Future of Electric Vehicle Charging

- Gautham Ram Chandra Mouli, Prasanth Venugopal, Pavol Bauer

- DC systems, Energy conversion & Storage
“Chicken and egg” problem

Disruptive technology?

Number

# people

# cars

# gas stations

Time

Electric vehicles

Slow charge points to ignite adoption of EV

Rise of fast charge points

Peak in number of slow charge points, as fast charging emerges

Reduction of slow charge points, in favor of fast charge points

Fast charging accelerates mass adoption of EV
1900 New York 5th avenue

1913 New York 5th avenue

Charging electric vehicles 1900
Charging electric vehicles 2017

Source: Tesla
Charging electric vehicles 1900-2017

Source: Tesla
Charging 2017

Charging 2030
Fast Charging versus Battery swap Comparison

- Requirement of Standardized Battery Interface across multiple manufacturers
- Consumer acceptance of not owning a battery and having to change the vehicle battery.
- The battery state of health estimation
- Safety Perspective
Conductive charging of EV
Conductive Charging – AC Vs DC

- AC charging uses on-board power converter
- DC charging uses off-board power converter
  - No size and weight limitation
  - High charging power
  - V2G !!!!
## AC charging

<table>
<thead>
<tr>
<th></th>
<th>Plug</th>
<th>Number of pins Communication</th>
<th>Charging level</th>
<th>Voltage &amp; current</th>
<th>Maximum power</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>US</strong></td>
<td>Type 1 SAE J1772</td>
<td>3 power pins – L1,N,E</td>
<td>AC Level 1</td>
<td>1Φ 120V, upto 16A</td>
<td>1.9 kW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 control pins – CP, PP (PWM over CP)</td>
<td>AC Level 2</td>
<td>1Φ 240V, upto 80A</td>
<td>19.2 kW</td>
</tr>
<tr>
<td><strong>Europe</strong></td>
<td>Type 2 Mennekes</td>
<td>4 power pins – L1,L2,L3,N,E</td>
<td>AC Level 1</td>
<td>1Φ 230V, upto 32A</td>
<td>7.4 kW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 control pins – CP, PP (PWM over CP)</td>
<td>AC Level 2</td>
<td>3Φ 400V, upto 80A</td>
<td>43 kW</td>
</tr>
</tbody>
</table>

**US SAE** | **European Mennekes** | **Tesla US**
## DC charging

<table>
<thead>
<tr>
<th>Plug</th>
<th>Number of pins Communication</th>
<th>Charging level</th>
<th>Voltage &amp; current</th>
<th>Maximum power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 4 SAE J1772 CCS</td>
<td>3 power pins – DC+,DC-,E 2 control pins – CP, PP (PLC over CP, PE)</td>
<td>DC Level 3</td>
<td>200-1000V DC, upto 200A</td>
<td>200kW</td>
</tr>
<tr>
<td>Type 4 Chademo</td>
<td>3 power – DC+,DC-,E 7 control pins (CAN communication)</td>
<td>DC Level 3</td>
<td>200-500V, upto 125A</td>
<td>62.5kW</td>
</tr>
<tr>
<td>Tesla US</td>
<td>3 power pins – DC+,DC-,E 3 power pins (reused) – L1,N,E 2 control pins – CP, PP</td>
<td>DC Level 3</td>
<td>For Model S, 400V, upto 300A</td>
<td>120kW</td>
</tr>
</tbody>
</table>
# AC Vs DC charging

<table>
<thead>
<tr>
<th></th>
<th>AC</th>
<th>DC</th>
<th>Tesla</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1Φ</td>
<td>3Φ</td>
<td>Higher power</td>
</tr>
<tr>
<td>USA /Japan</td>
<td><img src="image1" alt="AC plug" /></td>
<td><img src="image2" alt="DC plug" /></td>
<td><img src="image3" alt="Tesla plug" /></td>
</tr>
<tr>
<td>Europe /China</td>
<td><img src="image4" alt="AC plug" /></td>
<td><img src="image5" alt="DC plug" /></td>
<td><img src="image6" alt="Tesla plug" /></td>
</tr>
</tbody>
</table>
Future of EV charging

- **2016**
  - 50 kW for mainstream EVs: along highways, in city centers, at commercial locations, etc.

- **2021**
  - 150 - 300 kW for premium EVs: on long distance corridors

Source: ABB
Conductive Charging

• Fast charging – increase battery voltage 350-400 to 800V
• Charging current pattern for capacity fade
• Smart Charging +V2G
• Implementing multiplexing
400 Cell Battery: 100s 4p
Current Limited by CCS-Connector
→ Maximum 350 A Charge Current
→ Charge Power $P_{\text{max}} = 145.25$ kW

70% Increase of Charge Power

400 Cell Battery: 200s 2p
Current Limited by Cell Design: 150 A/Cell
→ Maximum 300 A Charge Current
→ Charge Power $P_{\text{max}} = 240$ kW
Tesla cooling tubes
Smart charging of EV
Smart Vs Conventional charging

- Change EV charging power with time

![Diagram showing Smart Charging and PV generation](image)
Smart Vs Conventional charging

• Change EV charging power with time:

1. Reduce charging cost by e.g. dynamic grid prices
2. Provide energy support to grid (V2G)
3. Match renewable generation
4. Reduce distribution system losses
5. Reducing the peak demand on the grid
6. Provide ancillary services
7. Implementing multiplexing of EV chargers
Smart charging via AC

PV Charging of EVs v1.0
Dynamic charging using AC, Chademo v2.0 and CCS/COMBO

Source - http://www.chademo.com/
Vehicle-to-grid (V2G)
Vehicle-to-X (V2X)

V2X is a generic name:

V2G (grid)
V2B (building)
V2H (home)
V2L (load)

Source - http://www.acpropulsion.com/
V2X via AC

1. **EV is MASTER, charger is SLAVE**
   - For V2X, charger cannot be the slave

2. **Smart charging – PWM on control pilot**
   - Higher level communication needed for V2X

3. **Current EVs have unidirectional chargers**
   - Bidirectional on-board charger needed for V2X

Source - http://www.acpropulsion.com/
Experimental testing of V2X - Chademo

Chademo v2.0 (CAN communication)
1. Extremely quick response between EV and charger
2. No buffer required
3. Smart charging and V2X demonstration
Charging of EV from PV
Implication on CO2 emissions

W2W results for best options

- VW DIESEL
- GASOLINE
- DIESEL
- EV ex NG
- EV ex EU-mix
- ES ex NG
- ES ex wind/sun
- EV ex wind/sun

Total W2W energy [MJ/100km]

W2W CHG emission gCO2eq/km
PV Charging of Electric Vehicles
PV Charging of Electric Vehicles
System architecture

AC interconnection of EV and PV
System architecture

DC interconnection of EV and PV

- Only one DC/AC converter → Lower cost of converter
- DC-DC connection of EV-PV → Improved efficiency
- Bi-directionality of DC/AC inverter → Charge / V2G

4 power flows

1. PV $\rightarrow$ EV
2. Grid $\rightarrow$ EV
3. EV $\rightarrow$ Grid
4. PV $\rightarrow$ Grid
10kW EV-PV power converter

- Higher power density
- Higher efficiency
- Bidirectional EV charging

- SiC MOSFET
- SiC diode
- Powdered alloy inductors

50cm x 50cm !!!
EV-PV power converter

Interleaved boost converter (IBC)
Integrating the technologies I

- PV charging
- Tramline 750V charging +PV (Arnhem)
- Traction line 1500-300V charging +PV

With Power Electronics!

17 February 2018
Motivation

TABLE 2
CO2 EMISSIONS AND TAXES WHEN USING GASOLINE VEHICLE, GRID AND SOLAR CHARGED EV

<table>
<thead>
<tr>
<th></th>
<th>Fuel car</th>
<th>Grid charged</th>
<th>Solar charged</th>
<th>Solar carport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Taxes/year</td>
<td>€ 912</td>
<td>€ 0</td>
<td>€ 0</td>
<td>€ 0</td>
</tr>
<tr>
<td>Vehicle purchase tax</td>
<td>€ 2884</td>
<td>€ 0</td>
<td>€ 0</td>
<td>€ 0</td>
</tr>
<tr>
<td>Tax benefit (PV, EV)</td>
<td>No</td>
<td>MIA/ KIA/ FIA</td>
<td>MIA/ KIA/ FIA</td>
<td>MIA/ KIA/ FIA</td>
</tr>
<tr>
<td>CO2 emission (g/km)</td>
<td>109</td>
<td>70.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CO2 emission for 14300 km (kg/yr)</td>
<td>1559</td>
<td>1008</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CO2 emission for 20,000 km (kg/yr)</td>
<td>2180</td>
<td>1410</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

TABLE 6
COST OF ELECTRICITY FROM 13kW SOLAR ROOFTOP AND CARPORT

<table>
<thead>
<tr>
<th></th>
<th>Cost of System (€)</th>
<th>Energy (kWh/year)</th>
<th>Electricity Cost (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rooftop PV</td>
<td>19,700</td>
<td>13,448</td>
<td>0.097</td>
</tr>
<tr>
<td>Solar carport</td>
<td>57,200</td>
<td>13,448</td>
<td>0.28</td>
</tr>
<tr>
<td>Grid</td>
<td></td>
<td></td>
<td>0.23</td>
</tr>
</tbody>
</table>

Fig. 5 – Annual PV revenues as a function of feed-in tariffs
Testing with Nissan Leaf EV

• Charging and V2G
• Chademo protocol
• 390V EV battery being successfully discharged and then charged with a current of 24A
Contactless Charging of EV
Contactless Charging of EV

Components:
- Base power electronics
- Charge pads
- Compensation Circuitry
- Vehicle electronics
Charge pads

DR Charge-pad

DR+Q Charge-pad

Rectangular Charge-pad

Circular Charge-pad
\[
e_1 = \frac{N_1}{N_2} \frac{d\Phi_m}{k_2} = \frac{N_1 k_2}{N_2 k_1}
\]
Compensation Circuitry

(SS) 

(SP) 

(PS) 

(PF) 

February 17, 2018
Charging while driving (On-road charging)

Coil configuration and definition of single and multi-turn coils

Sinusoidally distributed three phase windings
Contactless Charging of EV

Challenges:

- Charge pad design (magnetics)
- Misalignment
- Multifrequency pads (energy exchange)
- Harmonics (filtering)
- (Power line) communication
Implementing multiplexing
Multiplexing 1
Multiplexing II
Integrating the technologies II

• Roads powering electrical vehicles
• Self healing roads
• Roads generating sustainable energy
• Roads allowing automated driving

With Power Electronics!
Combination Inductive charging and self healing asphalt
Experimental Samples
Performance analysis

Power dissipation per volume in the asphalt samples, $I_{1,\text{rms}} = 10\, \text{A}$

- Regular IHA
- Sectioned IHA
- Anisotropic IHA
- Resonator Aggregates
- IPT maximum
- IHA minimum

Power per volume [W m$^{-3}$]

Frequency [Hz]

$10^3$  $10^4$  $10^5$  $10^6$

$10^0$  $10^1$  $10^2$  $10^3$  $10^4$  $10^5$  $10^6$
Thank you
Case study A – Charging at traffic signals

Vehicle speed, battery power flow and SOC of battery for (a) UDDS and (b) ECE-EUDC driving cycles (c)
Case study A – Charging at traffic signals

(a) SOC of battery for different driving cycles

(b) change in SOC
Case study B – Charging while driving

(a) Characteristics of HWFET 2

(b) Vehicle speed, battery power flow and SOC for HWFET2

(c) Primary winding coverage
SOC of battery for (a) 10kW, (b) 20kW, (c) 30kW, (d) 40kW CPT and (e) Change in SOC for the entire duration of HWFET2
Conclusions
Thank you

Further questions?