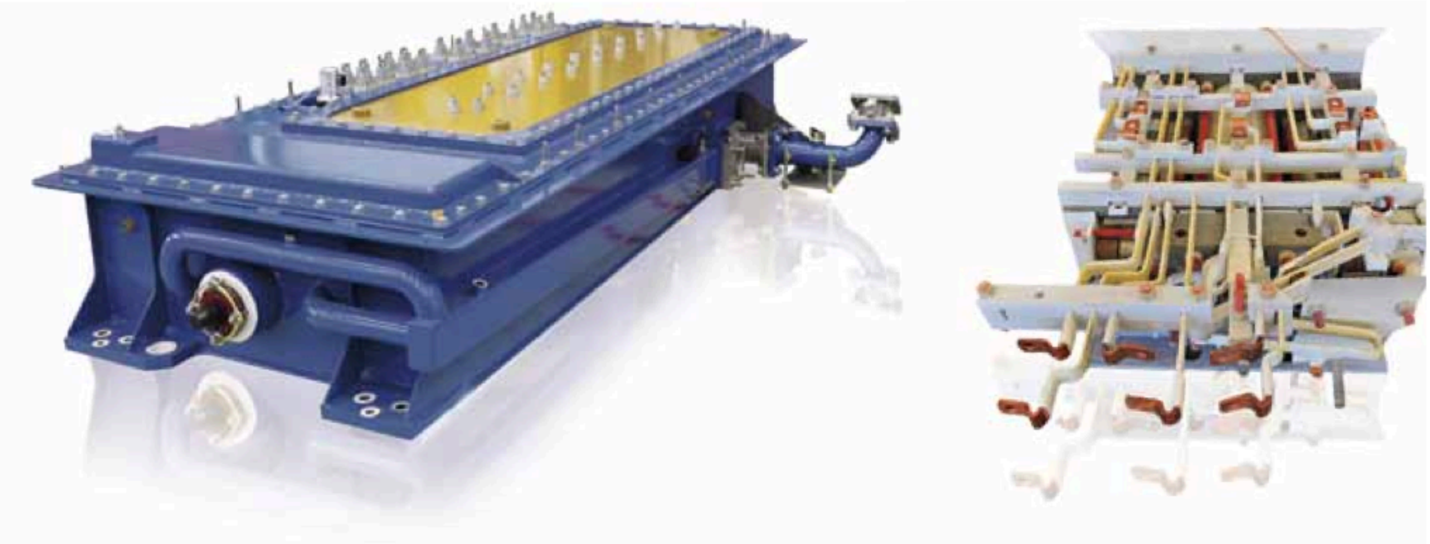
At 6 kHz:

Core Area = 100 in^2 → → 33.6 MW

Higher Frequency → Smaller Size

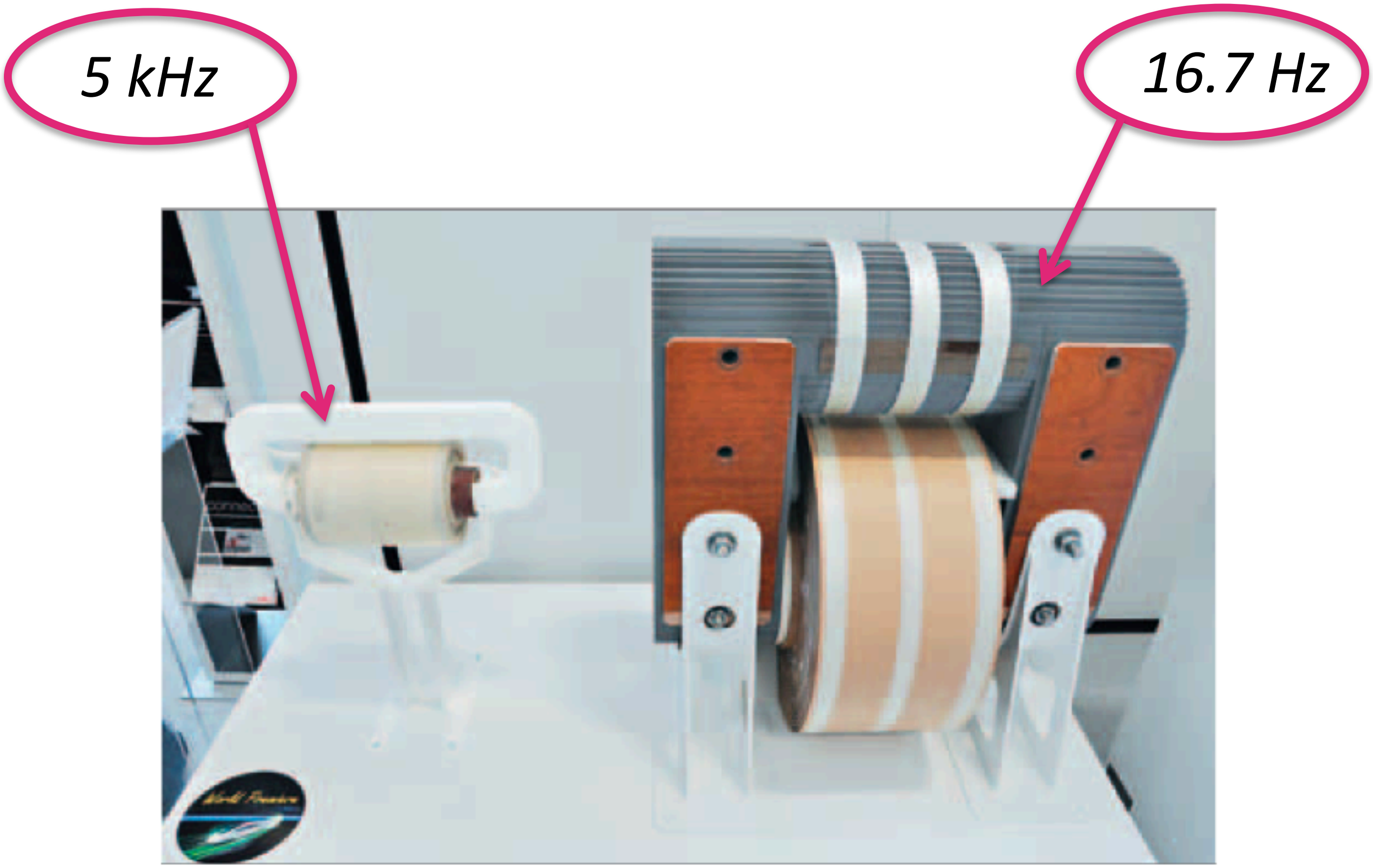
- Recall: $P = 0.56\,f\,\left(A_C\right)^2$ (watts)
- Examples for Traction Transformers

450 – 675 kW: at 1.75 kHz
Via: ABB



via: 'SR Transformers-121031.pdf'

Size – Frequency Relations



Left: 5 kHz Transformer. Right: 16.7 Hz Transformer. Both: 3.6 kV Primary, 1.5 kV Secondary.

via: ABB Brochure: “Shrinking the Core”

An Alternate Approach to Transformers

- Recall: Classical Transformer Approach
  - ‘Unity’ magnetic coupling via steel core
  - Steel core about 25% of weight and cost
  - Core-Losses = major source of heat

- New Approach – Technology from Wireless Power Systems
  - No physical contact between ‘primary’ and ‘secondary’
  - No core
  - Not ‘unity’ magnetic coupling
  - Higher frequency operation

- Achieved via ‘Resonant Coupling’
  - Originator = Tesla

Resonant Power - The ‘Pioneer’ = N. Tesla

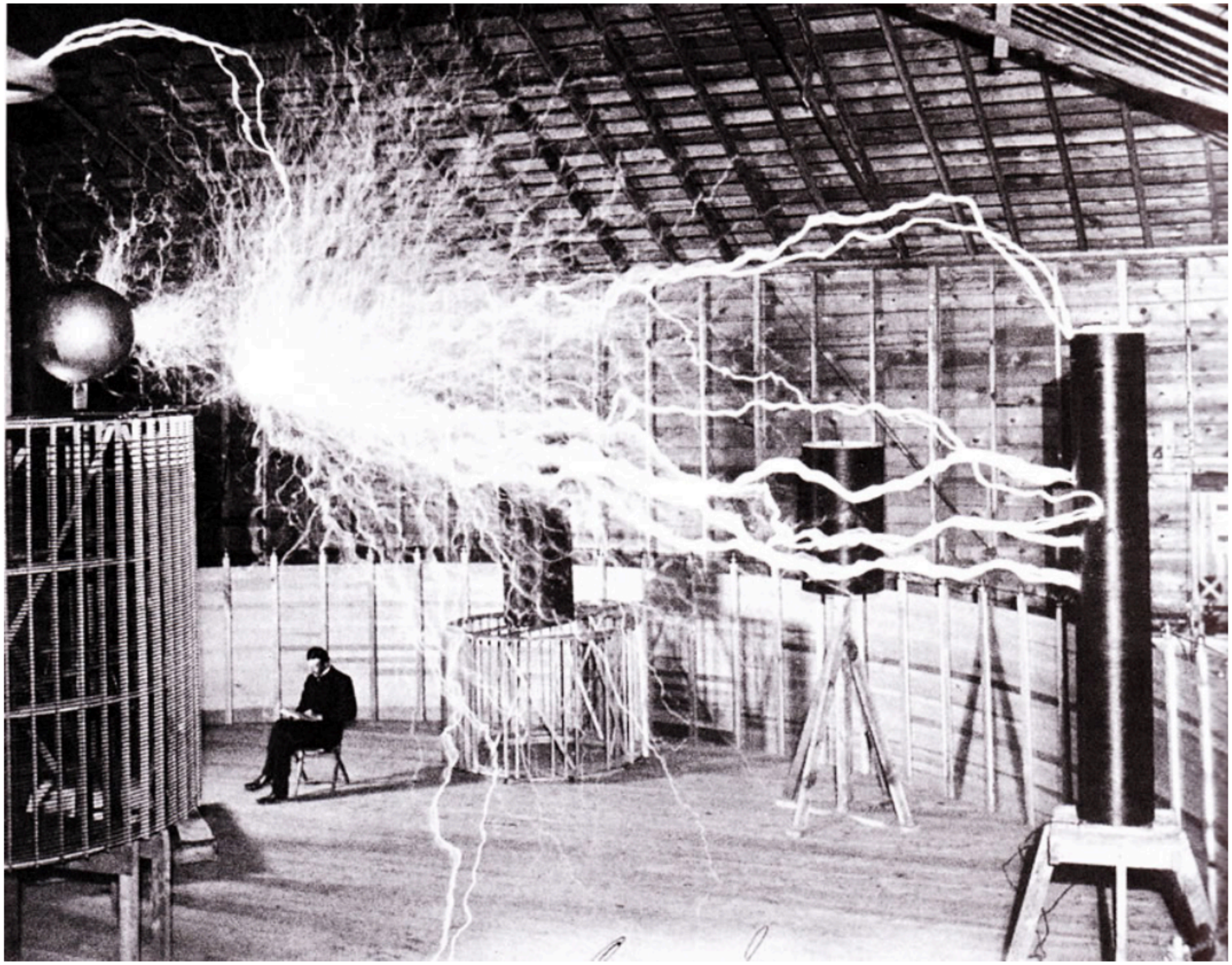
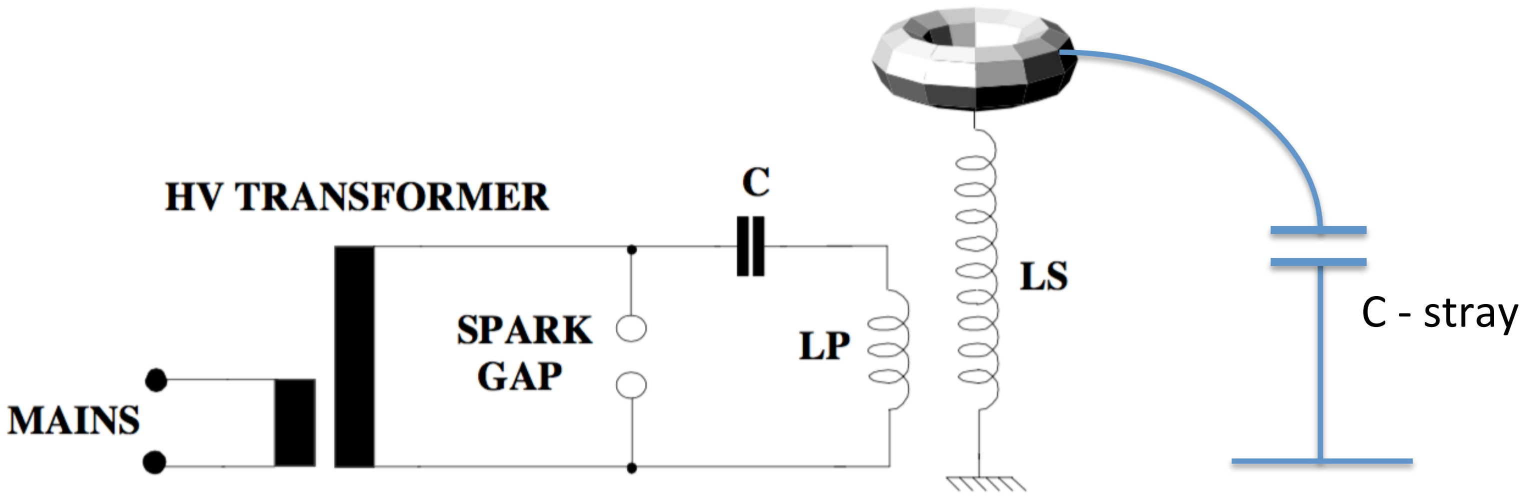


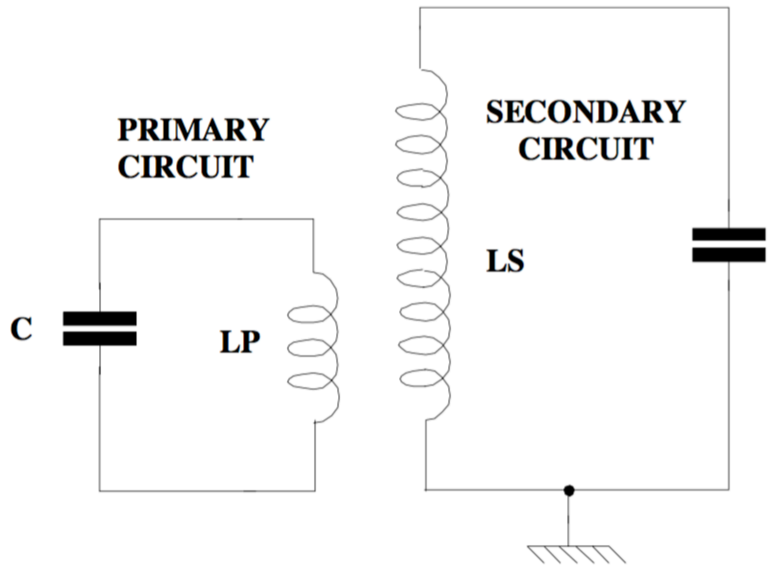
Figure 2.2: Tesla’s Colorado Springs experiments (from [26])

via: teslauniverse.com

Tesla: Double Resonant Coils

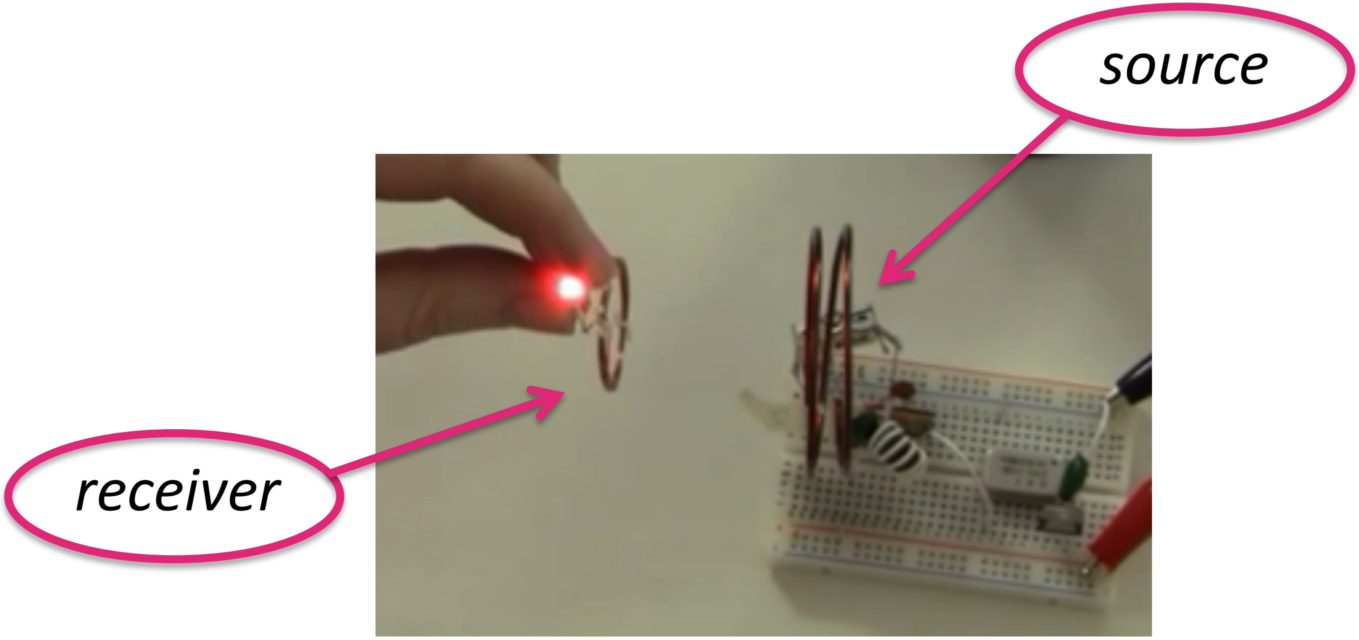


Two Magnetically Coupled Resonant L-C Circuits



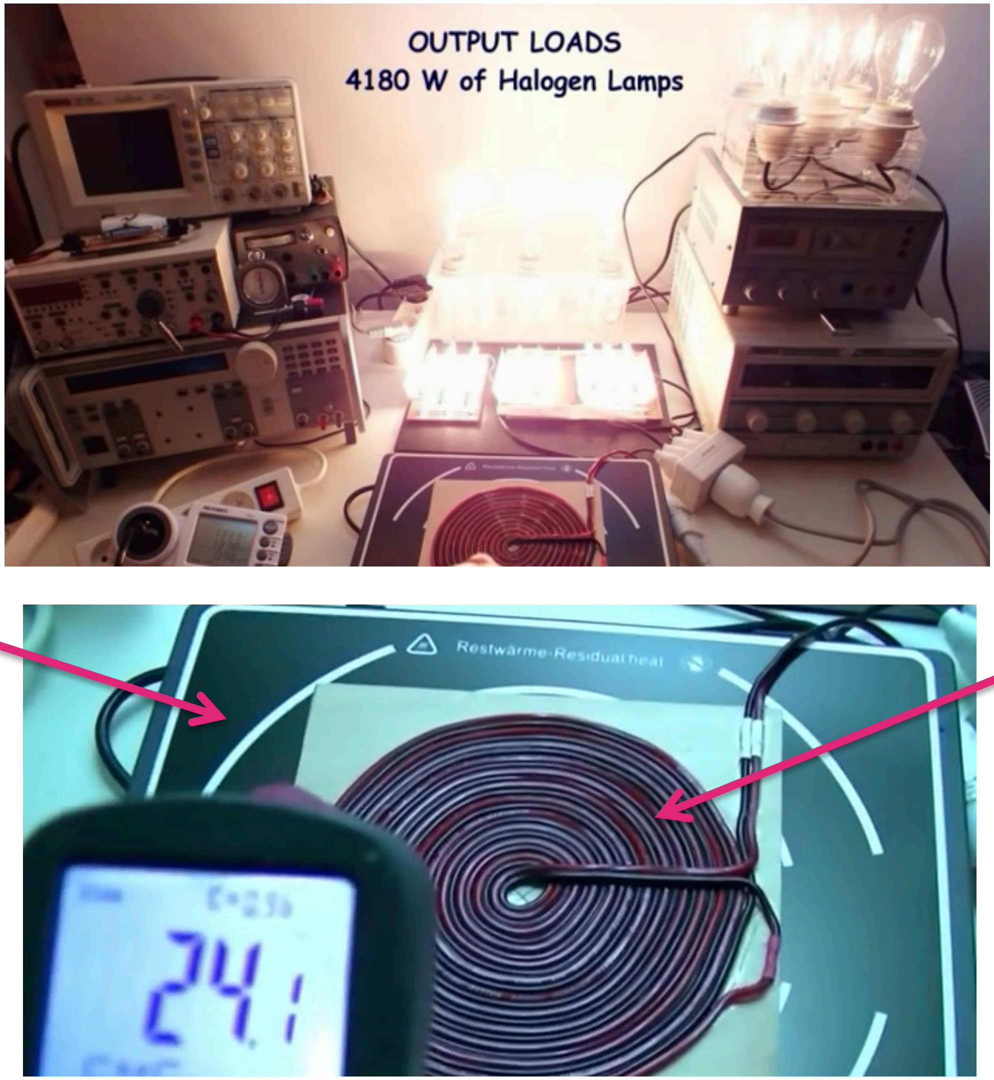
Key Concepts for Resonant Power

- Use 1st resonant L-C circuit as source of magnetic energy
- Use 2nd resonant L-C to collect magnetic energy
- Need ‘weak’ magnetic coupling between the two L-C circuits



via: www.youtube.com/watch?v=r1UT4NuygmQ

Induction Cooktop Yields 4kW Wireless Power



Induction Cooktop = Source

Receiver Coil

via: www.youtube.com/watch?v=JqgO7AEZXzI

Wireless Power Examples: Buses, Cars

United Kingdom – Wireless Milton Keynes electric bus route.
January 2014

Source: *http://transportevolved.com/2014/01/09/milton-keynes-uk-launches-wirelessly-charged-electric-bus-route/*

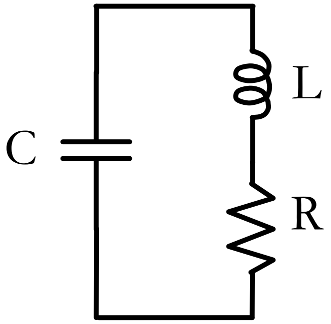
Frequency	?? Hz
Power Transfer Levels	120 kW
Wireless Mode	static

Belgium – Volvo & Bombardier test inductive charging.
October 2013

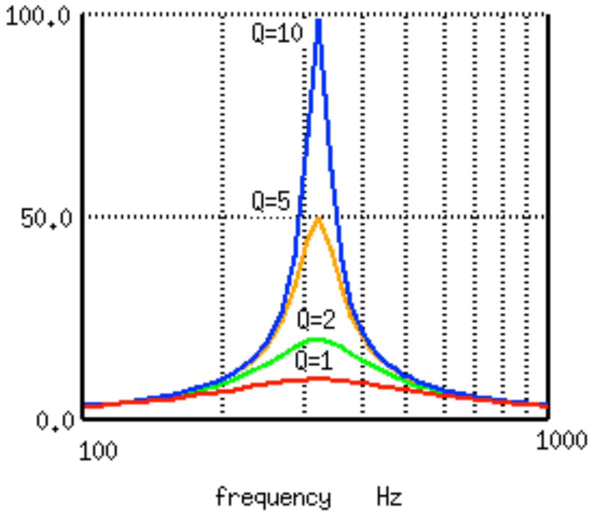
Source: *http://evworld.com/news.cfm?newsid=31633*

Frequency	140 kHz
Power Transfer Levels	20 kW
Wireless Mode	static

Resonance Equations – Single L-C



$$H(s) = \frac{\omega_0^2}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2}$$



$$Q \stackrel{\text{def}}{=} \frac{f_r}{\Delta f} = \frac{\omega_r}{\Delta \omega}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

Q = Quality Factor

$$Q \stackrel{\text{def}}{=} 2\pi \times \frac{\text{Energy stored}}{\text{Energy dissipated per cycle}} = 2\pi f_r \times \frac{\text{Energy stored}}{\text{Power loss}}.$$

$$Q(\omega) = \omega \times \frac{\text{Maximum energy stored}}{\text{Power loss}}$$

$$Q = \frac{X_L}{R}$$

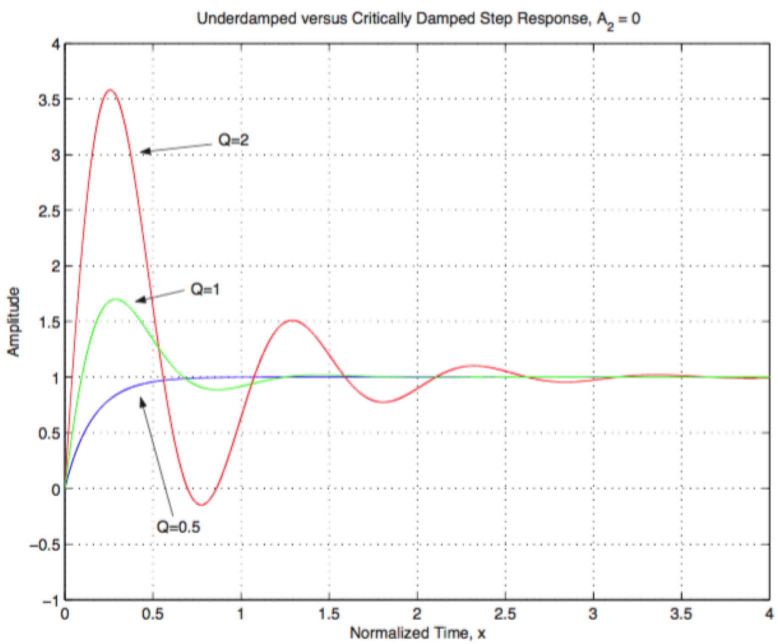
Series R-L-C Circuit

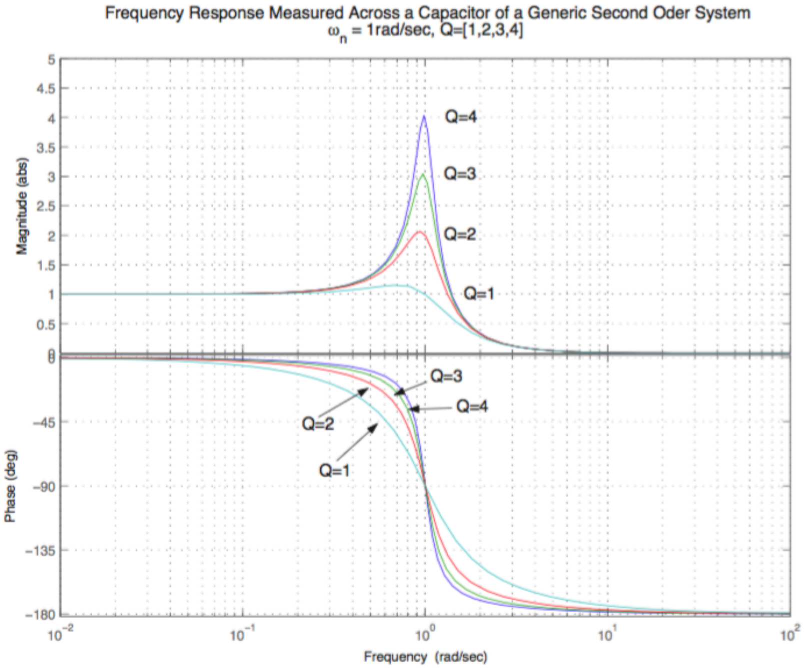
Single L-C: Time and Frequency Responses

$Q > 1$

Oscillatory Time Domain Response

Peaked Frequency Domain Response





$$y(x) = e^{-\frac{\pi x}{Q}}\left(A_1 \cos\left(\frac{\pi x}{Q}\sqrt{4Q^2-1}\right) + A_2 \sin\left(\frac{\pi x}{Q}\sqrt{4Q^2-1}\right)\right)$$

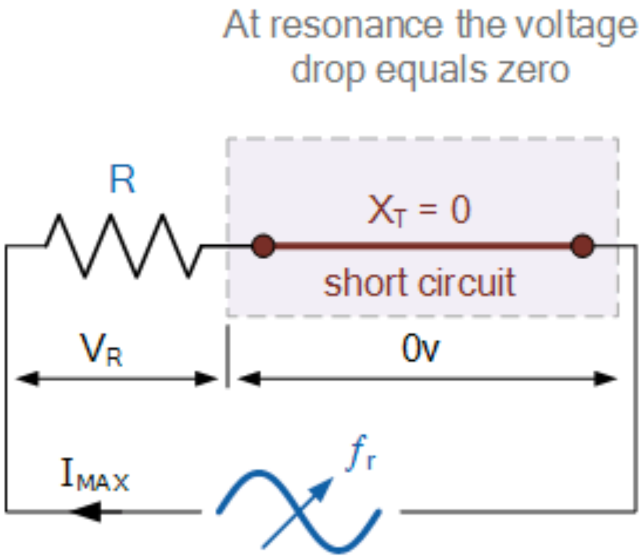
$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{\omega_n^2}{s^2 + \frac{\omega_n}{Q}s + \omega_n^2}$$

via: J.Stark III Thesis MIT 2004

At Resonance; L & C Reactance 'Cancel'

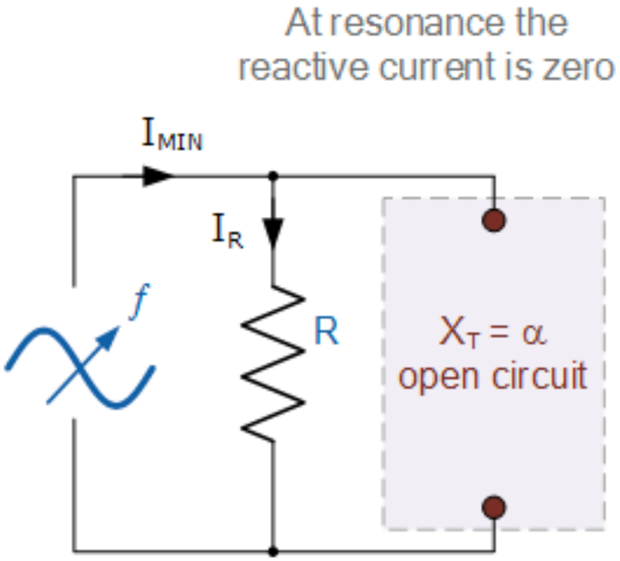
Series = Short Circuit
(zero voltage)

Parallel = Open Circuit
(zero current)



At resonance the voltage drop equals zero

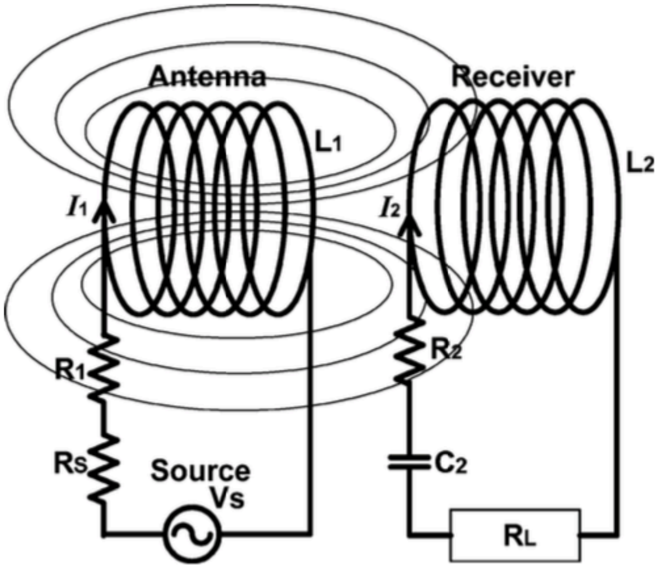
$$Q = \frac{X_L}{R}$$



At resonance the reactive current is zero

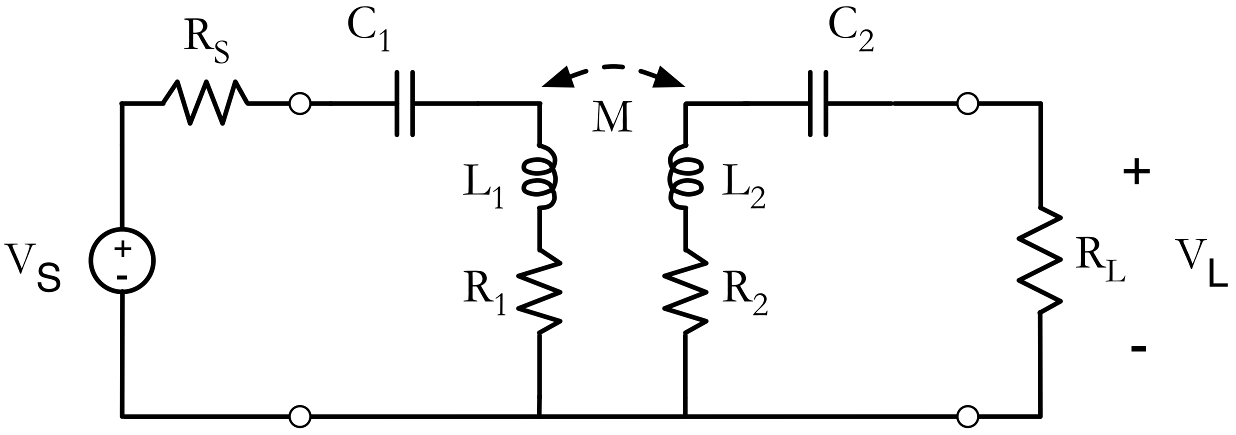
$$Q = \frac{R}{X_L}$$

Double Coupled L-Cs Resonant Circuits



Weakly linked magnetic flux

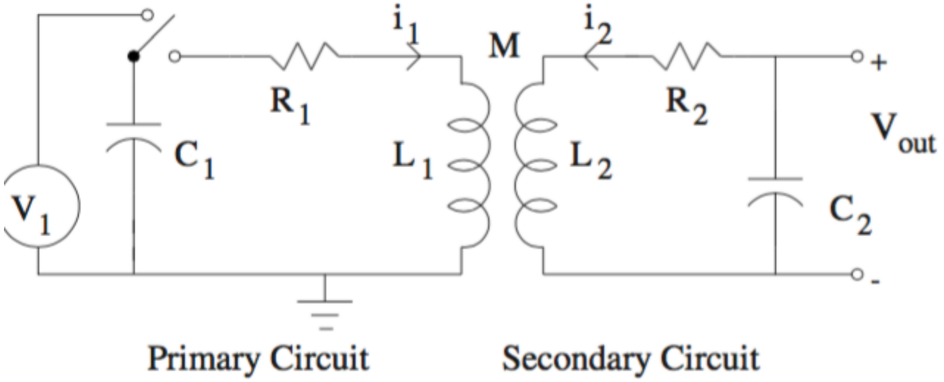
Coupled Equivalent Circuit:



Primary L-C

Secondary L-C

4th Order Equations – ‘Tesla Coil’



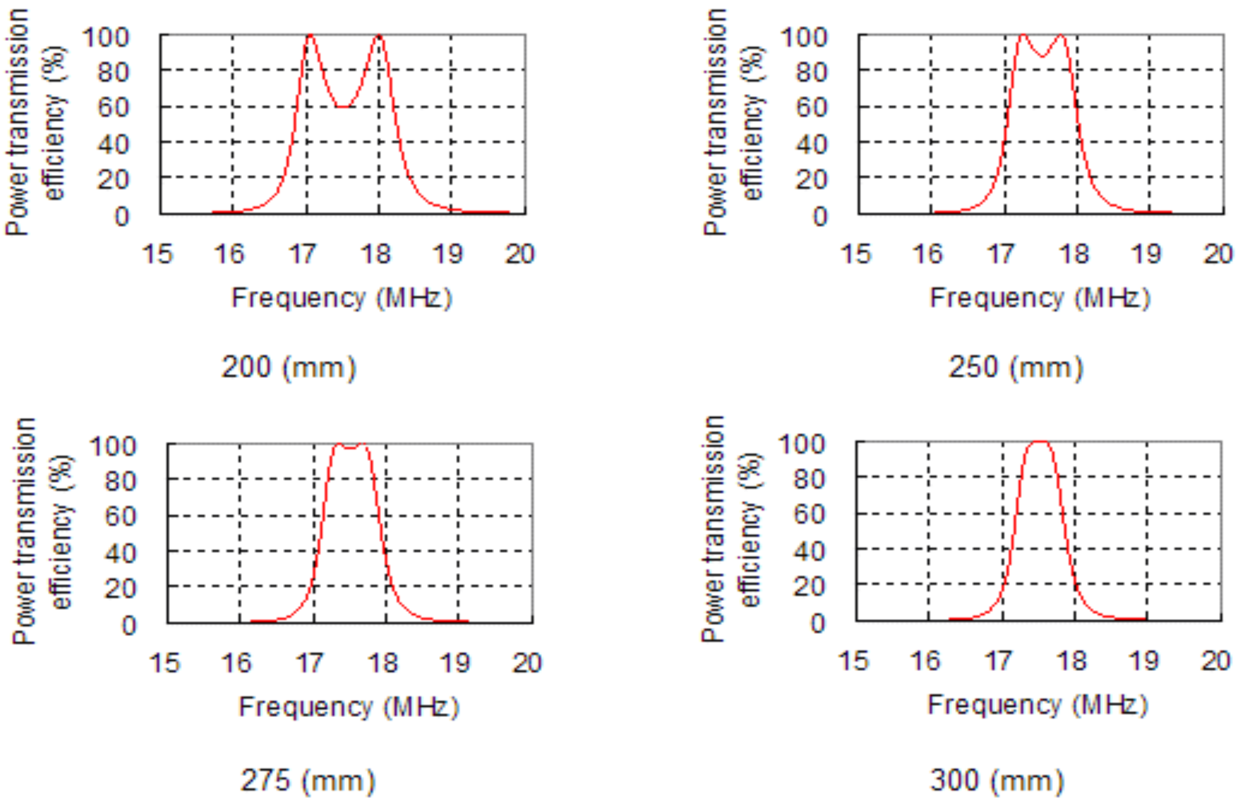
4 Energy Storage Elements

$$\frac{V_{out}}{V_{in}} = -\sqrt{\frac{L_2}{L_1}} \frac{s^2\omega_2^2 k}{\left\{ \begin{array}{l} (1-k^2)s^4 + (\frac{\omega_1}{Q_1} + \frac{\omega_2}{Q_2})s^3 + (\omega_2^2 + \omega_1^2 + \frac{\omega_1\omega_2}{Q_1Q_2})s^2 \\ +\omega_1\omega_2(\frac{\omega_2}{Q_1} + \frac{\omega_1}{Q_2})s + \omega_1^2\omega_2^2 \end{array} \right.}$$

$$\omega_i = \frac{1}{\sqrt{L_iC_i}} \text{ and } Q_i = \frac{\omega_i L_i}{R_i} \qquad M = k\sqrt{L_1L_2}$$

via: J.Stark III Thesis MIT 2004

Response: Single or Double Frequency Peaks



200 (mm)

250 (mm)

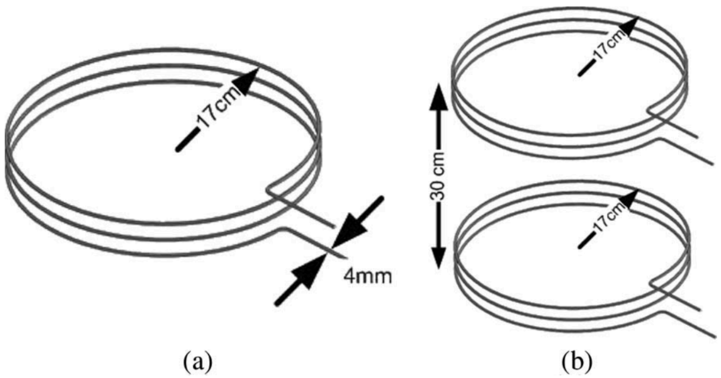
275 (mm)

300 (mm)

Fig. 1 Power transmission efficiency
(distance between transmission and receiving coils: 200 - 300 mm)

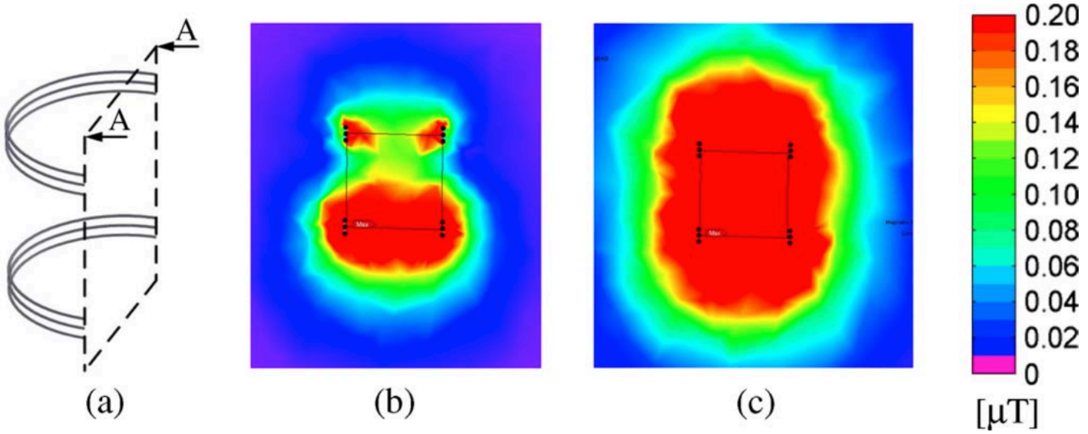
via: www.jmag-international.com/catalog/139_PowerTransmission_MagneticResonance.html

At Resonance: Highly Coupled



(a)   (b)

Fig. 6.   Drawings of an isolated coil and mutually coupled coils. (a) Isolated coil. (b) Two coupled coils.

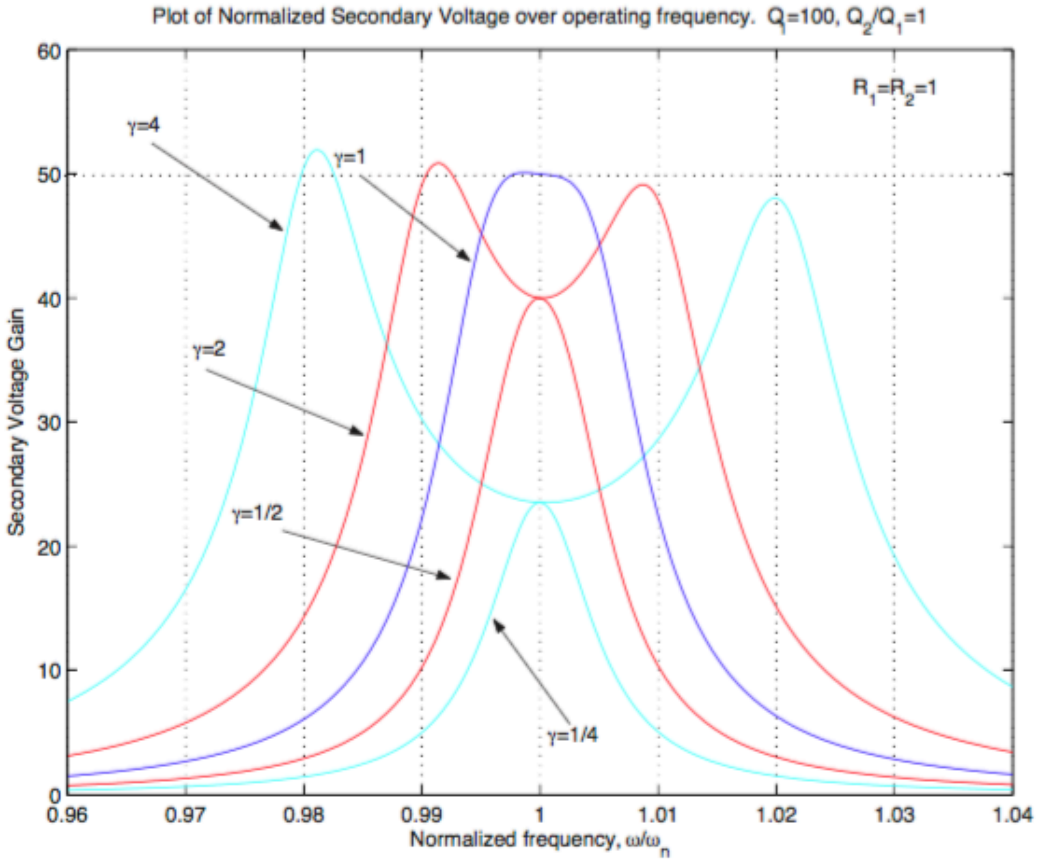


(a)   (b)   (c)

Fig. 7. Magnetic flux density dependence on operating frequency. (a) Sectional view. (b) 3.34 MHz. (c) 3.68 MHz (resonant frequency).

via: Lee, IEEE 2011

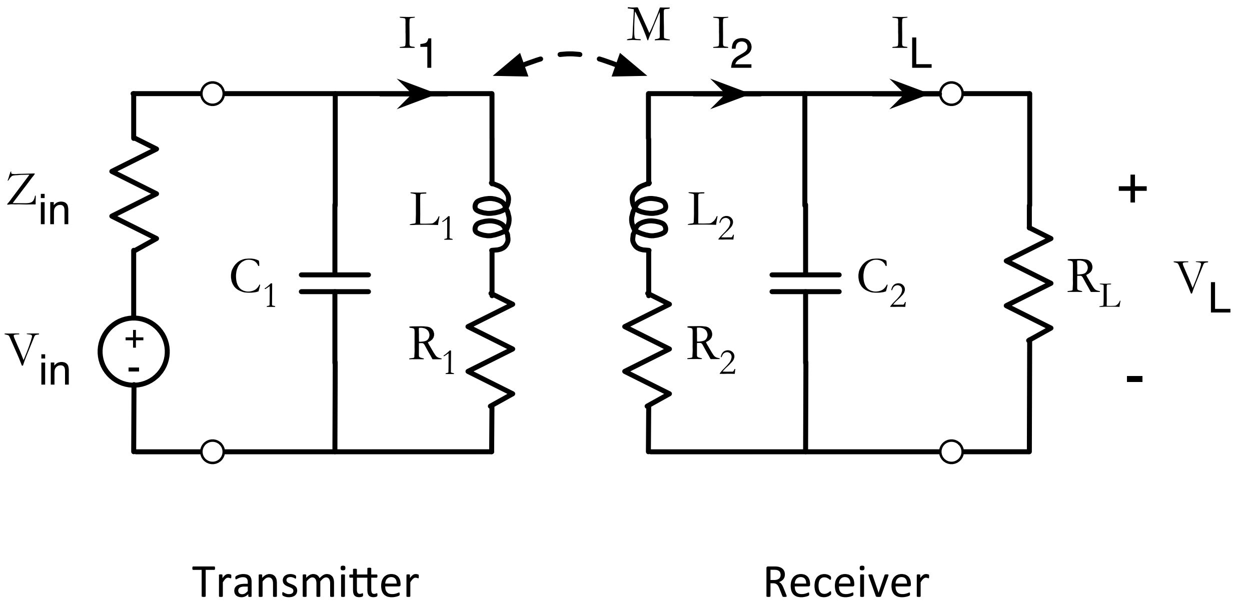
Coupling Changes Frequency Response



$$k \equiv \frac{M}{\sqrt{L_1 L_2}} \qquad k_{crit} = \frac{1}{\sqrt{Q_1 Q_2}} \qquad \gamma = \frac{k}{k_{crit}}$$

via: J.Stark III Thesis MIT 2004

Power Efficiency: Double Resonant Circuit



$$\eta_1 = \frac{\text{Power to Load}}{\text{Total Power (Loss+Load)}} = \frac{I_L^2 R_{Le}}{I_1^2 R_1 + I_2^2 R_2 + I_L^2 R_{Le}}$$

Max Power Efficiency at Resonance

Calculate:

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

Figure-of-Merit

$$\text{FOM} = k\sqrt{Q_1\, Q_2} >> 1$$

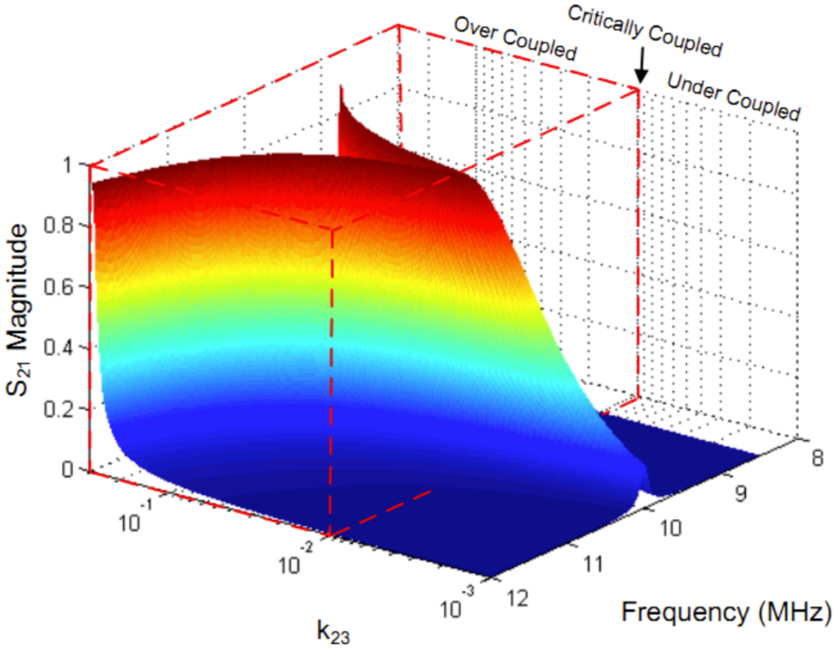
Where:

$$k \equiv \frac{M}{\sqrt{L_1 L_2}} \qquad Q_1 = \frac{\omega L_1}{R_1} \qquad Q_2 = \frac{\omega L_2}{R_2} \qquad \omega = \text{resonant angular frequency}$$

When at Optimum load resistance, $R_{\text{L-equiv-opt}}$

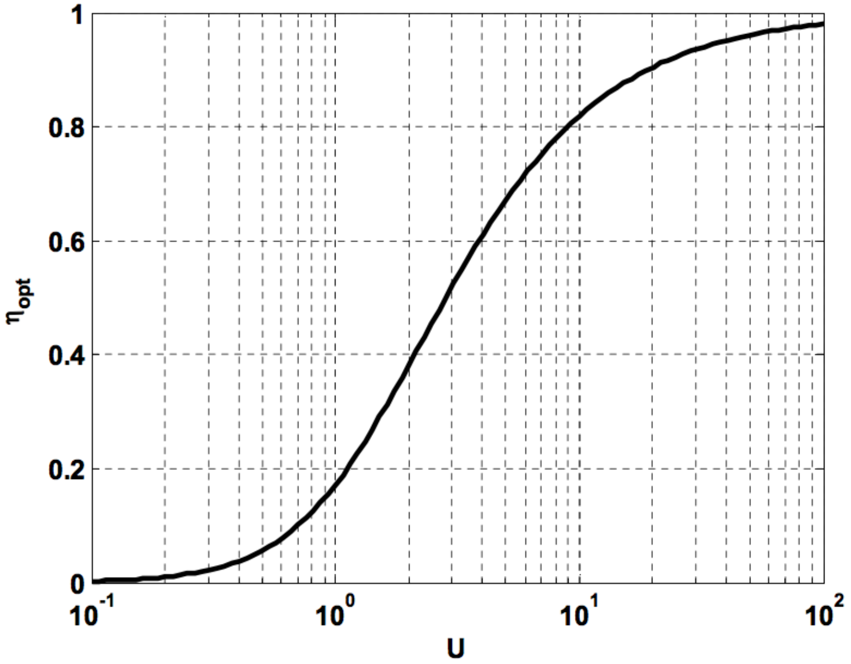
$$\mathrm{R}_{L-equiv} = R_2\left(1+k^2 Q_1 Q_2\right)^{1/2}$$

Double Resonant Power Transfer, Optimization



Sample: IEEE 2013

$$\eta_{opt} = \frac{U^2}{\left(1+\sqrt{1+U^2}\right)^2}$$

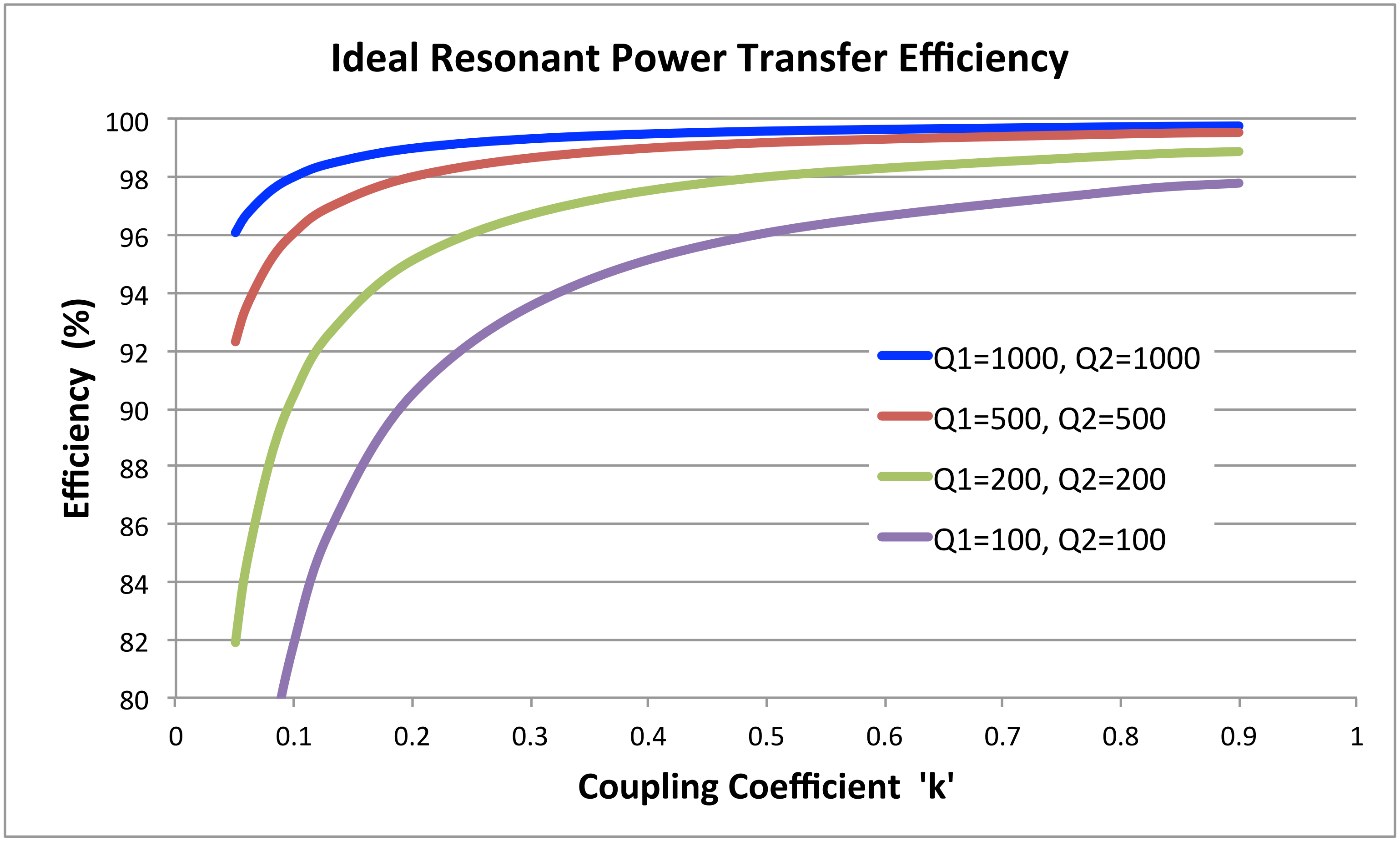


Kesler: Witricity 2013

‘Figure-of-Merit’ = U

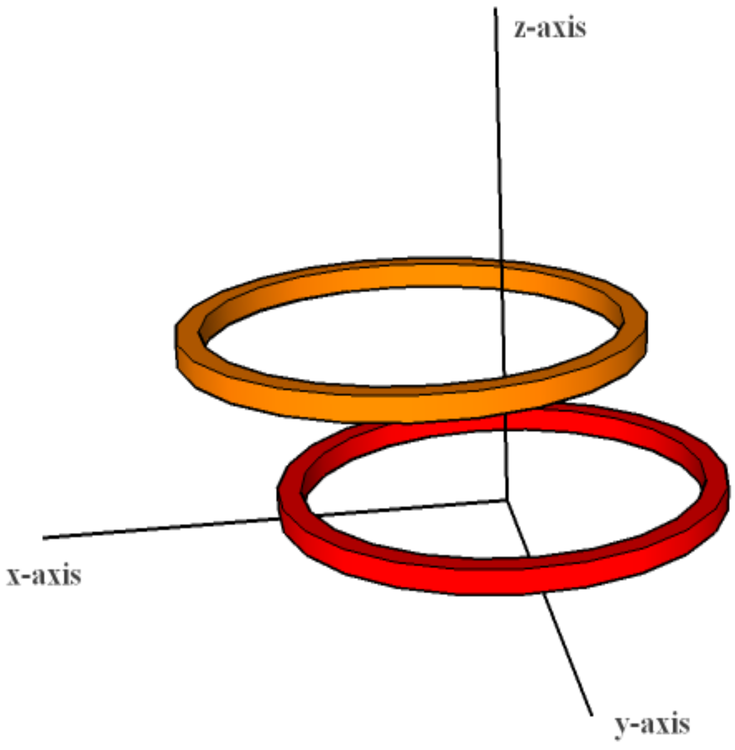
$$U = k\sqrt{Q_s\, Q_d}$$

Efficiency: ‘k’ Dependence with ‘Q’



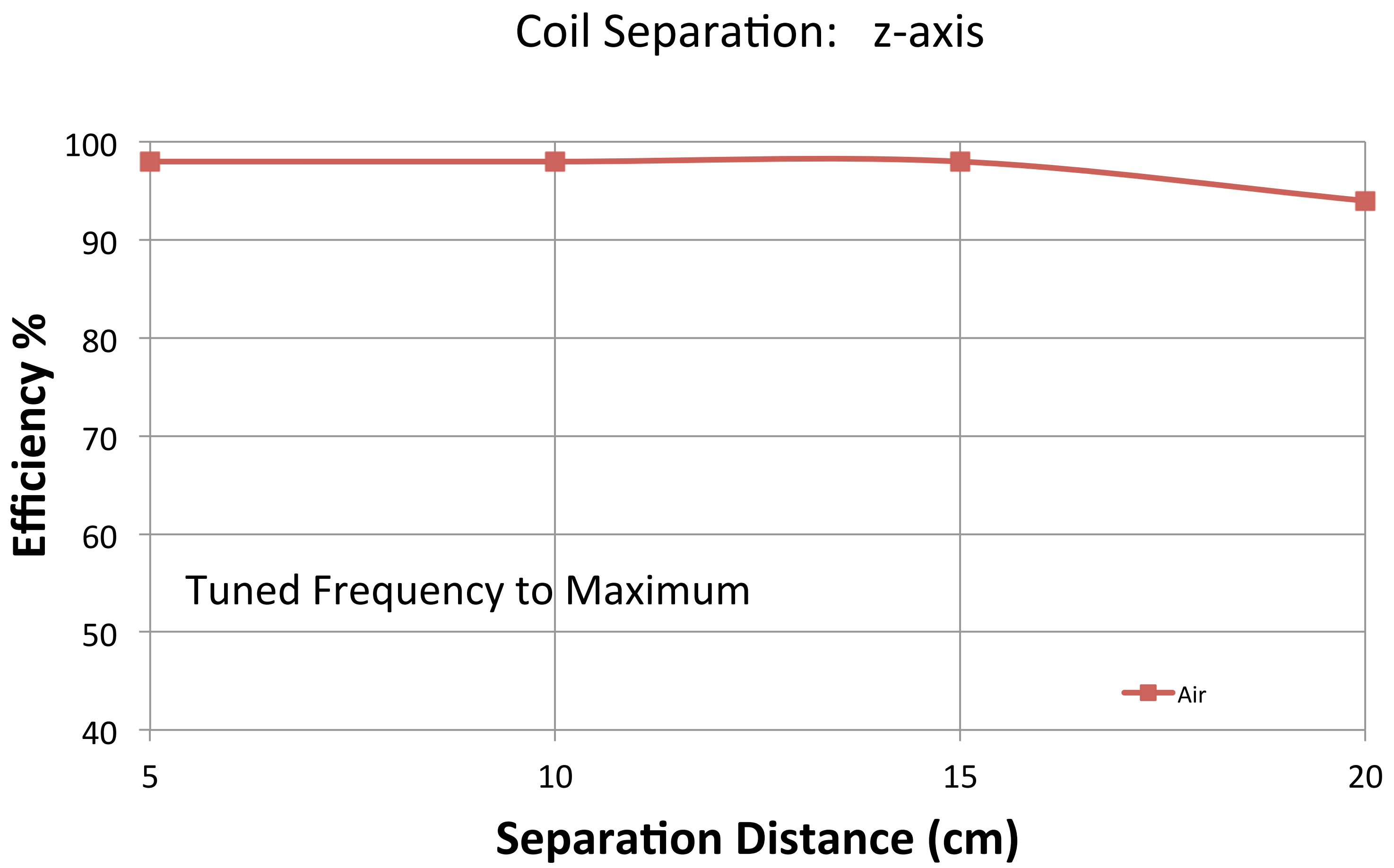
Coil Spatial Position Sensitivity Tests: Simple Circular Coils

- The transmitter (red) and receiver (orange) coils, aligned above one another and separated on the z-axis.
  - Separate: z-direction
  - 'Shift' : x-direction
- Litz-wire coils are employed.
  - Symmetric, 30cm Diam. Coils.



Defilippo, Cooke MIT 2015

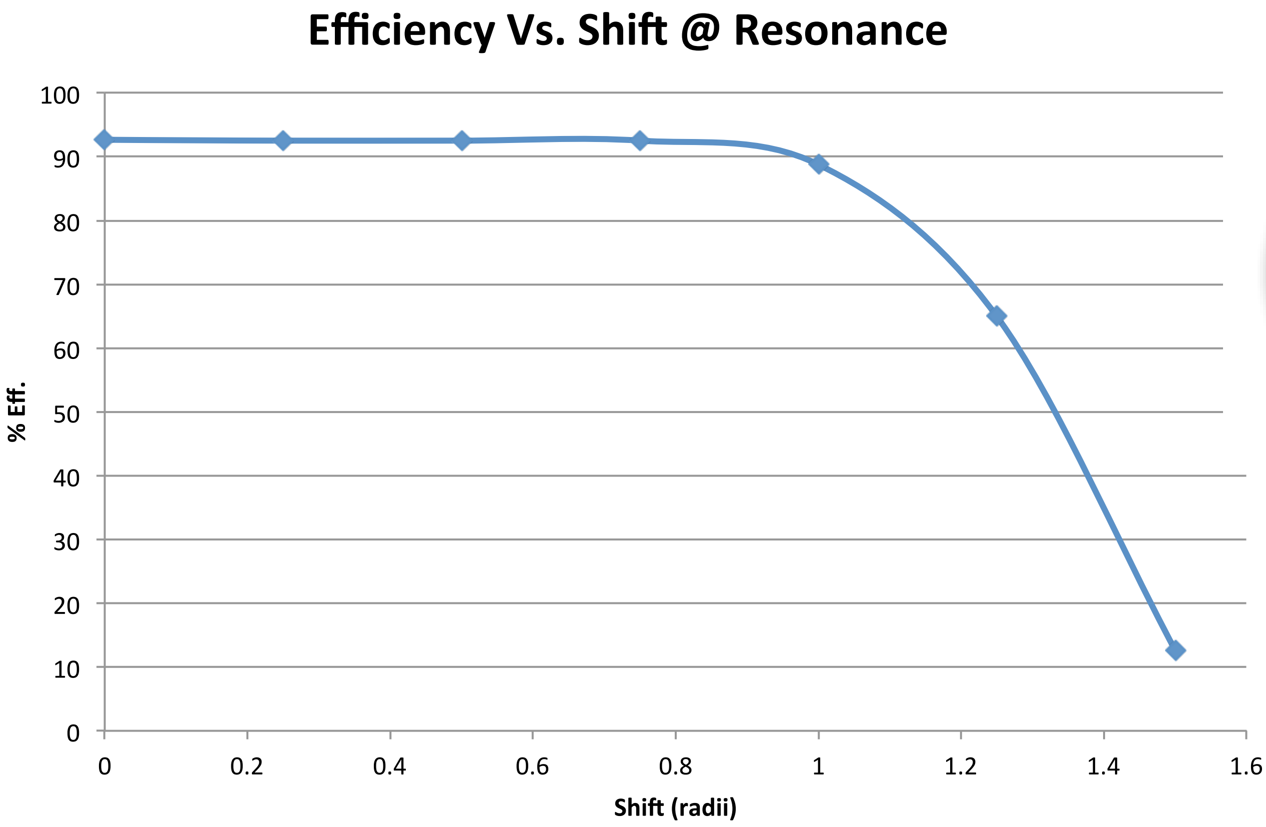
Position Sensitivity: Separation

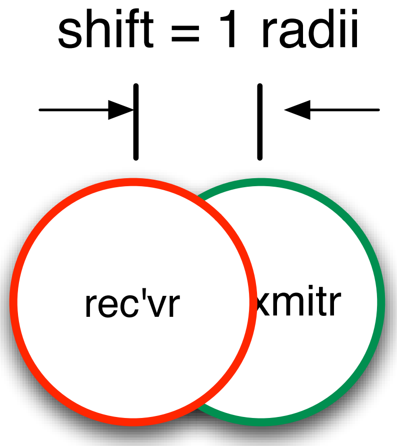


Defilippo, Cooke MIT 2015

Position Sensitivity: Off Axis Shift

Coil Shift: x-axis

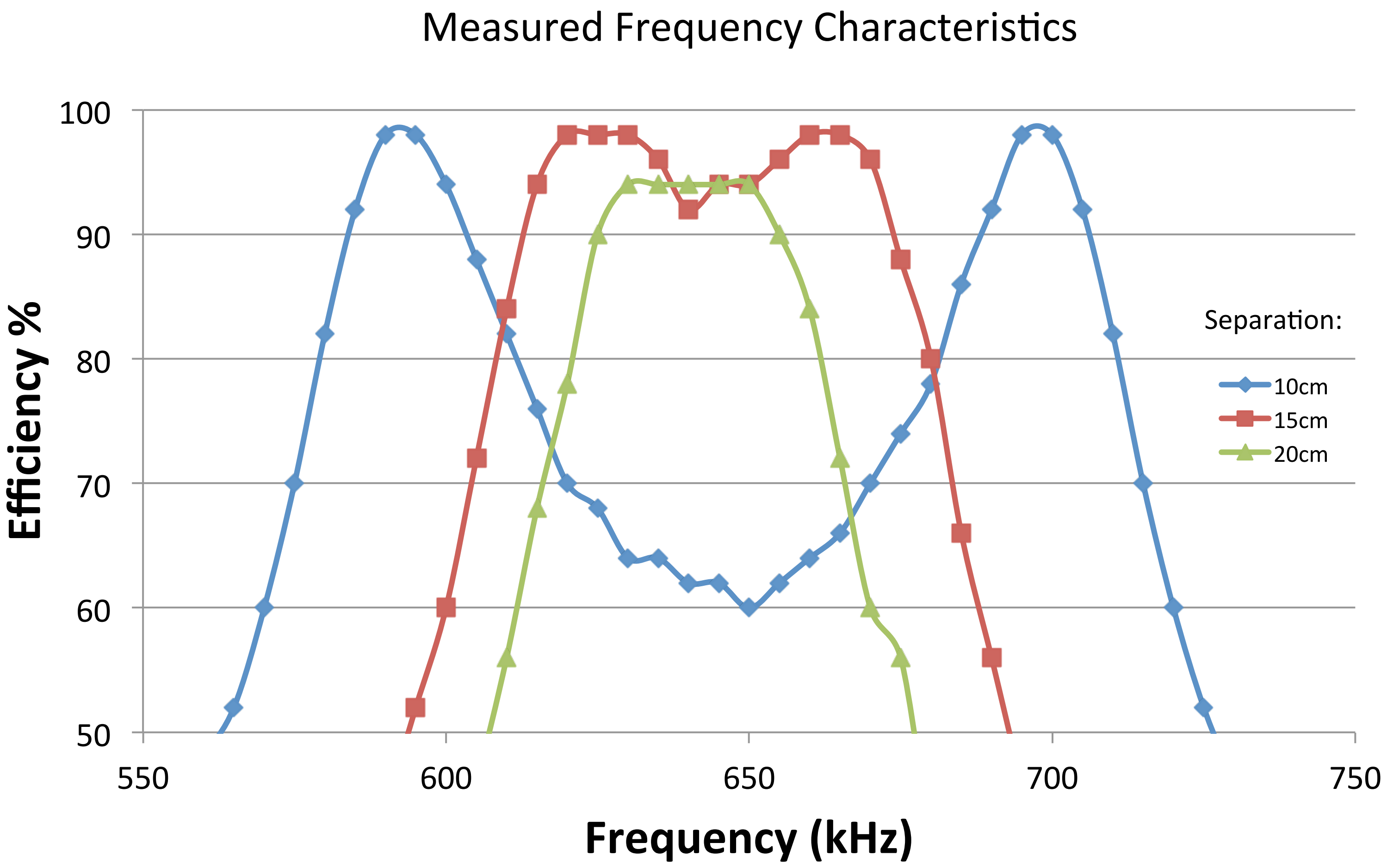




Circular Coils

Defilippo, Cooke MIT 2015

Circular Coils in Air, Litz Wire



Defilippo, Cooke MIT 2015

Lessons from Wireless World

- On-Going Development, Many Applications
  - Electric buses, cars
  - Autonomous-underwater-vehicles (AUV)
  - Medical implants, cell-phones, computers

- Theory and Experimental Agreement
  - High ‘Q’ is essential for low loss
  - Equivalent circuit models are okay and useful
  - Modal analysis models are okay and useful
  - Efficiency-power FOM = k [root(Q_1Q_2)] >> 1
  - Presently data only up to 10s kilowatt level

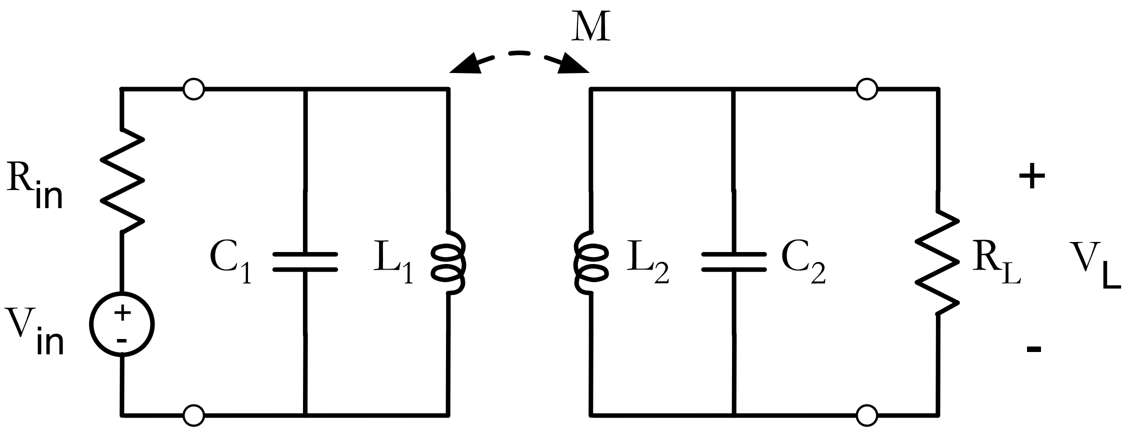
- Now: expand concepts to Megawatt Level

Resonant High-Power Transformers

- Maximize power transfer
- Minimize Loss: efficiency constraint
- Apply to 50 – 500 MW, 110 – 500kV designs
  - Requires high frequency
  - Recall transformer size relations
    - To keep similar size:
    - Mu reduced by 40,000
    - Frequency increase by ~40,000 (perhaps ~ 1MHz)
    - No core: less heat, better insulation

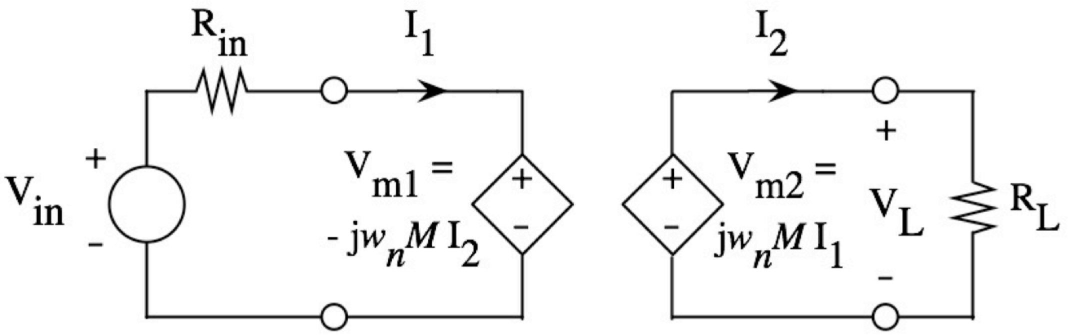
Optimized Power Transfer

Equivalent “Loss-Less” Resonant Circuit:



At Resonance:

$$k \equiv \frac{M}{\sqrt{L_1 L_2}}$$

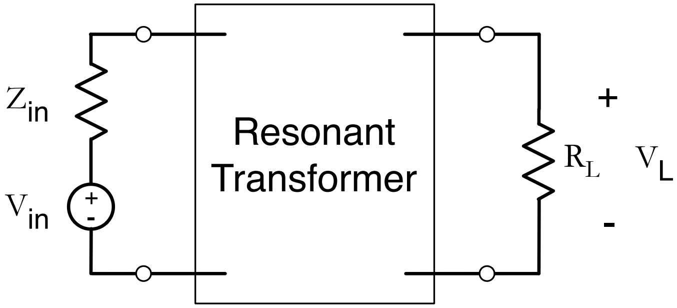


Optimized Power Transfer

At Resonance:

Idealized: Neglect Winding Losses

Define Power Transfer Efficiency (N1 = N2):



$$efficiency = \eta_2 = \frac{\text{Optimum Power to } \mathrm{R}_L \text{ with Transformer}}{\text{Optimum Power to } \mathrm{R}_L \text{ without Transformer}}$$

Max Power Transfer:

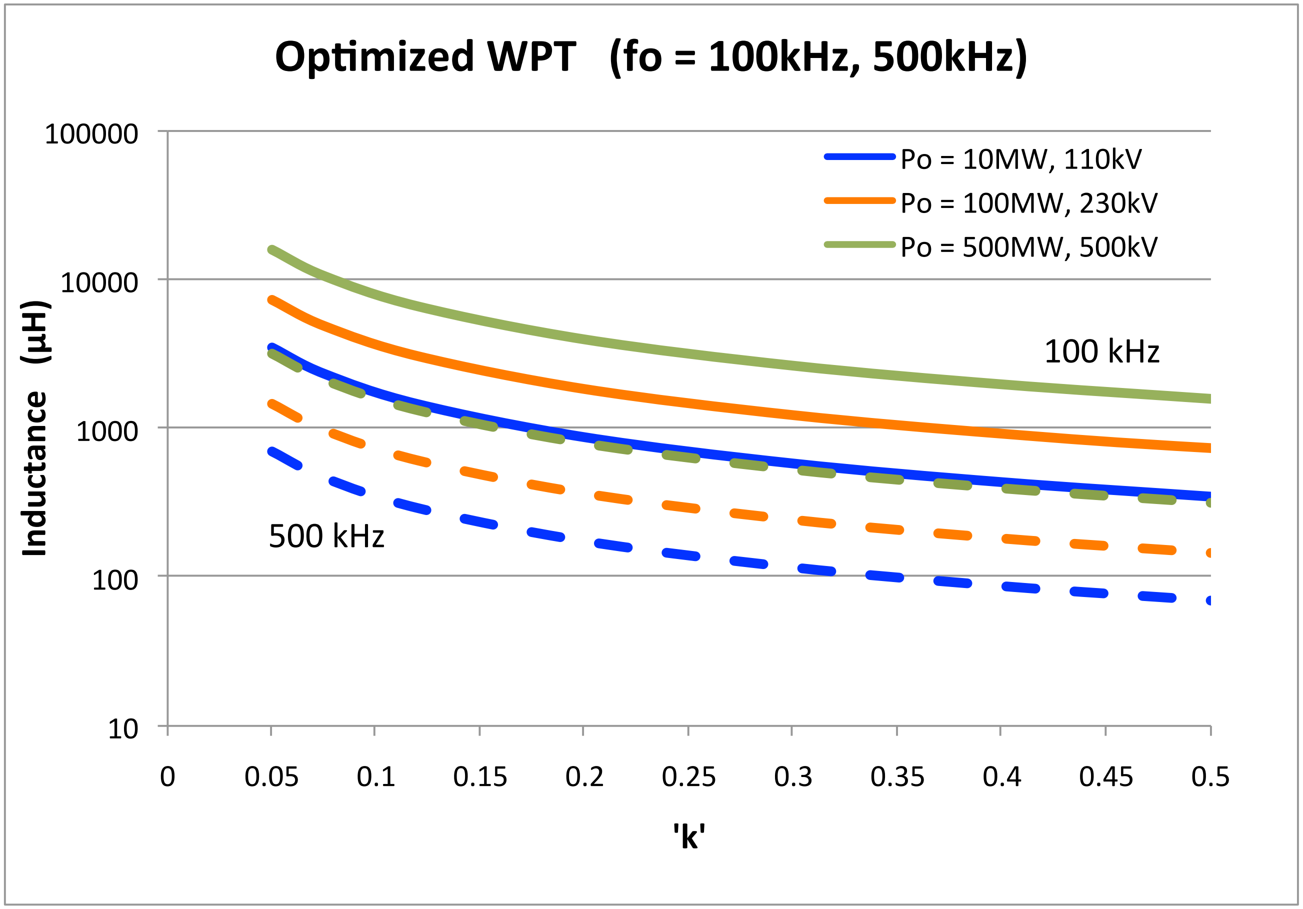
$$R_L = R_{in} \equiv R_{opt} \qquad k \equiv \frac{M}{\sqrt{L_1 L_2}}$$

Opt. Power Design: ($L_1 = L_2$)

Max Power, fixed *w*, fixed *M*:

$$R_L{}^2 = \omega_n{}^2 M^2 \longrightarrow \boxed{L_{opt} = \frac{(V_L)^2}{2\pi\ f_o\ k\ P_{out}}}$$

10 to 500 MW: Core-Less Design



Spiral Coil: 25 turns, 1.5” wire, 0.5” spacing, 24” ID: → 1000 µH

Spiral Coil = Shell-Form Pancake Coil

LV Tap Leads

Cooling Oil Flow Baffles

via: Hagman, PES transformer Course 2013

10 to 500 MW: Core-Less Design

- Coils
  - Control & Design separation for optimum ‘k’
  - Employ existing coil technology
    - spiral ‘pancake’ coils
    - Like in shell-form transformers
    - Exhibit better high frequency response
  - Control inductance for low-loss
  - Minimum resistance possible
    - fewer turns, large area wire (Litz)
- Without Core
  - No Core losses
  - More space for cooling
  - More space for insulation

Limitations, Needs

- Power Electronics (at the megawatt level !!!)
  - Costs for steel core → power electronics
- Non-magnetic coil supports
  - Magnetic forces still very large
- Stray field control
  - Use ferrite material external to windings
    - Example auto and bus chargers
- High 'Q' coils
  - Low losses, maybe superconductivity ??
    - Examples of superconductivity classical transformers

Conclusions

- Classical transformers
  - Costly; large heavy steel cores
  - Complicated construction
- Disruptive approach: eliminate the steel core
  - Use magnetically coupled resonance
  - Borrowed concepts from wireless power
    - No steel core
    - High frequency operation, needs power electronics
  - Structure of Pancake coils consistent with wireless power
    - High Q coils essential
- Added Bonus
  - Use power electronics to go 'breaker-less' ???

Thank You

And Thanks to the ‘Internet’ for Many Great Images