Event to start shortly
Scheduled time: 11:00 USA Eastern Standard Time

June 8th, 2016
Presenter: Prof. Zeljko Pantic, Utah State University
Title: Review of Recent Advances in Dynamic and Omnidirectional Wireless Power Transfer
Webinar Presenter

Dr. Zeljko Pantic
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- Ph.D., North Carolina State University, 2013
- Utah State University, Assistant Professor
- Associate Director of the Electrified Vehicles and Roadways (EVR) research facility at USU
- Associate Editor for the IEEE Transactions on Transportation Electrification (TTE) Special Issue on Dynamic Charging Systems
- Program Chair for Conference on Electric Roads and Vehicles (CERV), 2015-2016
Outline

- Concept and Basic Theory of Inductive Wireless Power Transfer
- Dynamic Wireless Power Transfer
- Challenges of Dynamic Wireless Power Charging for Electric Vehicle (EV) Applications
- State-of-the-Art Solutions for Dynamic Charging of EVs
- Dynamic Charging Research at Utah State University
- Omnidirectional Wireless Power Transfer: Directional Power Transfer Achieved Through the Transmitter Current Amplitude Modulation
Features of Wireless Power Transfer (WPT) Systems:
- Convenience
- Reliability
- Tolerance to snow, water, dust, nonmetal chemicals, and dirt
- Easy integration into urban landscape
- Offer a noninvasive solution for powering/recharging medical implants

Key factors for the recent progress in WPT technology:
- improved magnetic materials
- high-efficient power switching components operating in VLF/LF range
- advance in embedded systems
- novel control algorithms
Wireless Inductive Power Transfer

- Wireless (Inductive) Power Transfer: the transfer of electrical power from one system to another over an air gap, without wires
- Based on near-field (non-radiative) magnetic coupling between two (or more) loosely coupled coils
- The coils are loosely coupled if the distance between the coils is NOT much less than the equivalent diameter of the coils
- Radiative power transfer (microwaves and lasers) dominates in the long-range wireless power transfer applications, while W(I)PT dominates in the short-range applications
- Strongly coupled magnetic resonance (SCMR) as subcategory of inductive WPT
"Tesla coils" - high voltage resonant transformer circuits

Innovative approaches:

- A spark gap “switch” to control the power supply to the primary resonant circuit
- Coil parasitic capacitance used to tune the coil
- Direct LF AC to HF AC power conversion to energize the primary coil

References and Photo Credit: [R1]
Faraday’s and Ampere’s laws:
\[
\oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt} \int_S \mathbf{B} \cdot d\mathbf{A} \\
\oint_C \mathbf{H} \cdot d\mathbf{l} = \int_S \mathbf{J} \cdot d\mathbf{A} + \frac{d}{dt} \int_S \mathbf{D} \cdot d\mathbf{A}
\]

Compensation capacitors added:

For a tuned system:
\[
P_{out} = \omega_s I_1^2 \frac{M^2}{L_2} Q_2 = \omega_s I_1^2 L_1 k^2 Q_2 \\
\eta = \frac{k^2 Q_{c1} Q_{c2}}{\left(1+\sqrt{1+k^2 Q_{c1} Q_{c2}}\right)^2}
\]

Receiver quality factor:
\[
Q_2 = \frac{\omega_s L_2}{R_{Load}}
\]

Coil quality factors:
\[
Q_{c1} = \frac{\omega_s L_1}{R_{L1}} \\
Q_{c2} = \frac{\omega_s L_2}{R_{L2}}
\]
- Coils made of:
  - Litz wire
  - Tubular conductors

- Fe material is used to:
  - Shape magnetic field
  - Enhance power transfer
  - Suppress leakage flux

- “Reservoir” of the reactive power for the coil inductance
- Helps in filtering current harmonics
- Shapes the inverter output current
Compensation:
- Parallel
- Series
- Series-Parallel
- CCL

\[ x \cdot Q_2 \]

Rectifier +
- LC filter
- Boost
- Buck

Typical Inductive WPT - Topology
WPT - Applications

EV Charging

Material Handling

Consumer Electronics

Wireless Inductive Power Transfer

Biomedical implants and sensors

Robotics

Energy Harvesting

Photo credit: www.nissan.com

Photo credit: www.wampfler.com

Photo credit: www.metronic.com

Lenaert, Puers, [2006], IEEE

Photo credit: www.hizook.com

Photo credit: www.powercastco.com
Dynamic Wireless Power Transfer
“No More New Gas-Powered Cars by 2050?” (5 countries and 7 the US states)

25-mile EV → 79.8% real world driving cycles satisfied (J. Quinn et al., CERV 2016, to be published)

One possible solution: Tesla’s superchargers. Example: 90 kWh Model S battery and 120 kW supercharger:

- 40 min: 70 kWh of energy - 80% of charge
- 80 min: 90 kWh of energy – fully charged

25-mile EV → 97.8% real world driving cycles satisfied with the US interstates electrified with 50 kW dynamic WPT (J. Quinn et al., CERV 2016, to be published)
Why Dynamic Charging of EVs?

Inductive Wireless Power Transfer

Conductive Charging – Rail

Capacitive Wireless Power Transfer

Conductive Charging – Overhead Line

References and Photo Credit: [F1]-F[3]
Early Development of Dynamic WPT

- Santa Barbara Electric Bus Project and Partners for Advanced Transit and Highways (PATH) Program: 1979 - 1993
- Investigate the technical feasibility of EV dynamic charging (buses and passenger cars)
- Project limitations:
  - 400 Hz operation frequency
  - Low efficient ferromagnetic material
  - Bulky and heavy pads
- The PATH results:
  - Power: 60 kW
  - Efficiency: 60%
  - Vertical gap: 7.6 cm

References and Photo Credit: [R3]
Dynamic Charging – Key Challenges

- Impact on the electrical grid
- Optimum sizing of segments, coils/rails, power requirements
- In-road installation and maintenance
- Power conversion and power control
- Operation of the vehicle energy storage unit
- Communication requirements
- Standardization and interoperability
Modeling assumption about the EV penetration: 30% light vehicle/50% heavy vehicle

Power demand per mile (at 55 mph)

Example DWPT layout 1

Example DWPT layout 2

References and Photo Credit: [R4]
A market ready solution (TRL 9) – demonstrated at test tracks and in an operational environment

Fifth generation of technology

Innovative I-type rail structure for the primary side:
- maximum power: 27 kW (for a double pick-up coil)
- module width: 10 cm
- vertical gap: 20-cm air gap
- lateral misalignment: 24-cm
- active and passive compensation techniques

Potential disadvantages
- lower efficiency due to longer segments,
- leakage field,
- distributed compensation
EU – FABRIC Project

- FABRIC (Feasibility analysis and development of on-road charging solutions for future electric vehicles)
- Charging solutions and pilot programs (constructions in progress)

<table>
<thead>
<tr>
<th>Segment Length (m)</th>
<th>Segment Power (kW)</th>
<th>Number of Coils</th>
<th>Distribution Voltage</th>
<th>Activated coils</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>25</td>
<td>14</td>
<td>DC (?)</td>
<td>Single</td>
<td>VeDeCom-Qualcomm (France)</td>
</tr>
<tr>
<td>25</td>
<td>?</td>
<td>25</td>
<td>DC (600 V)</td>
<td>Single</td>
<td>Polito (Italy)</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>20</td>
<td>AC (400V)</td>
<td>Multiple</td>
<td>SAET (Italy)</td>
</tr>
<tr>
<td>20</td>
<td>200</td>
<td>1</td>
<td>DC (750 V)</td>
<td>Single</td>
<td>Scania (Sweden)</td>
</tr>
</tbody>
</table>
- Lumped IPT EV highway with Double-Coupled Systems (DCS) for power distribution
- Work on development of the new pad structures:
  - Circular
  - DD
  - DDQ
  - Bipolar
- Power null points were eliminated via the DDQ coil structure
- Preferred configuration: DD (primary) and DDQ (vehicle)
- Bidirectional WPT

References and Photo Credit: [R9-R11]
- A working prototype demonstrated in laboratory conditions
- GEM vehicle laboratory tests: 20 kHz, 2.2 kW with an efficiency of 74% (limited by the 72 V DC battery)
- Toyota RAV 4 laboratory tests: 20 kHz, peak power 9kW, SS and SP compensation configurations
- Passive and active parallel electrochemical capacitors and lithium-capacitor (LiC) for in-vehicle and grid power smoothing
In-Road Installation and Maintenance

- Integration into existing road and highway infrastructure
- Durability and reliability (to match 20 years (in the US) road lifetime)
- Maintenance (pavement resurfacing)
- Impact of the concrete and asphalt to the pad magnetic properties
- Improving inverter devices by evaluating wide bandgap device materials to reduce the thermal stress.
- New resonant converters and compensation topologies
- System modeling – to improve the reference tracking for the primary coil current
- Modeling techniques suitable for low order resonant type converters (GSSA of GUFT)
- Independent power regulation/protection provisions at the vehicle and the charger side:
  - limited input power for supplying multiple receivers
  - control of the battery charging power
While moving over road-embedded pads, the vehicle energy storage system is exposed to short-duration, high-energy bursts delivered from the road-embedded equipment.

High current form factor \( (F=I_{\text{rms}}/I_{\text{avg}}) \)
- reduces the battery charge capacity
- reduces the battery specific energy

References and Photo Credit: [R14-R15]
A hybrid energy storage (Battery – supercapacitor (SC))

- **Proposed solution 1**: Parallel passive connection of SC-battery modules
- **Proposed solution 2**: a SC bank integrated in the secondary resonant circuit
- **Proposed solution 3**: battery and SC modules actively connected to an internal DC bus. Full active topology provides the operation of the SC as a power buffer for the power delivered from the WPT system.

References and Photo Credit: [R13, R16-R17]
Peer to peer communication between the roadside controller and the onboard controller. Message types: control commands, event-based messages and monitoring data. Small packet size.

Low-rate wireless personal area network (PAN) (ZigBee (IEEE 802.15.4) and Bluetooth (802.15.1)) are not adequate for dynamic WPT systems due to low data rate and small range.

DSRC (Dedicated Short Range Communication) based on 802.11(n) IEEE standard:
- 75 MHz bandwidth at 5.9 GHz
- Vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication
- Supported by the US Department of Transportation (USDOT)
- Low latency
- Data rate 3-27 Mbps and range 300-1000 m
- Recommended by SAE J2954: DSRC+GPS +Cellular
Society of Automotive Engineers (SAE) published Technical Information Report (TIR) J2954 for wireless power transfer and alignment standard for stationary charging applications.

- Frequency range 81.38-90.00 kHz
- Maximum input power levels (3.7/7.7/11/22 kW)
- Minimum target efficiency (aligned) : 85%
- 3 ground clearance categories for above the ground mounting
  - Master/reference coils (circular and DD topology)

There is no standard or TIR for dynamic charging applications.

FABRIC: 10/20/40/200 kW, 85 kHz, and lateral misalignment 20 cm

Recommendation: when possible, maintain compliance with J2954
Dynamic Charging Research at USU
EVR Research Facility at USU

- Specialized research laboratory for vehicle and roadway systems integration

- Technology areas: dynamic WPT, EV drivetrain, roadway construction and materials, automation, security

Resources:

- 4800 ft² high bay, 750 kVA utility, a quarter-mile track/ 2x120 ft. electrified.

- High voltage capabilities: 480V 3P4W AC, +/-600V DC, and 208 V single-phase AC. Power distribution rated at 400A each

- Indoor trench with grating cover identical to outdoor ones

- Vehicle dynamometer, motor-generator group, Li-ion battery packs (55 kWh)

References and Photo Credit: [R21]
Technical Specifications:

- Maximum power: 25 kW (for 8 inch (20 cm) nominal gap)
- Constant power range 15 cm (6 inches) around the point of best alignment
- 20 kHz operation frequency
- Maximum efficiency > 91 % and energy efficiency > 85% for nominal gap
- Compliance with ICNIRP health and safety recommendations
- Multi-coil charging operation
- Independent power regulation/protection provisions at the vehicle and the charger side.
Hardware – Primary (Charger)

- Primary charging subsystem acting as an intelligent power switch: fast, reliable, and safe
- Single phase IGBT-based inverter unit with LCC compensation for load-independent primary coil current
- Multi-coil system with shared portion of the primary compensation circuit.
- Relay/contactor based coil sequencer
- Vehicle detection system based on magnetic sensors
Contactor-based sequencer allows sharing the portion of the compensation circuit (series inductor and parallel capacitor)

Contactors position in the circuit is selected with the objective to minimize total cost of the compensation system
- 2x30 kWh battery packs; 350 V rated voltage
- CCL compensation to provide an effective quality factor ranged from 3 - 6
- Output current regulated buck converter to control the charging current
- Extensive protection scheme to prevent the unloaded operation of the receiver
The primary side controller consists of two loops:
- Power controller (outer control loop) controls the amount of power transferred
- Current controller (inner control loop) controls the RMS current of the primary coil.

The current controller at the secondary adjusts the duty cycle of the buck converter in a way to limit the received power to 25 kW.
Power Transfer Control

- Fully energized system in less than 5 ms with no overshoot
- Optimum control is provided at no load. Establishing the track current under the full load is demonstrated, as well
- The bandwidth of this controller is about 60 Hz
- Magnetic sensors are used for the vehicle and speed detection
- Magnetic sensors: expensive, limited reliability, susceptible to saturation and damage in case of high magnetic field exposure
- New detection system testing is in progress:
  - based on induction principle between a coil on the vehicle and coils in the road
  - Provides vehicle detection, as well as, the misalignment information
  - Both driver and foreign object detection system can activate/deactivate system remotely and control magnetic “detectability” of the vehicle
Foreign Object Detection System

- Computer Vision (CV) is used for real-time detection of a metallic clutter on the charging path.
- Infrared cameras for night object detection.
- Picture processed by Canny edge detector and probabilistic Hough Transform.
- Contour analysis is applied to detect contours.
- Future Work: distributed image processing and sensor fusion (for different weather conditions).
Omnidirectional Wireless Power Transfer
("directional" power flow control through current amplitude control)
Introduction

- IMPLANTABLE biomedical devices - monitoring, diagnostic, therapeutic and interventional applications
  - body sensors for monitoring of various health parameters
  - brain implants and brain-computer interface (BCI)
  - capsules for transcutaneous endoscopy treatments
  - retinal prosthesis
  - Ventricular Assist Devices (VADs)
  - cardiac pacemakers
- Military applications
- Powering sensor nodes

- Ranged few mWs for brain implants to 15-20 W for VADs. Power range limited due to recommended maximum limits for the field exposure.
Omnidirectional WPT systems

- **Transmitter** with three orthogonal coils
- **Receiver** with three orthogonal coils wound on a ferrite cube
- Unnecessary power flow directed to the regions with no load
- Magnetic field is not uniform

References and Photo Credit: [R23-R24]
Identical and Non-Identical Currents

**Identical Currents**

- Graph showing the trajectory of the peak magnetic field for coil x and coil y.
- Efficiency comparison graph at $I_1$ and $I_2$ are in phase.

**Non-Identical Currents**

- Graph showing the trajectory of the peak magnetic field for coil x and coil y.
- Efficiency comparison graph at $I_1$ and $I_2$ are 90 degree phase shift.

References and Photo Credit: [R25-R27]
Omnidirectional WPT for 2D systems

\[
\begin{bmatrix}
  I_1 \\
  I_2 \\
\end{bmatrix} = \begin{bmatrix}
  \cos \theta \\
  \sin \theta \\
\end{bmatrix} I
\]

- amplitude modulation to control directivity of the maximum field and efficiency
- $\theta$ is the physical angle of resulting magnetic field vector

E.g. if the receiver is located at 45°, then select $\theta=45^\circ$ for maximum power transfer

- If the plane of the receiver coil is parallel to the 2D plane of the 2D WPT system, the receiver will not receive any power

References and Photo Credit: [R25-R27]
New method to enhance the power delivery performance. The power delivered to the \( N \) points can be determined first. Then, according to the power demand, a weight time-sharing scheme is proposed.
Thank you!
References and Photo Credit


References and Photo Credit

If you have any question for the presenter:
Use the Webex Q&A tab to send your question to the moderator
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CONCLUSION

We thank the presenter, Prof. Pantic, and we thank you for your attention.

This session was recorded and will be posted online at:
www.ias.ieee.org

Next webinar: September 7th, 2016

Presenter: Marcelo Valdes, GE Industrial Solutions

Tile: Modern Selectivity Techniques for LV & MV Systems, Beyond the Time-Current-Curve