Electromagnetic Compatibility for Wireless Power Transfer

November 20th, 2020

Seungyoung Ahn

EMC Laboratory
CCS Graduate School of Green Transportation
KAIST
# Introduction to EMC Lab in KAIST

<table>
<thead>
<tr>
<th>Professor</th>
<th>Education</th>
<th>Experiences</th>
<th>Academic Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1998 B.S. EE, KAIST</td>
<td>2001-2002 Visiting Researcher, SIMTech, Singapore</td>
<td>Chapter Chair IEEE EMC Korea Chapter</td>
</tr>
<tr>
<td></td>
<td>2000 M.S. EE, KAIST</td>
<td>2005-2009 Senior Researcher, Samsung Electronics</td>
<td>Distinguished Lecturer IEEE EMC Society</td>
</tr>
<tr>
<td></td>
<td>2005 Ph.D. EE, KAIST</td>
<td>2009-2011 Research Professor, KAIST</td>
<td>Assoc. Editor IEEE T-CPMT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2011-2015 Assistant Professor, KAIST</td>
<td>Assoc. Editor IET Electronics Letters</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2016- Associate Professor, KAIST</td>
<td>Topic Editor MDPI Energies</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Researcher</th>
<th>Ph. D. Course</th>
<th>Master Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mr. Yangbae Chun</td>
<td>Jedok Kim (Railway WPT)</td>
<td>Seongho Woo (WPT Protection)</td>
</tr>
<tr>
<td>Dr. Junsung Choi</td>
<td>Jongwook Kim (Underwater WPT)</td>
<td>Dong-Ryul Park (AI EMC)</td>
</tr>
<tr>
<td>Dr. Jaehyoung Park</td>
<td>Bumjin Park (Mag. Energy Harvesting)</td>
<td>Dawon Jung (WPT EMI)</td>
</tr>
<tr>
<td>Ms. Youngjoo Kim</td>
<td>Jangyong Ahn (EMF on Human)</td>
<td>Nguyen Minh Nghiem (Vehicular WPT)</td>
</tr>
<tr>
<td></td>
<td>Kyunghwan Song (EMI Shielding)</td>
<td>Seonghoo Ryu (Magnetic Sensor)</td>
</tr>
<tr>
<td></td>
<td>Seongho Woo (WPT Protection)</td>
<td>Semin Choi (WPT EMC)</td>
</tr>
<tr>
<td></td>
<td>Sunghee Lee (Package Modeling)</td>
<td></td>
</tr>
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Contents

- Introduction
- Wireless Power Transfer (WPT) Technologies
- EMC Issues and Solutions for WPT Applications
- Future EMC Design
- Conclusion
Wireless Power Transfer Technology

➢ Nikola Tesla (New York American, May 22, 1904)
  ▪ Tesla's Tower - Amazing scheme of the great inventor to draw millions of volts of electricity through the air from Niagara Falls and then feed it out to cities, factories and private houses from the tops of the towers without wires.

http://www.teslasociety.com/tesla_tower.htm
Wireless Power Transfer Applications

- **IoT / Sensor**: µW ~ mW
- **Biomedical Implants**: mW ~ W
- **Mobile / Home**: W
- **E-Vehicle / Robot**: kW ~ MW
- **Space / Underwater**: kW ~ GW

Size & Distance & Power:
- mm
- mm ~ cm
- cm
- m
- km
### Categories of Wireless Power Transfer Technology

<table>
<thead>
<tr>
<th></th>
<th>Magnetic Resonant WPT (Inductive Power Transfer)</th>
<th>Electric Resonant WPT (Capacitive Power Transfer)</th>
<th>Microwave Power Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td>kHz ~ MHz</td>
<td>kHz ~ MHz</td>
<td>GHz</td>
</tr>
<tr>
<td><strong>Distance</strong></td>
<td>cm ~ m</td>
<td>cm ~ m</td>
<td>m ~ km</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>mW ~ MW</td>
<td>mW ~ MW</td>
<td>W ~ GW</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>30 % ~ 90 %</td>
<td>30 % ~ 90 %</td>
<td>1 % ~ 50 %</td>
</tr>
<tr>
<td><strong>Applications</strong></td>
<td>Mobile, EV, Biomedical</td>
<td>Mobile, EV, Drone</td>
<td>Mobile, Sensor, Solar Power Satellite</td>
</tr>
</tbody>
</table>

- Resonance is generally used to enhance the distance and efficiency.
Magnetic and Electric Resonant WPT Systems

Magnetic Resonance WPT (Inductive Power Transfer)

\[ v_2 = j\omega M_i_1 \]

Electric Resonance WPT (Capacitive Power Transfer)

\[ v_2 = \frac{i_1}{j\omega C_M} \]
Microwave Power Transmission

220V (110V)/60Hz
AC from the wall

Power Tracking
AC/DC Converter

Power control (RF PA)

Wireless Communication
(Beacon)

Phase Shifter

ANT

ANT

ANT

FPGA
(Digital Beam Forming)

Baseband
Precooder

Rx RF Chain

FPGA
Logic

Tx RF Chain

< Transmitter >

2.4 GHz, 5.8 GHz

Antenna

Diode

Filter

Load

< Receiver >

Phased Array Antenna

Diode/Rectifier (main beam)
Wave Impedance of WPT Coils

\[
\frac{E}{H} = Z_w \text{ (Wave Impedance)}
\]

- Electric field predominant - \( E \propto 1/r^3, H \propto 1/r^2 \)
- Magnetic field predominant - \( H \propto 1/r^3, E \propto 1/r^2 \)
- Plane wave - \( E \propto 1/r, H \propto 1/r \)
- Asymptote - \( Z_0 = 377 \Omega \)

Distance from source normalized to \( \lambda/2\pi \)

\( (= \text{distance} \times \frac{2\pi f}{C_0}) \)
Solving battery and charging problems by developing OLEV, which enables wireless electric power transmission while vehicle is stopped or running.
Wireless Charging EVs in Korea

Seoul Grand Park (Jul. 2011)

Yeosu Expo (May-Aug. 2012)

Shuttle Bus at KAIST (Oct. 2012)

Gumi City (Mar. 2014)

Sejong City (Jun. 2015)
Autonomous Driving and WPT for EV
Autonomous Driving Infrastructure using WPT

- Autonomous Vehicle Alignment System
  - Automatic steering control based on magnetic field

Limitations of Current Railway System

- Catenary & Pantograph Railway System
  - High construction cost
  - High maintenance cost
  - Low reliability & security
  - Environmentally unfriendly
  - Friction issue for high speed
  - Electrical shock

- Third Rail Railway System

Solution

Elimination of contact-based parts
Inductive Wireless Power Transfer application
Benefits of Railway WPT System

- Elimination of Power line and Pantograph
  - Aesthetic feature of city
  - Friction-less power transmission
  - Less requirement of Tunnel cross section

- No conductive contact is required.
- Safe for electrical shock and cost effective railway system operation
Importance of Vehicle Location Detection

- Precise estimation of vehicle’s location can prevent accidents.
- Precise vehicle location can reduce headway between vehicles and increase road capacity
Autonomous Driving Infrastructure

- Accurate global/local positioning of WPT vehicles
  - Code map of vehicle position using magnetic field


Wireless Charging System for Drone

Test Service of Parcel Delivery in Korea (2017)

Wireless Charging Station

Receiving Coil

Transmitting Coil

Ferrite ($\mu_r > 1000$)

Resonant Magnetic Field
Wireless Charging using Capacitive Power Transfer

Conventional Coupler

Center-aligned Circular coupler

Sensitive to rotational misalignment

Robust to rotational misalignment.

Low Weight Capacitive Power Transfer for Drone

<table>
<thead>
<tr>
<th></th>
<th>Transfer Distance</th>
<th>Coil to coil Efficiency</th>
<th>Output power</th>
<th>Tx weight</th>
<th>Rx weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPT system</td>
<td>25 mm</td>
<td>93 %</td>
<td>100 W</td>
<td>1443 g</td>
<td>911 g</td>
</tr>
<tr>
<td>IPT system [1]</td>
<td>&lt; 3 mm</td>
<td>91 %</td>
<td>150 W</td>
<td>908 g</td>
<td>504 g</td>
</tr>
<tr>
<td>Proposed CPT system</td>
<td>25 mm</td>
<td>89 %</td>
<td>100 W</td>
<td>306 g</td>
<td>228 g</td>
</tr>
</tbody>
</table>

EMC Issues and Solutions in WPT System
Magnetic Field in Resonance

- Result: $S_{11} = -10\text{dB}$, $S_{21} = -4\text{dB}$

Source: Dr. Youngjin Park (KERI)
## Electric Vehicle Wired Charger

<table>
<thead>
<tr>
<th>Classification in use here</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 3</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level 1</td>
<td>Level 2</td>
<td>Level 2</td>
<td>Level 3</td>
<td>Level 3</td>
<td>Level 3</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>AC</td>
<td>AC</td>
<td>AC, triphase</td>
<td>DC</td>
<td>DC</td>
</tr>
<tr>
<td></td>
<td>≤ 3.7 kW</td>
<td>&gt; 3.7 kW and ≤ 22 kW</td>
<td>≤ 22 kW</td>
<td>&gt; 22 kW and ≤ 43.5 kW</td>
<td>Currently &lt; 200 kW</td>
<td>Currently &lt; 150 kW</td>
</tr>
<tr>
<td>China</td>
<td>Devices installed in private households, the primary purpose of which is not recharging electric vehicles</td>
<td>GB/T 20234 AC</td>
<td>IEC 62196 Type 2</td>
<td>IEC 62196 Type 2</td>
<td>GB/T 20234 DC</td>
<td>Tesla and CHAdeMO connectors</td>
</tr>
<tr>
<td>Europe</td>
<td>SAE J1772 Type 1</td>
<td>SAE J1772 Type 1</td>
<td>SAE J1772 Type 1</td>
<td>SAE J3068 (under development)</td>
<td>CCS Combo 2 Connector (IEC 62196 Type 2 &amp; DC)</td>
<td>CHAdeMO</td>
</tr>
<tr>
<td>Japan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CCS Combo 1 Connector (SAE J1772 Type 1 &amp; DC)</td>
</tr>
<tr>
<td>North America</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: IEA Global EV Outlook 2017
Battery Capacity and Wireless Charging Power

- The wireless charging power should be increased.
  - $3.3 \text{ kW} \rightarrow 7.7 \text{ kW} \rightarrow 20 \text{ kW} \rightarrow ?$

- Hyundai Ionic
  - (28 kWh)

- Nissan Leaf
  - (40 kWh)

- Tesla
  - Model S (100 kWh)
  - Model 3 (78 kWh)
Power System Structure for Railway WPT

- Urban Railway: 1 MW
- High-Speed Train: 10 MW

<Schematic Diagram of Railway WPT Power System>
Electrical & Electromagnetic Safety

**Electrical Safety**

- Electrical safety regulation
- Parts and observation point
- Measurement method
- On establishing

**EM Safety**

**EMF Human Exposure**

- 9kHz – 30MHz
- 30MHz – 300MHz
- 300MHz – 1GHz
Electromagnetic Problems in WPT System

- EMC Issues due to Wireless Transfer of High Power

- Effect on Human Body
- Fundamental Frequency
- Near Field
- Shielding, etc.

- Effect on Electronic System
- Harmonic Frequency
- Near and Far Fields
- Filtering, etc.
Electromagnetic Field (EMF) Regulations

[Table] Reference levels for general public exposure to time-varying magnetic fields

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>B-field (µT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>up to 1 Hz</td>
<td>$4 \times 10^4$</td>
</tr>
<tr>
<td>1–8 Hz</td>
<td>$4 \times 10^4/f^2$</td>
</tr>
<tr>
<td>8–25 Hz</td>
<td>5,000/f</td>
</tr>
<tr>
<td>0.025–0.8 kHz</td>
<td>5/f</td>
</tr>
<tr>
<td>0.8–3 kHz</td>
<td>6.25</td>
</tr>
<tr>
<td>3–150 kHz</td>
<td>6.25</td>
</tr>
<tr>
<td>0.15–1 MHz</td>
<td>0.92/f</td>
</tr>
<tr>
<td>1–10 MHz</td>
<td>0.92/f</td>
</tr>
<tr>
<td>10–400 MHz</td>
<td>0.092</td>
</tr>
<tr>
<td>400–2,000 MHz</td>
<td>0.0046$f^{1/2}$</td>
</tr>
<tr>
<td>2–300 GHz</td>
<td>0.20</td>
</tr>
</tbody>
</table>

- EMF limits on whole-body exposure levels of 6.25 µT for the general population.
- Earth magnetic field ~ 50 µT

“Guidelines for Limiting Exposure to Time-varying Electric, Magnetic, and Electromagnetic Fields (Up to 300 GHz),” ICNIRP Guidelines, 1998
Electromagnetic Field Reduction for WPT EV

- Electromagnetic field from WPT EV is inevitable for high power charging.

Source: Infiniti LE concept introduced by NISSAN motor company
Shielding Methods for Leakage Magnetic Fields

- **Passive Shielding (Conductor)**
  - Conductive Material
  - Magnetic Field

- **Passive Shielding (Magnetic Material)**
  - Magnetic Material
  - Magnetic Field

- **Active Shielding**
  - Active Shield
  - Magnetic Field
  - Additional Source
  - Loss
  - Synchronization

- **Reactive Shielding**
  - Magnetic Field
  - Reactive Shield
Leakage Magnetic Field from WPT System in EV

- Incident Magnetic Field
- Transmitting Coil
- Receiving Coil
- Resonant Reactive Shield
- Induced Cancelling Magnetic Field
- Target Area
Low EMF Design – Reactive Shielding

- EMF cancellation using reactive shield
  - Impedance of the shield coil determines the cancelling magnetic field

\[ I_{sh} = \frac{V_{ind}}{Z_{sh}} \]

Low EMF Design – Reactive Shielding

- Additional 90° phase shift using impedance control
  ➔ 180° difference between WPT coil current and shield coil current

\[ V_{ind} = -j\omega MI_s \]

Additional +90 degree due to induction

\[ I_{sh} = \frac{V_{ind}}{Z_{sh}} \]

Inductive shield impedance

\[ I_{sh} = \frac{V_{ind}}{Z_{sh}} = \left( j\omega L_{sh} + \frac{1}{j\omega C_{sh}} \right) + R_{sh} \]

\[ Z_{sh} \approx j\omega L_{eq} \]
Simulated EMF cancellation

Advantages of Reactive Shield
- Automatic Magnitude Control
- Automatic Phase Control
- Minimal Power Loss
- Compact Size
Planar Reactive Shield

## Planar Reactive Shield

<table>
<thead>
<tr>
<th></th>
<th>Leakage Field</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/O Shield</td>
<td>Reference</td>
<td>96.2 %</td>
</tr>
<tr>
<td>Active Shield</td>
<td>- 47 %</td>
<td>75.1 % (- 21.1%)</td>
</tr>
<tr>
<td>Non-resonant Shield</td>
<td>- 3 %</td>
<td>95.0 % (- 1.2 %)</td>
</tr>
<tr>
<td>Reactive Shield</td>
<td>-53 %</td>
<td>90.2 % (- 6.0 %)</td>
</tr>
</tbody>
</table>

### Graph:

- **Without shield**
- **Active shield**
- **Non-resonant shield**
- **Prop. Resonant reactive shield**

#### Without Shield

- **Leakage Field**: Reference
- **Efficiency**: 96.2 %

#### With Reactive Shield

- **Leakage Field**: Reference
- **Efficiency**: 90.2 % (- 6.0 %)
Interference due to Harmonic EMI from WPT System

- Harmonic electromagnetic field generated from WPT systems can affect other electronic application.
- In order to reduce the influence on other peripheral electronic devices, standards and electromagnetic interference regulations are established.
Trends of EMI Regulations in WPT System

- Regulations and measurement methods are being carried out to suit the characteristics of the products.
- The operating frequency has high regulation level but the harmonic frequency has low regulation level.

**Harmonic frequencies EMI reduction method are needed!**

Ref) EN 303 417
Ref) CISPR 11 B/710/CD
Planar Multi-Frequency Reactive Shield

Planar Multi-Frequency Reactive Shield

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Without shield</th>
<th>With reactive shield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>79.32</td>
<td>75.96</td>
</tr>
<tr>
<td>3rd</td>
<td>59.43</td>
<td>48.59</td>
</tr>
<tr>
<td>5th</td>
<td>68.78</td>
<td>68.44</td>
</tr>
</tbody>
</table>

- **Efficiency (%):**
  - **Simulation:** Without shield: 98.3, With reactive shield: 93.6 (4.7↓)
  - **Measurement:** Without shield: 96.2, With reactive shield: 90.2 (6.0↓)

- **SE (dB):**
  - Without shield: 19.89 dB reduction, 27.37 dB reduction
Implementation of Drone on Vehicle

- 150 W-Class Three-phase WPT Charger for Drone

Drone charger system is located on the commercial vehicle with 12V lead acid battery.

Three-phase resonant magnetic field charger with high coupling coefficient can reduce leakage EMFs with closed structure.

Switching Time Control for 3-Phase Inverter

- THD$_v$ of 3-phase inverter is smaller than the single-phase.
- Elimination of 3$^{rd}$ harmonic components is possible.

\[ V_{an} = \frac{2V_{DC}}{\pi} \left[ \sin(\omega t) - \frac{1}{5} \sin 5\omega t - \frac{1}{7} \sin 7\omega t + \ldots \right] \]

Future WPT and EMC Design
Market Trend of Biomedical Devices

With increase of telehealth device for higher service quality and low service cost, **implantable and telehealth devices will increase 10 times by 2025.**

Source: IHS Technology, Jan. 2014.
WPT for Implantable Medical Devices

Wireless Health Monitoring

RF

Magnetic Resonant

Cochlear Implants

Deep Brain Neurostimulators

Implantable Nervous System Interface using WPT

Attachable Monitoring Sensor

RF

Cardiac Defibrillators Pacemakers

Gastric Stimulators

Chulhun Seo, “Intelligent Biomedical Wireless Power Transfer Research Center”, Korea WPT Workshop, Oct. 2018
Key Technologies in Biomedical WPT Systems

**Biomedical WPT Technology**
- Implantable *Ultra-Small* Coil Structure
- High-efficiency WPT using Metamaterial
- Non-interference Wireless Power Transfer

**Material and Device for Biomedical WPT**
- *Bio-Friendly* WPT Material
- CNT Material for Implantable Devices
- High Efficiency Flexible Antenna

**Bio Interface based on WPT**
- Wire-Free Patient Monitoring Service
- Nervous System Treatment using WPT Implants
- Wireless Charging Cardiac Sensor

Chulhun Seo, “Intelligent Biomedical Wireless Power Transfer Research Center”, Korea WPT Workshop, Oct. 2018
Artificial Intelligence and Deep Learning

- AI is a model inspired by a biological neural network
- Values of AI
  - Save time, labor, resources, capital, energy
  - Provide time for human for creative activities
  - Improve life quality
  - Save earth
  - Freedom from labor and nature

Technology Innovation for Artificial Intelligence

Improved Computer Performance

Artificial Intelligence

Deep Learning Algorithm

Future EMC Design

Conventional EMC Design

- Complexity in EMC design
  - Long time and huge effort are required.
- AI-based EMC design S/W is needed.

- High-quality big data will enhance the AI EMC.

Al-based EMC Design

- High quality data and optimal AI model
  - High Quality EMC Big Data
  - New EM Core Technology
  - Computing Power
  - DL Algorithm


- Optimal AI design tool for EMC
Conclusion

- The WPT technology is changing the future electronic system.

- Electromagnetic problems can be critical in WPT technology.

- The solutions for WPT EMC problems should be developed.

- Future design methodologies using AI will enhance the development of WPT and EMC.