Introduction

- Welcome
- FREEDM Overview
- Zoom Functionality
Outline

• Introduction
• WPT Concept
• FAQ on WPT
• DWPT Research projects
  – Sensorless/Seamless Transition
  – Misalignment Estimation
• Current work at NC State
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Introduction

2015-2020:
Grad. Researcher/PhD Student
Utah State University
SELECT Research Center

Since Feb. 2020:
Post Doctoral Researcher
NC State University
FREEDM Systems Center

Photo taken at 2016 SELECT Showcase
Nikola Tesla published a paper on November 17, 1898

Ampere’s Law \[ \oint B \cdot dl = \mu_0 NI \]

Faraday’s Law \[ \oint E \cdot dl = -\frac{d\Phi}{dt} \]

"Tesla Apparatus and Experiments—How to Build Both Large and Small Tesla and Oudin Coils and How to Carry On Spectacular Experiments With Them," by H. Winfield Secor, Practical Electrics, November 1921
WPT Applications

Electric vehicles
- carbuzz.com

AGV
- alibaba.com

Personal Transportation
- www.thesuperboo.com

Bio implants
- www.alansonsample.com

Robotics
- docs.mistyrobotics.com

Cell Phone
- www.cellphonecover.com

Energy Harvesting
Inductive

Stationary

Capacitive

Dynamic

Hybrid = Inductive + Capacitive

Basic Structure

**RECEIVER (secondary)**
- Battery
- Power conditioner
- Compens. tank
- HF inverter
- Compens. tank
- Power conditioner
- Battery

**TRANSMITTER (Primary)**
- DC rectifier
- (optional) Buck Converter
- HF inverter
- Compens. tank
- HF inverter
- Compens. tank
- DC rectifier

Symbols and Equations:
- $I_{DC}$
- $V_{DC}$
- $I_{inv}$
- $V_{inv}$
- $I_t$
- $V_t$
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FAQ on WPT

50 kW is 50 kW


https://www.cnbc.com/2020/06/08/researchers-work-on-the-next-generation-of-wireless-charging-for-evs.html
FAQ on WPT

Good for Battery?
FAQ on WPT

Is it efficient?

Conductive charging

Inductive charging

Losses do not occur in the airgap

Is it Safe?

Pad is not energized unless there is a vehicle.

IEEE C95 standard:
Tissue heating starts at 300kHz
Standards recommend 85 kHz
FAQ on WPT

Impact on Grid?

Intermittent charging vs fast charging

FAQ on WPT

Compatibility?

Conductive or inductive; we need two parts, one on the ground and another one on the vehicle.

Nissan Leaf

Momentum Dynamics
FAQ on WPT

Compatibility?

Electromagnetic interference:

• ADAS or any power electronics
• conducted or radiated emissions
• FCC parts 18 and 15

https://www.motor1.com/photo/161006/electromagnetic-compatibility-emc-tests/
Economic Incentive?

Autonomous driving is the future
But it needs autonomous fueling
Automated parking + Automated charging

Market:
- Fleet
- Port facilities
- Trucks and busses, taxis
- Last mile delivery vehicles, then
- Passenger vehicles
- Northern Europe, electrification is happening

FAQ on WPT

Commercialized DWPT?

Higher Cost

Lower Efficiency

Misalignment/Autonomy

Need for Standards
• Introduction
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Research on DWPT:

i) coil/pad designs (Tx and Rx pads),
ii) compensation topologies and
iii) power converters and control methods
Transmitter (Tx) pad configuration for DWPT

- **Elongated Rails**
  - Stable power transfer
  - Simple controller
  - Low efficiency

- **Lumped Pads**
  - Pulsating power transfer
  - Complicated controller
  - High efficiency

- **Elongated Pads**
  - A compromise between above options
DWPT System

Tx pad Optimization

Shorter pads

Longer pads

Pareto Front

Lower Cost

Higher Efficiency

Coil with $N$ turns

Ferrite

Pad Length (m)

Pad Cost ($/m$)

Efficiency (%)
DWPT System

Gap between Tx pads
Sensorless Activation Deactivation

DC Link Current

Tx Coil Current

Mutual Inductance Rx & Tx

Movement Direction

I_{thr\_on}

I_{thr\_off}

I_{act}

x-axis

Tx

Rx
DWPT System

Seamless Transition

DC Link Current

Tx2 Coil Current

Tx1 Coil Current

Mutual Inductance Rx & Tx

Transition Zone

Movement Direction

$I_{dc1}$ $I_{dc2}$

$M_1$ $M_2$
Comprehensive Controlling Scheme

**Total DC Link Current**

- DC Link Current
- $I_{dc1}$
- $I_{dc2}$
- $I_{dc3}$
- $I_{dc}$

**DC Link Current**

- $I_{dc1}$
- $I_{dc2}$
- $I_{dc3}$

**CAN Bus**

- $\mu C_1$
- $\mu C_2$
- $\mu C_3$

**DWPT System**
DWPT System

Rx Pad

Tx3 Pad

Tx2 Pad

Tx1 Pad

Rx Pad
DWPT System
Vehicle Speed = 10 mph

Vehicle Speed = 40 mph
DWPT System
In 600 µs:

- Inverter phase increase to 30°
- \( I_{\text{track}} \) increases to 11 A
- EV moves 2 cm, at 80 mph
- In 3.2 ms, \( I_{\text{track}} \) reaches full current
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Misalignment Estimation

If Misalignment \[\rightarrow\] Power Transfer \[\rightarrow\] Efficiency
Misalignment Estimation

System Structure

EV Bottom View

System 3D view
Magnetic field above Tx pads

3D view $B_y$

2D view $B_y$
Exp

$\text{Experimental Setup}$

Misalignment Estimation

$\begin{align*}
  d_{\text{LTM}} &= 15 \text{ cm} \\
  d_{\text{VM}} &= 16.5 \text{ cm} \\
  d_{\text{LTM}} &= 0 \text{ cm} \\
  d_{\text{VM}} &= 19.5 \text{ cm}
\end{align*}$
Misalignment Estimation

Integrating Misalignment Estimation & DWPT

DC Link Current

Tx2 Coil Current

Tx1 Coil Current

Mutual Inductance
Rx & Tx

Vehicle Position @ x2

Movement direction

Magnetic sensors

ON, 85 kHz
OFF

ON, 85 kHz ON, 4.3 kHz

ON, 85 kHz OFF

ON, 85 kHz
OFF

ON, 85 kHz
OFF

ON, 85 kHz
OFF

ON, 85 kHz
OFF

Magnetic sensors

@ x1

@ x2

@ x3

@ x4

@ x5

@ x7

@ x6

@ x7

85 kHz

4.3 kHz

85 kHz

85 kHz
Misalignment Estimation

Transition between modes

Transition between modes
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• Survey about futuristic transportation or mobility invention – winning proposition: New Energy Source (34%)

• Need for public charging ecosystem: 1.1 million EVs (US) - 22,000 public charging stations (Sept. 2018)

• 1.7 million PMDs (US) only 17 public charging spots

• The Next-Generation Public Charging Infrastructure and Cyber-Information Network for Power Mobility Devices (DHHS funded)
  o Development of the charging infrastructure
  o Chapel Hill (NC) as the testing site
  o NCSU-UNC collaboration
Underwater Charging System

- Wet-mate connectors for underwater power delivery - weakest part of an underwater energy system
- Deployment of divers or sophisticated ROVs to establish underwater connection
- Recharging AUVs: passive latching techniques and docking stations with a tapered cone and capture tube
- Wave energy harvesting and delivery - flexible underwater grid
- Loosely coupled coils and near-field resonance (DOD):
  - Water layer causes power loss
  - Alignment issue due to water currents

Photo credit: https://www.youtube.com/watch?v=lMfnwZiPp2s
Photo credit: https://www.teledynemarine.com/
Photo credit: https://www.eenewspower.com/news/wireless-charging-underwater-vehicles
Photo credit: https://www.kongsberg.com/
DWPT Test Station

Bridging gap between DWPT bench and macro-scale outdoor testing/implementation

Challenges of prototype testing

- Laboratory prototype reaching $4,000 per meter or $7,000 per pad
- 50-m test track allows around 5 seconds of testing
- Thermal characteristic
- Limited repeatability
- Limited speed range
- Testing of accidental and fault conditions
Class E Inverters for Wireless Charging

- Variable inverter load impedance - varying output power and reduced efficiency
- Passive and active compensation methods, new topologies, new tuning techniques, new components
- Challenges: complex design, tuning sensitivity, no closed-form tuning algorithm problem to incorporate parasitic capacitance
- PowerAmerica funded project
WPT applications

Key Enabling Technology

*Key technology that defines space and scope of the application*
- Biomedical electronic implant
- Mobile factory automation
- Underwater charging

Autonomy Enabling Technology

*Key enabler for full autonomy due to energy storage constraints*
- Unmanned Arial Vehicles
- Personal transpiration (micromobility)
- Dynamic EV Charging

Technology for Convenience Improvement

*Customer-centric business (convenience, predictability, and efficiency)*
- Cellphone chargers
- Consumer electronics
- Static EV charging

Design Objectives

*WPT optimization*

*WPT to support autonomy; WPT uses the device autonomy and intelligence*

Effective time utilization, portability, and avoidance of unpleasantness
WPT – Challenges and Directions

• Standardizations (J2954, Qi, AFA)
• Modular design for high power operation
• Integrated intelligence and automation (alignment, FOD and LOD, EM measurements and safety, cybersecurity)
• Grid integration
• Power metering
• Advanced materials (new switching devices, magnetic materials, wire)
• Testing procedures and testbeds
• System construction and installation
• Economic evaluation
Group Members

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Power electronics, WPT, Micromobility Electrification

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High-frequency WPT, Inductive WPT

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Thank you