Assessment of Plug-in Electric Vehicles Charging on Distribution Networks

Master Thesis Defense - Tsz Kin (Marco) Au

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Presentation Outline

I. Introduction of PEV
II. The developed tool for investigating the impact of PEV
III. Test system characteristic
IV. Test result
V. Conclusion
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Technological Impacts of PEVs

*Potential benefits:*

- Lower operating cost than combustion engine vehicles: 3.7 vs. 16.7 cents
- On road CO2 emission will be lower
- V2G and ancillary services provide business opportunities

*Problems:*

- 10% penetration = additional 300 GWh per day in the U.S.
- Increase grid losses
- Reduce system spare generation and harder to schedule maintenance
- Poorer voltage profile and transformer overloading in weakly meshed distribution networks
What causes poor voltage profile and transformer overloading?

- Line impedance
- Coincidence between PEV charge time and system peak load
- Lack of interconnection

Poor voltage profile and overload transformer
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Monte Carlo Simulation

- Suitable for analysis when uncertainties present
- 4 uncertainties needed to be address:
  - Charging time
  - Battery state of charge (SOC)
  - Charging method
  - Customer load variation
- 7 major functional blocks
- Each trail represent 24 hours
1. Data Processing and Initialization

- 34,000+ drivers’ behavior from CMAP, which consists of their to-work and to-home arrival times.
- Electric vehicle parameters
  - Battery capacity
  - Energy consumption per unit distance
- Distribution network conductor parameters
- Average power consumption and load type at each node
  - Residential area
  - Commercial area
2. PEV Penetration and Charging Points

\[ \text{PEV Penetration} = \frac{\text{Total number of passenger PEV}}{\text{Total number of passenger vehicles}} \]

Charge at home or at work?

- Type 1: Charge at home only
- Type 2: Charge at home and work

- 33.33% Charge at home only
- 66.67% Charge at home and work
3. PEV’s Arrival Time

- PEV drivers will charge their vehicles anytime at their convenience
- Their arrival times affect the charge profile
- Drivers’ behaviors varies from day to day, which creates uncertainty
- Must model the uncertainty in order to simulate its effect to the power system
3. PEV’s Arrival Time

Inverse transformation for random number generation

- Map \( \text{rand}(0,1) \) → actual distribution
4. PEV’s Battery State of Charge

- Commute distance have an effect on the battery state of charge
- A driver’s commute distance although is similar everyday, it may vary sometime, which causes uncertainty
- Must model this uncertainty in order to simulate its effect to the power system
- Convert commute distance to battery state of charge (SOC)

\[
SOC = \text{Battery Cap. (kWh)} - \text{Commute Dist. (mile)} \times 0.34 \text{ kWh/mile}
\]
4. PEV’s Battery State of Charge

<table>
<thead>
<tr>
<th>Commute distance (miles)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 4.0</td>
<td>19.19</td>
</tr>
<tr>
<td>4.1 – 8.0</td>
<td>22.95</td>
</tr>
<tr>
<td>8.1 – 12.0</td>
<td>16.67</td>
</tr>
<tr>
<td>12.1 – 16.0</td>
<td>13.77</td>
</tr>
<tr>
<td>16.1 – 20.6</td>
<td>9.37</td>
</tr>
<tr>
<td>20.1 – 24.0</td>
<td>6.07</td>
</tr>
<tr>
<td>24.1 – 28.0</td>
<td>4.59</td>
</tr>
<tr>
<td>28.1 – 32.0</td>
<td>2.69</td>
</tr>
<tr>
<td>32.1 +</td>
<td>4.70</td>
</tr>
</tbody>
</table>

Commute Distance Distribution

Quantile Function of Commute Distance

\[ y = 353.04x^5 - 725.13x^4 + 526.87x^3 - 140.15x^2 + 22.691x - 0.0038 \]

\[ R^2 = 0.9997 \]
5. PEV Charge Profile

- Computed individually based on arrival time, battery state of charge, and charging method

\[
\text{Total Charge Profile}_{hr} = \sum_{i}^{\# \text{ of PEV}} P_{i,hr}
\]
6. Customer Load Profile

• Varies from day to day
• The variation is assumed to be Gaussian distributed:

\[
f(P_{bus,ti}) = \frac{1}{\sigma_{bus,ti} \sqrt{2\pi}} e^{\frac{1}{2} \left( \frac{(P_{bus,ti} - AvgP_{bus,ti})}{\sigma_{bus,ti}} \right)^2}
\]

\[
AvgP_{bus,ti} = P_{type,ti}^{norm} \times AvgP_{bus}
\]
7. Running Power Flow Analysis for the Distribution System

• Cannot use Newton-Raphson based methods

• Distribution networks characteristic:
  – High R/X ratio → Decoupled and fast decoupled methods won’t work
  – Weakly meshed, sparse network → Newton-Raphson method won’t work

• Forward-backward sweep method is used
7. Running Power Flow Analysis for the Distribution System

Forward-backward sweep method example:

\[ z = 0.3 + j0.6 \ \Omega/mile \]

\[ z_{12} = 0.1705 + j0.3409 \ \Omega \]
\[ z_{23} = 0.2273 + j0.4545 \ \Omega \]

\[ s_2 = 1500 + j750 \ \text{kW} + j\text{kVar} \]
\[ s_3 = 900 + j500 \ \text{kW} + j\text{kVar} \]
7. Running Power Flow Analysis for the Distribution System

Forward-backward sweep method example:

Forward sweep:

1) Assume voltage at node 3 is 7200V

2) Compute $I_3$

$$I_3 = \left( \frac{s_3}{V_3} \right)^* = 143.0 \angle -29.0 \ A$$

3) Compute $I_{23}$

$$I_{23} = I_3 = 143.0 \angle -29.0 \ A$$

4) Compute $V_2$

$$V_2 = V_3 + Z_{23} \cdot I_{23} = 7260.1 \angle 0.23 \ V$$

5) Compute $I_2$

$$I_2 = \left( \frac{s_2}{V_2} \right)^* = 231.0 \angle -26.3 \ A$$

6) Compute $I_{12}$

$$I_{12} = I_{23} + I_2 = 373.9 \angle -27.3 \ A$$

7) Compute $V_1$

$$V_1 = V_2 + Z_{12} \cdot I_{12} = 7376.2 \angle 0.97 \ V$$

8) Compute mismatch between $V_1$ and $V_s$

$$Mismatch = ||V_s| - |V_1|| = 176.2 \ V$$

Not satisfy!
7. Running Power Flow Analysis for the Distribution System

Forward-backward sweep method example:

Backward sweep:

1) Assume voltage at node 1 is 7200V, and use the line currents computed from forward sweep

2) Compute \( V_2 \)
   \[ V_2 = V_1 - Z_{12} \cdot I_{12} = 7085.4\angle -0.68 \text{ V} \]

3) Compute \( V_3 \)
   \[ V_3 = V_2 - Z_{23} \cdot I_{23} = 7026.0\angle -1.02 \text{ V} \]
7. Running Power Flow Analysis for the Distribution System

Forward-backward sweep method example:

Perform forward sweep again:

1) Use the voltage at node 3 from the backward sweep

2) Compute $I_3$

$$I_3 = \left( \frac{s_3}{V_3} \right)^* = 146.5 \angle -30.1 \ A$$

3) Compute $I_{23}$

$$I_{23} = I_3 = 146.5 \angle -30.1 \ A$$

4) Compute $V_2$

$$V_2 = V_3 + Z_{23} \cdot I_{23} = 7087.6 \angle -1.02 \ V$$

5) Compute $I_2$

$$I_2 = \left( \frac{s_2}{V_2} \right)^* = 236.6 \angle -27.2 \ A$$

6) Compute $I_{12}$

$$I_{12} = I_{23} + I_2 = 383.0 \angle -28.3 \ A$$

7) Compute $V_1$

$$V_1 = V_2 + Z_{12} \cdot I_{12} = 7206.5 \angle 0.0 \ V$$

8) Compute mismatch between $V_1$ and $V_s$

$$\text{Mismatch} = ||V_s|| - |V_1| = 6.535 \ V$$

Satisfy!
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Test System Characteristic

Assumption:

• 4000 residents
• Average 2.35 people and 1.78 passenger vehicles per household
• power factor = 0.9
• power factor = 0.8
• Avg. 959.5 W/household
• Average power consumption:

  = 81.6 + 40.8j (kW+kVar)

  = 100 + 75j (kW+kVar)

= residential area = 85 households

= commercial area = 1 small shopping plaza
Test System Characteristic

Charging method and scenario:

- Level 1: 1.3 kW
- Level 2: 3.3 kW
- Level 3: 50 kW

Type 1

- Level 1: 75%
- Level 2: 25%

Type 2a (charge at residential area)

- Level 1: 85%
- Level 2: 15%

Type 2b (charge at commercial area)

- Level 1: 60%
- Level 2: 30%
- Level 3: 10%
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Test Result: Voltage Violation

Voltage Profile

- Voltage should operate ±0.05 p.u.
- Voltages at the End Buses have higher chance to suffer low voltage violation
Test Result: Voltage Violation

Voltage profile confidence interval at bus 16

- 0% Penetration
- 30% Penetration
- 50% Penetration
- 100% Penetration
Test Result: Voltage Violation

Voltage distribution for 0% Penetration Scenario

- Bus: 5
  - Mean voltage: 0.98 p.u.
  - Violation: 0%
  - 5% limit

- Bus: 11
  - Mean voltage: 0.97 p.u.
  - Violation: 0%
  - 5% limit

- Bus: 16
  - Mean voltage: 0.97 p.u.
  - Violation: 0%
  - 5% limit

- Bus: 23
  - Mean voltage: 0.98 p.u.
  - Violation: 0%
  - 5% limit
Test Result: Voltage Violation

Voltage distribution for 50% Penetration Scenario

Bus: 5
- Mean voltage: 0.98 p.u.
- Violation: 0%
- -5% limit

Bus: 11
- Mean voltage: 0.97 p.u.
- Violation: 0.33%
- -5% limit

Bus: 16
- Mean voltage: 0.96 p.u.
- Violation: 9.7%
- -5% limit

Bus: 23
- Mean voltage: 0.98 p.u.
- Violation: 0%
- -5% limit
Test Result: Voltage Violation

Voltage distribution for 100% Penetration Scenario

Bus: 5
Mean voltage: 0.97 p.u. Violation: 0%
-5% limit

Bus: 11
Mean voltage: 0.96 p.u. Violation: 19%
-5% limit

Bus: 16
Mean voltage: 0.96 p.u. Violation: 29%
-5% limit

Bus: 23
Mean voltage: 0.98 p.u. Violation: 0%
-5% limit
Test Result: Transformer Load

- Although transforms usually can be overloaded for short period of time with limited amount, overloading it by too much or too long will decrease its life time
- Transformer overloaded: loaded above its capacity
- Transformer violation: loaded 20% above its capacity
Test Result: Transformer Load

Transformer load profile

Transformer load distribution

- Transformer load profile
  - 100% of rated power
  - 30% of rated power
  - 20% above rated power
  - 0% of rated power

- Transformer load distribution
  - Probability distribution for different load levels (50%, 70%, 50%, 30%, 10%)
  - Average and Penetration levels indicated for each load level
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Conclusion

• Electricity for transportation? Yes or No?
• PEVs impacts vary from system to system
  – Voltage violation: long radial networks
  – Substation transformer violation: Heavy load, high PEV penetration
• A tool to evaluate PEVs impacts is developed
Thank you!