Examining Wireless Power Transfer

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Agenda

• **Introduction**  
  – Foundational principles of electromagnetics  
  – Power transfer - near and far field

• **Existing and Emerging Wireless Power Standards**  
  – WPC, PMA, A4WP comparison  
  – Electromagnetic field safety implications of WPT

• **Theory of Operation**  
  – Considering loosely coupled coils  
  – Modeling resonant power transfer  
  – Magnetic link efficiency  
  – Topological analysis with SPICE and FEA

• **Design Considerations**  
  – RX to TX communication  
  – Intelligent voltage positioning and load response  
  – EMI, efficiency/loss measurement  
  – Foreign object detection – eddy loss detection  
  – Single coil, 5 W WPC design example
Notable Dates in Wireless Power Transfer

- **1820**: Biot–Savart / André-Marie Ampère / H. Oersted discover and quantify relationship between electric current and magnetic fields

- **1831**: Michael Faraday / H. Hertz discover electromagnetic induction

- **1834**: Lenz (Lenz's law) → N. Callan invents the electrical transformer

- **1864**: James Clerk Maxwell synthesizes previous observations and mathematically models electromagnetic radiation

- **1891-1917**: Nicola Tesla – enormous contribution to the practical application of resonant power transfer and electromagnetic induction; numerous discoveries and patents

- **2007**: WiTricity research group, led by Professor Marin Soljacic advances magnetic resonance to wirelessly power a 60 W light bulb with 40% efficiency at 2 m using 60 cm-diameter coils

- **2008/9**: A consortium of companies called the Wireless Power Consortium (WPC) announces the evolution of a industry standard for low-power (5 W) inductive charging
Electromagnetic Wave Propagation

- Field defined by antenna and distance from source
- Dipole(red) and loop(blue) antennas shown
- Wave impedance = E/H, converges at $\lambda >> 1$
- Reactive near field below $\lambda/2\pi$ is non-radiative
Race for a Wireless Charging Standard
Safety, Performance, Reliability and Interoperability

Wireless Power Consortium (WPC)
- Power Frequency Band: 105-205 kHz
- Communication Frequency Band: Same as power transfer band
- Range of Coupling: 0.4 to 0.7

Powermat (PMA)
- Power Frequency Band: 277-357 kHz
- Communication Frequency Band: Same as power transfer band
- Range of Coupling: 0.6 to 0.8

Alliance for Wireless Power (A4WP)
- Power Frequency Band: 6.78 MHz
- Communication Frequency Band: 2.4GHz ISM (ZigBee or BLE)
- Range of Coupling: 0.1 to 0.5
Safety Considerations
Electromagnetic Radiation Effect

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<th>Frequency Range</th>
<th>E-field (V/m)</th>
<th>H-field (A/m)</th>
<th>B-field (µT)</th>
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<td>1-10 MHz</td>
<td>87/f^0.5</td>
<td>0.73/f</td>
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Theory of Operation

\[ \oint E \cdot dA = \frac{\Sigma Q}{\varepsilon_0} \]

\[ \oint B \cdot dA = 0 \]

\[ \oint E \cdot dl = -\frac{d}{dt} \oint B \cdot dA \]

\[ \oint B \cdot dl = \mu_0 I_{enc} + \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} \]

\[ \mu_0 = \text{Vacuum permeability} \]

\[ \varepsilon_0 = \text{Vacuum permittivity} \]
Loosely Coupled Coils
Self and Mutual Inductance

Physical representation of flux coupling

Electrical representation of flux coupling

\[ V_1(t) = R_1 i_1(t) + L_1 \frac{di_1(t)}{dt} + M \frac{di_2(t)}{dt} \]

\[ V_2(t) = R_2 i_2(t) + L_2 \frac{di_2(t)}{dt} + M \frac{di_1(t)}{dt} \]

\[ P = \frac{\phi}{N_i} = \mu A, \phi = PNi \]

\[ V_c = N \frac{d\phi}{dt} = N \frac{d(PNi)}{dt} = N^2 \frac{\mu A}{l} \frac{di}{dt} = L \frac{di}{dt} \]

\[ L = \frac{N\phi}{i}, \phi_1 = \phi_{11} + \phi_{21} \]

\[ V_2 = N_2 N_1 P_{21} \frac{di_1}{dt} \rightarrow M = N_2 N_1 P_{21} \]

\[ \phi = \rho N_i \]

\[ V_c = N \frac{d\phi}{dt} = N \frac{d(PNi)}{dt} = N^2 \frac{\mu A}{l} \frac{di}{dt} = L \frac{di}{dt} \]

\[ L = \frac{N\phi}{i}, \phi_1 = \phi_{11} + \phi_{21} \]
Power Transfer, Wired and Wireless

Wired/
Tightly
Coupled

\[ P_{out} = \frac{V^2}{RL} \]

Non-Ideal Transformer \( k \ll 1 \)

Load Reflected to Primary is Proportional to \( k^2 \)

Load Reflected to Primary

\[ RL' = N^2 \cdot RL = RL \cdot k^2 \cdot \frac{L_P}{L_S} \]

Ideal Transformer \( k = 1 \)

\[ \frac{V_P}{V_S} = \frac{I_S}{I_P} = \frac{N_P}{N_S} \]

\[ P_{out} = \frac{V_P^2}{RL} \cdot \left[ \frac{N_S}{N_P} \right]^2 \]

Cantilever Transformer Model

\[ L_{lk} = (1 - k^2) \cdot L_P \]

\[ L_m = k^2 \cdot L_P \]

\[ N = k \cdot \sqrt{\frac{L_P}{L_S}} \]

Leakage Impedance Cancelation

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Considering Resonance

**Series Resonant Tank**

\[ X_L = \omega L \quad \text{R} \omega \]

\[ X_C = \frac{1}{\omega C} \]

\[ I = \frac{V}{Z_{eqs}} \]

**Parallel Resonant Tank**

\[ X_L = \omega L \quad \text{R} \omega \]

\[ I = \frac{V}{Z_{eqp}} \]

\[ X_C = \frac{1}{\omega C} \]

\[ I = \frac{V}{Z_{eqp}} \]

\[ Z_{eqp} = \sqrt{R^2 + \left(\frac{V}{I}\right)^2} \]

\[ Q = \frac{f_r}{\Delta f_{3dB}} \]

\[ f_r = \frac{1}{2\pi \sqrt{LC}} \]

\[ \Delta f_{3dB} = \frac{f_r}{Q} \]
Coil Skin and Proximity Losses (Eddy Induced Losses)

\[ R_{p_{\text{ac}}} = \frac{\omega L_p}{Q_p} \]

\[ R_{s_{\text{ac}}} = \frac{\omega L_s}{Q_s} \]

\[ R' = k^2 \cdot \frac{L_p}{L_s} (R_s + RL) \]
Typical WPC TX/RX Coil Q and Skin/Proximity Effect

**TX:**
- 43 mm diameter with shield
- Litz wire, 105 strand
- 20 turns, 2 layers
- $Q = 100 \@ 130 \text{ kHz}$
- $R_{ac} = 176 \text{ m}\Omega$

**RX:**
- 40 x 30 mm with shield
- Litz wire, 2 strands
- 14 turns, 1 layer
- $Q = 2.3 \@ 130 \text{ kHz}$
- $R_{ac} = 515 \text{ m}\Omega \@ 130 \text{ kHz}$
Primary Current vs. Frequency and Coupling Coefficient

\[ Z_{IN}(f,k) = R_P + R(k) \cdot \frac{Q_p(f,k)^2}{1 + Q_p(f,k)^2} + j(X_{LS}(f,k) - X_{C_r}(f)) + R(k) \cdot \frac{Q_p(f,k)}{1 + Q_p(f,k)^2} \]

\[ ir(f,k) = \frac{V_{fundamental}}{Z_{IN}(f,k)} \]
Coupling Efficiency

Coupling Efficiency in Relationship to Coil Separation (z) and the Ratio of Coil Diameters

Magnetic Efficiency vs. Coil Vertical Displacement z/(D), Normalized

- Drx = Dtx
- Drx = 0.3 Dtx
- Drx = 0.1 Dtx
- Drx = 0.03 Dtx
- Drx = 0.01 Dtx

Q=100
Magnetic Figure of Merit
\( F(k,Q) \)

30 mm Planar Coils

- \( Q = \text{geometric mean of coil quality factors} = \sqrt{Q_p \times Q_s} \)
- \( Q \) influenced strongly by skin and proximity effect
- High \( Q \) compensates for poor coupling
- High \( Q \) requires greater control bandwidth

\[
\lambda(k,Q) = \frac{2}{(k \times Q)^2} \times \left[ 1 + \sqrt{1 + (k \times Q)^2} \right]
\]
Coupling Coefficient and Mutual Inductance from Transfer Gain

\[ k = \sqrt{L_{rx} \cdot \frac{V_{tx}}{L_{tx}}} \cdot \frac{V_{rx}}{V_{tx}} \quad \text{Gain} \quad L_{rx} = 10.8 \ \mu H \]

\[ M = k \cdot \sqrt{L_{rx} \cdot L_{tx}} \]

\[ k \text{(gap = 0 mm)} = \frac{0.516}{\sqrt{L_{rx}}} = 0.83, \quad M = 13.6 \ \mu \]

\[ k \text{(gap = 8 mm)} = \frac{0.208}{\sqrt{L_{rx}}} = 0.321, \quad M = 5.27 \ \mu \]
Intelligent WPT
Digital Power, Resonant Battery Charger

- A transmitter (TX) driving a resonant coupled inductor
- A receiver (RX) with rectification, load modulation and post regulation
- A load, commonly a single cell, secondary battery pack
Resonant Circuit Analysis

- VG1 is a variable frequency AC signal in frequency domain
- VG1 is a 50% duty cycle, 19 V square wave in the time domain
- Power regulated by changing the frequency or voltage

\[
20 \times \log\left(\frac{V_{\text{OUT}}}{V_{\text{IN}}}\right) = 20 \times \log\left(\frac{7.65}{19}\right) \text{dB} = -7.902 \text{ dB}
\]

- **VG1**: variable frequency AC signal
- **VG1**: 50% duty cycle, 19 V square wave
- **Power** regulated by changing the frequency or voltage

**Diagram:**
- Resonant circuit components
- Frequency vs. Gain plot
- Waveforms for different conditions

**Table:**
- Frequency (Hz)
  - 70.00 k
  - 167.33 k
  - 400.00 k
- Gain (dB)
  - -24.23
  - -2.48
  - 19.26

**Waveforms:**
- VOUT
- VAC
- VG1
- Vcoil_TX
Examining Circuit Behavior in SPICE

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2-D FEA Plot of Magnetic Flux Between TX/RX Coils

- Receiver side shielding is important
- Poorly designed shields expose battery and external circuits to magnetic field
- AC/DC winding losses of TX/RX coils correspond with empirical results = 0.32 W

![2-D FEA Plot of Magnetic Flux Between TX/RX Coils](image)
Quantifying Losses – Typical 5 W Wireless Power Transmitter/Receiver

\[ \eta = \frac{P_{\text{OUT}}}{P_{\text{OUT}} + P_{\text{RX}} + P_{\text{TX}}} \]

\[ P_{\text{TX}} = P_{\text{TXcoil}} + P_{\text{Bridge}} + P_{\text{control}} + P_{\text{DC–DC}} \]

\[ P_{\text{RX}} = P_{\text{RXcoil}} + P_{\text{rectifier}} + P_{\text{Ido}} + P_{\text{comm}} \]
Design Considerations, WPC

- Feedback communication
- Loop response
- Foreign object detection
- Electromagnetic compatibility
- System efficiency
WPC 1.1 Compliant
5 W TX Reference Design
Qi Power Transfer Communication Protocol

- **TX generates a shared magnetic field**
  - TX coil creates magnetic field
  - Magnetic field induces current in RX coil

- **Communication in power field**
  - TX waits until its field perturbed by RX
  - TX sends seek energy “ping”
  - TX waits for a digital response
  - If digital response is valid, transfer power

- **Power transferred at level needed**
  - RX reports power received/needed
  - TX adjusts power based on RX feedback
  - If feedback is lost, power transfer stops

From WPC Qi System Description. Part 1
WPC RX Load Modulation

Integrated Transmitter IC

Integrated Receiver IC

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Measurement

• Power transfer waveforms
  – Coil resonance
  – Harmonic content

• Load response

• Efficiency –
  – Loss contributors
  – PCB coil vs. Litz

• RX/TX communication

• EMI, FOD

• Spatial freedom

VNA – Bode 100 – Coil gain/impedance characteristics

MDO4104 – Mixed domain oscilloscope

Differential voltage probe capable of > 40 V, current probe, IR probe
Reference Design Waveforms at 5 W
Time and Spectrum Domain

Centered coils force operation further from resonance
V_{pp\_tx} = 20 V, f_{SW} = 170 kHz
RMS gain = 0.56

Misaligned coils force operation closer to resonance
V_{pp\_tx} = 40 V, f_{SW} = 135 kHz
RMS gain = 0.509
Intelligent Voltage Positioning

Dynamic Voltage Positioning

Load current step = 250 mA-0 A

Maximum data rate package during transition

240 ms
Transient Load Response

\( I_{\text{OUT}} = 0 \text{ to } 1 \text{ A} \)

- 5 V TX Supply Current
- 12 V TX Supply Current

Voltage Response

WPC Wireless Power RX Phone “Skin”
Transient Load Step Response
Litz TX Coil / PCB RX Coil

0 to 250 mA load step at ~ 1 A/µs

45 mm TX coil with shield
bq51013B based RX design
2.65 in x 1.35 in x 0.02 in
System Efficiency – DC Input to DC Output
PCB Coil vs. 105 Strand Litz Coil
Designing for Spatial Freedom
Efficiency Across Charging Area

- Efficiency map at a 5 W load measured over the PCB coil area
- +/- 40 mm in x-direction and 30 mm in y-direction, 5 mm steps
Design for Electromagnetic Compatibility

- GND Plane Under TX Coil
- TX Conductive Enclosure
- Wireless Transmitter
- Wireless Receiver
- Common Mode Filter
- Multilayer Electric Shield

Non-Optimized Performance

Optimized for EMC

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Foreign Object Detection

- Metal objects between TX and RX can induce eddy current losses
- Field density of 5 W wireless chargers can result in significant eddy losses
- Depending on specific heat capacity, foreign object temp rise can be > 60°C
- Battery pack is especially sensitive

\[ \Delta T = \frac{P \times t}{C \times m} \]

Where:
- \( P \) = Power dissipated in FO
- \( C \) = FO specific heat capacity
- \( M \) = FO mass
- \( t \) = time
Dynamic RX / TX Loss Accounting

Transmit & Receive Power (mW)

Loss vs. Threshold (mW)

45 mm FO placed adjacent to misaligned TX coil

FO placed next to TX coil, losses increase by > 1 W

Loss threshold set high

FOD reaches 55°C in under 60 s

FO removed
A Vision for Wireless Power Transfer

Wired Model

Limited Resource

AC

85% Efficient

Customized/Product Specific
AC to 5 VDC USB Adapter

Customized Charging Cable

Phone/Portable
Electronic Device

Charger IC

Wireless Power Vision

85% Efficient + Plus Low Power Shutdown Modes

Multi-Mode Universal
WPT Transmitter
Charges All Compliant Devices

Intelligent Wireless Power Transfer

Phone/Portable
Electronic Device

Charger IC

WTP Receiver

~80% Full Load

PDA

Charger IC

WTP Receiver

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Summary

• Market studies project rapid growth in wireless power technology

• Wireless power transfer is useful when a wired solution is inconvenient, hazardous or impossible

• WPT standards have emerged to accelerate growth, reliability, acceptance and safety in consumer electronics

• Developing a wireless power solution does not require compliance to any standard other than those affecting consumer safety and EMC

• Standard compliance may provide advantages in marketability (interoperability), performance, reliability and time to market

• Achieving spatial freedom and good efficiency requires a deep understanding of magnetic field theory
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