2019 AUT Conference

An Inductively-coupled Wireless Power Transfer Application for Autonomous Underwater Vehicles

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Electrical & Computer Engineering
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Aim of Presentation

Introduce the trend of Wireless Power Transfer (WPT) System

Deliver the experiment results of prototype

Discuss what parameters are to be considered for underwater WPT
CONTENTS

01  Introduction
02  Underwater WPT Review
03  Design WPT for AUT
04  Prototype Experiment
05  Consideration
1. Introduction

Classification of Wireless Power Transfer

- WPT introduced: By N. Tesla in 1898
- Advancement of information and communication with microwave technology
- Necessity of WPT: Demand for battery-powered devices, EV and sensors

Inductive Coupling:
- Simple Implementation
- Eddy current loss

Capacitive Coupling:
- Eddy current free
- High voltage

Microwave WPT:
- Long transfer distance
- Radiation exposure

Non-radiation method [Near field]

Radiation method [Far field]
1. Introduction

Inductive power transfer (IPT)

In 1994 J. Boys (University of Auckland) introduced the 10kHz inductively coupled power transfer (IPT) system to charge the EV’s battery.

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Power</th>
<th>Efficiency</th>
<th>Airgap</th>
<th>Frequency</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>USA (MIT)</td>
<td>60 W</td>
<td>15%</td>
<td>2 m</td>
<td>9.9 MHz</td>
<td>-</td>
</tr>
<tr>
<td>2009</td>
<td>Korea (KAIST)</td>
<td>100 kW</td>
<td>85%</td>
<td>17 cm</td>
<td>20 kHz</td>
<td>EV (Commercial Bus)</td>
</tr>
<tr>
<td>2013</td>
<td>N.Z (Uni of Auckland)</td>
<td>2 kW</td>
<td>-</td>
<td>20 cm</td>
<td>20 kHz</td>
<td>EV Battery Charging</td>
</tr>
<tr>
<td>2015</td>
<td>Korea Railroad</td>
<td>818 kW</td>
<td>82.7%</td>
<td>5 cm</td>
<td>61.5 kHz</td>
<td>High speed train</td>
</tr>
<tr>
<td>2017</td>
<td>Wärtsilä Norway</td>
<td>1 MW</td>
<td>97%</td>
<td>0.1-0.5 m</td>
<td>2-8 kHz</td>
<td>Vessel</td>
</tr>
</tbody>
</table>
1. Introduction

Inductive power transfer (IPT)

Gap: 10cm-50cm
Transfer power: 1 MW

Source
- Another world’s first for Wärtsilä - wireless charging for hybrid coastal ferry successfully tested
1. Introduction

Inductive power transfer (IPT)

Length: 128m, The rated output current: 300 A, Max. output voltage: 4000V

## 2. Underwater Wireless Power Transfer

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Power</th>
<th>Efficiency</th>
<th>Airgap</th>
<th>Frequency</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>USA</td>
<td>240 W</td>
<td>70%</td>
<td>2 mm</td>
<td>50 kHz</td>
<td>Underwater Vehicle Charging</td>
</tr>
<tr>
<td>2010</td>
<td>China</td>
<td>400 W</td>
<td>90%</td>
<td>2 mm</td>
<td>94.3 kHz</td>
<td>4000-m Deep sea</td>
</tr>
<tr>
<td>2013</td>
<td>China</td>
<td>45 W</td>
<td>84%</td>
<td>2 mm</td>
<td>167 kHz</td>
<td>Underwater Vehicle Charging</td>
</tr>
<tr>
<td>2017</td>
<td>China</td>
<td>10 W</td>
<td>&lt;47% [Z matching]</td>
<td>82 mm</td>
<td>90 kHz</td>
<td>Frequency bifurcation study</td>
</tr>
<tr>
<td>2018</td>
<td>USA</td>
<td>1 kW</td>
<td>92.41 %</td>
<td>21 mm</td>
<td>465 kHz</td>
<td>3phase Underwater Vehicle Charging</td>
</tr>
<tr>
<td>2019</td>
<td>China</td>
<td>200 W</td>
<td>&lt;90 %</td>
<td>66 mm</td>
<td>60-600 kHz</td>
<td>Underwater Vehicle Charging</td>
</tr>
</tbody>
</table>
2. Underwater Wireless Power Transfer

Transfer gap: 2 mm
Transfer power: 400 W
Sea water pressure: 40MPa

Fig. 1 Illustration of the contactless power transmission (CLPT) system used in underwater applications
(a) Application of a CLPT system; (b) Schematic diagram of the system; (c) Physical structure of the electromagnetic (EM) coupler

Fig. 7 The 2-mm-gap electromagnetic coupler with P48 pot cores and Litz wire windings
(a) Core halves with windings; (b) Coaxial and noncoaxial alignments of the coupler

2. Underwater Wireless Power Transfer

Transfer gap: 21 mm
Size: \( \approx 300 \times 300 \text{mm} \)
Transfer power: 1 kW

Fig. 12. (a) Simulation and (b) experimental models of the proposed coil structure in Section IV.

Fig. 17. System performance in three conditions.

2. Underwater Wireless Power Transfer

Transfer gap: 66 mm
Transfer power: 200 W

Fig. 2. General overview of the underwater WPT system. Fig. 6. Experimental prototype.

### 3. Design WPT for AUT

#### WPT Coil Design

<table>
<thead>
<tr>
<th>Wire Material</th>
<th>Wire Radius</th>
<th>Wire Insulation</th>
<th>Loop Shape</th>
<th>Loop Radius</th>
<th>Loop Turns</th>
<th>Ferrite Rods</th>
<th>Ferrite Rod $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>0.565mm</td>
<td>PVC 0.8mm</td>
<td>Spiral</td>
<td>40mm (in)</td>
<td>22</td>
<td>12 (per 30°)</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100mm (out)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Transmitter [Tx]**

**Receiver [Rx]**

**Graphs:**
- Self-Inductance
- Coupling Coefficient $k_{12}$
3. Design WPT for AUT

Circuit of WPT Application

- DC Source
- DC-AC Inverter
- Compensating Capacitor
- Coils (Inductor) & Magnetic Coupling
- Compensating Capacitor
- AC-DC Rectifier
- Load

- Switching loss (soft switching ZVS, ZCS)
- Types of converter
- Protection
- Compensation topologies (SS, SP, PS, PP, LCL and etc)
- E.M.I & Safety
- Wire loss (Litz coil)
- Constant voltage or current
- Regulation
- Battery modelling

- Constant voltage or current
- Regulation
- Battery modelling
For resonance of WPT circuit: \( jX_{in} = 0 \) [Zero imaginary (Reactive) element]

For maximum power transfer: \( R_s = Z_{in} \)

For maximum power efficiency: \( R_s=0 \) and high \( Z_{in} \)

For the WPT circuit:

- **Series-Series**
  \[ Z_{in} = \frac{\omega^2 M_{12}^2}{R_L} \]
  - \( R_L \uparrow \) \( Z_{in} \downarrow \)
  - \( \omega \uparrow \) \( Z_{in} \uparrow \uparrow \)
  - \( M_{12} \downarrow \) \( Z_{in} \downarrow \downarrow \)

- **Series-Parallel**
  \[ Z_{in} = R_L \frac{M_{12}^2}{L_2^2} \]
  - \( R_L \uparrow \) \( Z_{in} \uparrow \)
  - \( L_2 \downarrow \) \( Z_{in} \uparrow \uparrow \)
  - \( M_{12} \downarrow \) \( Z_{in} \downarrow \downarrow \)

- **Parallel-Series**

- **Parallel-Parallel**

3. Design WPT for AUT
3. Design WPT for AUT

Magnetic coupling over distance

3. Design WPT for AUT

Electromagnetic field study

<table>
<thead>
<tr>
<th>Distance</th>
<th>Inductance L1</th>
<th>Parasitic Wire Resistance</th>
<th>Coupling Coefficient k12</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm</td>
<td>104 uH</td>
<td>0.3 Ω</td>
<td>0.3703</td>
<td>20 kHz</td>
</tr>
</tbody>
</table>
3. Design WPT for AUT

Electric and Magnetic Field Guideline

- IEEE C.95: H [A/m]
- ICNIRP: H [A/m]
- IEEE C.95: E [V/m]
- ICNIRP: E [V/m]

- 163 A/m
- 5 A/m
- 20 kHz
- 614 V/m
- 87 V/m
- 20 kHz
3. Design WPT for AUT

**Frequency Response Analysis**

- **Voltage Gain**
  - 10 mm
  - 50 mm

- **Phase Angle**
  - 20 kHz
  - 20 kHz
3. Design WPT for AUT

Frequency Response Analysis

Voltage Gain (40 mm)

Seawater

Air

High-frequency

Phase Angle
4. Prototype Experiment

Experiment Setup

- **FRA**
- **Full-bridge Converter**
- **Micro Controller**
- **Load**
- **C1**
- **C2**
- **Rectifier**

*Tx and Rx Coil in seawater*
4. Prototype Experiment

Transfer Power Measurement

Air 50 [mm]

*Tx*
15.24 W

*Rx*
12.79 W

Seawater 50 [mm]

*Tx*
14.41 W

*Rx*
11.50 W
## 4. Prototype Experiment

### Efficiency of prototype

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air</td>
<td>SEawater</td>
<td>FEKO</td>
<td>Air</td>
<td>SEawater</td>
<td>FEKO</td>
</tr>
<tr>
<td>10mm</td>
<td>5.33</td>
<td>4.60</td>
<td>3.87</td>
<td>4.26</td>
<td>4.24</td>
<td>90.70%</td>
</tr>
<tr>
<td></td>
<td>6.77</td>
<td>6.77</td>
<td>5.70</td>
<td>5.65</td>
<td>5.89</td>
<td>89.47%</td>
</tr>
<tr>
<td></td>
<td>8.88</td>
<td>7.88</td>
<td>8.40</td>
<td>7.42</td>
<td>6.81</td>
<td>89.29%</td>
</tr>
<tr>
<td></td>
<td>14.10</td>
<td>13.32</td>
<td>13.0</td>
<td>11.55</td>
<td>11.42</td>
<td>86.15%</td>
</tr>
<tr>
<td>20mm</td>
<td>20.76</td>
<td>17.21</td>
<td>19.5</td>
<td>15.24</td>
<td>14.14</td>
<td>82.05%</td>
</tr>
<tr>
<td></td>
<td>23.43</td>
<td>25.65</td>
<td>28.0</td>
<td>17.62</td>
<td>18.47</td>
<td>78.57%</td>
</tr>
<tr>
<td></td>
<td>30mm</td>
<td>40mm</td>
<td>50mm</td>
<td>60mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10mm</td>
<td>20mm</td>
<td>30mm</td>
<td>40mm</td>
<td>50mm</td>
<td>60mm</td>
</tr>
</tbody>
</table>

### Transfer Efficiency [Tx coil - Rx coil]

- **Distance** (mm)
- **DC Input [Watt]**
- **AC Pin [Watt]**
- **AC Pout [Watt]**
- **Transfer Efficiency**

### DC to DC Efficiency

- **Distance** (mm)
- **Air**
- **Seawater**

- **Data points for DC to DC Efficiency**
5. Consideration for AUT WPT system

- **Purpose**
  - Stationary or dynamic charging?

- **Size**
  - Fit on AUT hull?
  - How much power required?

- **Frequency**
  - Is it safe (EMI)?
  - Characteristic variation in high frequency?

- **Housing**
  - Depth of implementation?
  - Magnetic characteristic variation due to Housing?

- **Gap**
  - How much transfer gap required?
  - How is the gap kept steadily?

- **Maintenance**
  - Cost effective?
  - Electrical insulation?

- **Voltage**
  - How is voltage regulation achieved?

For the extension of WPT technology in AUTs
- The standards (rated power, voltage, frequency, gap and etc.) should be established.
- A joint research is necessary. (Marine + Electrical + Mechanical + ...)
- It needs to clarify how/what the implemented WPT affects AUT practically.
Question?
THANK YOU