Wireless Charging of Electric Vehicles

Khurram Afridi

University of Colorado Boulder

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The Future of Road Transportation

- Vehicle Electrification
- Autonomous Driving
- Wireless power transfer (WPT) can enable this future:
  - Increase penetration of electric vehicles
  - Make electric vehicles fully autonomous
- Ridesharing
Road Transportation’s Impact on Environment

- Road transportation accounts for:
  - 23% of energy consumption
  - 59% of petroleum consumption
  - 22% of greenhouse gas emissions

- Electric Vehicles (EV) in conjunction with renewable sources can substantially reduce greenhouse gas emissions
Electric Vehicle Strengths and Weaknesses

Efficiency

Internal Combustion Engine

- 38% Efficiency

Electric Motor

- 95% Efficiency

Energy Density

- Gasoline & Diesel: 0.5 MJ/kg
- Batteries: 46 MJ/kg


Source: Institute for Energy Resourcefulness
Penetration of Electric Vehicles

- Penetration of EVs remains low due to limitations in battery technology:
  - Limited range due to limited energy density
  - Long charging times
  - High cost

U.S. vehicle sales in 2016
Total: 17.55 million
EV: 0.13 million

WPT can change this situation by drastically reducing the need for batteries in EVs
Wireless Power Transfer History

Nikola Tesla (1891)

John Boys & Andrew Green (1994)

M. Hutin & M. Leblanc (1894)

UC Berkeley PATH - RPEV (1994)
Wireless Power Transfer via Strongly Coupled Magnetic Resonances

André Kurs,³ Aristeidis Karalis,² Robert Moffatt,¹ J. D. Joannopoulos,¹ Peter Fisher,³ Marin Soljačić¹

Marin Soljačić (2007)
Wireless Power Transfer Concepts for EV

Stationary wireless charging

Dynamic wireless charging

Source: Qualcomm
Inductive WPT Basic Concept

- Loosely coupled transformer with reactive compensation
- Utilizes resonance to enhance power transfer
State of the Art of Inductive WPT for EV Charging

Stationary

Dynamic

Source: ORNL

Source: ORNL

Source: WiTricity

Source: Qualcomm
Limitations of Inductive WPT

- Inductive systems require ferrite cores for magnetic flux guidance and shielding
  - Expensive
  - Fragile and difficult to embed in roadway

- Inductive systems operate at relatively low frequencies to limit ferrite losses
  - Large and heavy

Source: ORNL

Source: KAIST
Alternative Approach: Capacitive WPT

Capacitive WPT systems do not have ferrites and can be:
- Less expensive
- More efficient
- Smaller
- Lighter
- Easier to embed in roadway
Conventional Wisdom Regarding Capacitive WPT

- Capacitive WPT usable for low-power small-gap applications
- Capacitive charging of EVs through tires has been tried
  - Low efficiency due to carbon black filler
  - Inadequate power transfer due to limited area

Source: Toyohashi University of Technology
Our Early Experiments with Capacitive WPT

![Image showing experiment setup with 0.5 cm separation between primary and secondary coils.]

![Image of a vehicle with capacitive WPT components on a wooden platform.]

![Graph showing efficiency (%) vs. output power (W).]

- Efficiency [%] vs. Output Power [W]:
  - Efficiency drops from 90% to 70% as output power increases from 20 W to 120 W.
Challenges in Capacitive WPT for EVs

- Small coupling capacitance due to large gap between road and vehicle
- Need high frequency operation to achieve high power transfer levels
- Need high voltage/current gain to limit fringing fields and meet safety limits
- Need large reactive compensation
Matching networks can provide voltage/current gain and reactive compensation
- Size of compensation inductors is substantially reduced by the impedance transformation
- What is optimal distribution of gains and compensation, and number of stages?
Optimal Distribution of Gain and Reactive Compensation

Inverter

\[ V_{IN} \]

Current Gain and Compensation Network

\[ 1 \rightarrow \ldots \rightarrow n - 1 \rightarrow n \]

CS

Rectifier

\[ V_{BAT} \]

Voltage Gain and Compensation Network

\[ 1 \rightarrow \ldots \rightarrow m \]

Road Side

Vehicle Side

Current Gain [\Omega]

1/(Current Gain)

Compensation [\Omega]

Stage Number
Overwhelming Parasitic Capacitances

Vehicle Chassis

Road

\[ C_{rv} = C_{pvf} + C_{pn} \]

\[ C_{rv} = C_{pvf} - C_{pn} \]

\[ C_{rv} = C_{pvf} + C_{pn} \]
Absorbing the Parasitic Capacitances

\[
\begin{align*}
L_0 & \quad L_1 \\
C_0 & \quad C_1 \\
C_# & \quad C_# \\
C_# & \quad C_# \\
V_3 & \quad V_4 & \quad V_5 \\
C_# & \quad C_# & \quad C_# \\
C_# & \quad C_# \\
C_8 & \quad C^*_9 \\
L_0 & \quad L_1 \\
C_0 & \quad C_1 \\
C_# & \quad C_# \\
C_# & \quad C_# \\
V_3 & \quad V_4 & \quad V_5 \\
C_# & \quad C_# & \quad C_# \\
C_# & \quad C_# \\
C_8 & \quad C^*_9 \\
\end{align*}
\]
Capacitive WPT Systems

**Output Power: 1216 W**
- Power Transfer Density: 51.6 kW/m²
- Efficiency: 74.7%
- Coupler Power to Weight Ratio: 11.1 kW/kg

**Output Power: 589 W**
- Power Transfer Density: 19.6 kW/m²
- Efficiency: 88.2%
- Coupler Power to Weight Ratio: 4.3 kW/kg

Air gap: 12 cm
Operating frequency: 6.78 MHz
Modular Phased-Array Capacitive WPT System

Diagram showing the system's components:
- Rectifier and Matching Network
- Inverter and Matching Network
- Vehicle Battery
- Power Source (grid)
- ac-dc Converter

Graph showing the electric field intensity (E in V/m) with color scaling from 0 to 300.
Two-Module Capacitive WPT System

Output Power: 1108 W
Power Transfer Density: 19 kW/m²
Efficiency: 90%
Coupler Power to Weight Ratio: 4.1 kW/kg

Air gap: 12 cm
Operating frequency: 6.78 MHz

Vehicle Chassis
Ground

Coupling Plates (12.25 cm x 12.25 cm)
Variable Compensation

Charging Pad

Charging Pad

Charging Pad

V_{IN} 

Matching Network

Inverter

Matching Network

Rectifier

Road Side

Vehicle Side

Vehicle Battery

V_{BAT}
Active Variable Reactance Rectifier

$P_0 = P_1 + P_2$

Normalized $V_1$

Normalized Power

Normalized Compensation

High Frequency Inverter

Gain and Compensation Network

Gain and Compensation Network

Active Variable Reactance (AVR) Rectifier

$R_f + jX_f$

$-jX$

$+jX$

$V_1$

$V_2$

$V_{OUT}$

$V_{IN}$

$R_f$

$X_f$

$dc - dc$

$dc - dc$

Gain and Compensation Network

$V_1$

$V_2$

$V_{OUT}$

$V_{IN}$

$R_f + jX_f$

$-jX$

$+jX$

$dc - dc$

$dc - dc$

Gain and Compensation Network

$V_1$

$V_2$

$V_{OUT}$

$V_{IN}$

$R_f + jX_f$

$-jX$

$+jX$

$dc - dc$

$dc - dc$

Gain and Compensation Network

$V_1$

$V_2$

$V_{OUT}$

$V_{IN}$

$R_f + jX_f$

$-jX$

$+jX$

$dc - dc$

$dc - dc$

Gain and Compensation Network

$V_1$

$V_2$

$V_{OUT}$

$V_{IN}$

$R_f + jX_f$

$-jX$

$+jX$

$dc - dc$

$dc - dc$

Gain and Compensation Network

$V_1$

$V_2$

$V_{OUT}$

$V_{IN}$

$R_f + jX_f$

$-jX$

$+jX$

$dc - dc$

$dc - dc$

Gain and Compensation Network

$V_1$

$V_2$

$V_{OUT}$

$V_{IN}$

$R_f + jX_f$

$-jX$

$+jX$

$dc - dc$

$dc - dc$

Gain and Compensation Network

$V_1$

$V_2$

$V_{OUT}$

$V_{IN}$

$R_f + jX_f$

$-jX$

$+jX$

$dc - dc$

$dc - dc$

Gain and Compensation Network

$V_1$

$V_2$

$V_{OUT}$

$V_{IN}$

$R_f + jX_f$

$-jX$

$+jX$

$dc - dc$

$dc - dc$

Gain and Compensation Network

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$V_2$

$V_{OUT}$

$V_{IN}$

$R_f + jX_f$

$-jX$

$+jX$

$dc - dc$

$dc - dc$

Gain and Compensation Network

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$V_{OUT}$

$V_{IN}$

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Gain and Compensation Network

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$+jX$

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$V_{OUT}$

$V_{IN}$

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$+jX$

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$dc - dc$

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$V_{OUT}$

$V_{IN}$

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$+jX$

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$dc - dc$

$dc - dc$

Gain and Compensation Network

$V_1$

$V_2$

$V_{OUT}$

$V_{IN}$

$R_f + jX_f$

$-jX$

$+jX$

$dc - dc$

$dc - dc$

Gain and Compensation Network

$V_1$

$V_2$
Embedding WPT System into the Roadway
Back to the Future

- Vehicle Electrification
- Autonomous Driving
- Ridesharing
Questions?

and yes, your dog can drive you to work in the future