Electric Vehicles Aggregator/System Operator Coordination for Optimal Charging Scheduling and Services Procurement

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Introduction

• Decarbonisation of the transportation sector:
  – Electricity as energy carrier
  – Ideally, energy from RES
  – Large fleets of EVs will constitute a significant share of the wide system demand

• Advent of the Smart Grid
  – Demand will feature higher degrees of communication and control
Electric vehicles (EVs)

- Unlike most existing loads, EVs are equipped with a battery:
  - Waive their energy requirements in time
  - Energy storage
  - Provide ancillary services, e.g. reserve
Impacts

• The pliant nature of the EVs as demand makes them good candidates to impact the system:
  
  – Technically: provide *flexibility* to the system
  
  – Economically: trading that *flexibility*
EVs operating modes

- Vehicle charging
- Vehicle discharging (V2G)
- Vehicle plugged-in
- Vehicle unused
- Vehicle circulating
Power system + EVs

Energy

Co-ordination

Wholesale

Retail

Aggregator
Aggregator

• Bridge between EVs and power system players:

\[ g_T(x, u, p) \leq 0 \]

\[ g_D(x, u, p) \leq 0 \]
Interaction Aggregator & SO

• **Generation scheduling**
  - Minimize total operating costs
    - Power balance constraint (including EVs’ charge and discharge)
    - Security: system reserve requirements (unforeseen events)
    - Units technical operating constraints:
      - Minimum up- and down-times
      - Up and down ramp rate limits

• **EVs scheduling**
  - Sell flexibility services to the system
    - EVs’ energy requirements
    - EVs operating constraints:
      - State of charge
      - Charging and discharging rates
From day-ahead to real-time

- Schedules are performed a day-ahead on the basis of:
  - Wind power generation forecast
  - Demand forecast
  - Forecasted EVs availabilities

- Deviations between forecasts and actual values materialize in real-time
  - Conventional generation deployment to meet net demand deviations
  - Deployment of EVs’ flexibility services as a function of the agreed prices the day before
Test system

• IEEE-RTS omitting hydro generation
  – 26 Units, 3105 MW installed

<table>
<thead>
<tr>
<th>Group</th>
<th># Units</th>
<th>Capacity (MW)</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5</td>
<td>12</td>
<td>oil/steam</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>20</td>
<td>oil/CT</td>
</tr>
<tr>
<td>C</td>
<td>4</td>
<td>76</td>
<td>coal/steam</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>100</td>
<td>oil/steam</td>
</tr>
<tr>
<td>E</td>
<td>4</td>
<td>155</td>
<td>coal/steam</td>
</tr>
<tr>
<td>F</td>
<td>3</td>
<td>197</td>
<td>oil/steam</td>
</tr>
<tr>
<td>G</td>
<td>1</td>
<td>350</td>
<td>oil/steam</td>
</tr>
<tr>
<td>H</td>
<td>2</td>
<td>400</td>
<td>nuclear</td>
</tr>
</tbody>
</table>

Cost functions

Composition

Price, $/MWh

Power, MW

Power Reserve

Time, hrs

EVs, %

Market Clearing at Period 20
Demand and wind profiles

• Forecasted and actual values...
## EVs’ characteristics

<table>
<thead>
<tr>
<th>EV parameter</th>
<th>BEV</th>
<th>City-BEV</th>
<th>PHEV</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV fleet composition (%)</td>
<td>37</td>
<td>10</td>
<td>53</td>
<td>100</td>
</tr>
<tr>
<td>Battery capacity (kWh)</td>
<td>35</td>
<td>16</td>
<td>18</td>
<td>24.1</td>
</tr>
<tr>
<td>Energy consumption (kWh/km)</td>
<td>0.2</td>
<td>0.12</td>
<td>0.2</td>
<td>0.192</td>
</tr>
<tr>
<td>EV range (km)</td>
<td>175</td>
<td>133</td>
<td>90</td>
<td>125.5</td>
</tr>
<tr>
<td>Average distance (km/day)</td>
<td></td>
<td></td>
<td></td>
<td>40.0</td>
</tr>
<tr>
<td>Daily consumption (kWh/day)</td>
<td></td>
<td></td>
<td></td>
<td>7.68</td>
</tr>
<tr>
<td>Charge/discharge rate (kW/h)</td>
<td></td>
<td></td>
<td></td>
<td>3.70</td>
</tr>
<tr>
<td>Total number of vehicles</td>
<td></td>
<td></td>
<td></td>
<td>689,475</td>
</tr>
</tbody>
</table>

### Graphs

<table>
<thead>
<tr>
<th>Graph</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>EVs, % over time, hrs</td>
</tr>
<tr>
<td>b)</td>
<td>EVs, % over time, hrs</td>
</tr>
</tbody>
</table>
System with no EVs

a) actual $\ell^t$ and $w^t$  
forecasted $\ell^t$ and $w^t$

b) residual  
$\sum_i p^t_i$  
$w^t$  
c $a^t$  
$P^t_{V2G}$  
$\eta_D$

c) $K^t_{up} + Q^t_{up} + \sum_i \tau^t_i$  
$\sum_i \tau^t_i$  
$K^t_{up} + Q^t_{up}$  
deployed

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Uncontrolled EVs – 30% penetration

a) $$/MWh

b) demand, MW

c) SR, MW

d) Unused, %

e) $$/MWh

f) $$/MWh

g) $$/MWh

h) $$/MWh

i) $$/MWh

j) $$/MWh

k) $$/MWh

l) $$/MWh

m) $$/MWh

n) $$/MWh

o) $$/MWh

p) $$/MWh

q) $$/MWh

r) $$/MWh

s) $$/MWh

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Uncontrolled EVs – 30% penetration

\[ \sum_i p_i^t \left( \begin{array}{c} \text{Miguel Ortega-Vazquez} \\
\text{Electrical Engineering} \\
\text{UNIVERSITY of WASHINGTON} \end{array} \right) \]
Effect of the EVs’ penetration

Optimized

Uncontrolled

Effect of the EVs’ penetration.

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Effect of the V2G markup

- Actual $\ell^t$ and $w^t$ vs. forecasted $\ell^t$ and $w^t$

- Residual, $\sum_i p_i^t$, $w^t$, $c \alpha^t$, $P_{V2G}^t$, $\eta_D$

- $K_{up}^t + Q_{up}^t + \sum_i r_i^t$, $\sum_i r_i^t$, $K_{up}^t + Q_{up}^t$, deployed

- $S^t$, $S_{min}$, $S^t + c$, $S^t - d$, $B$

- Injected in V2G, Discharging losses
Effect of the pricing of the reserve from EVs

- The price of the reserve from the supply side is 20% of the bids of energy
- Reserve from EVs at 2 $/MW
Reducing the exercise price for reserve deployment

- Price of the reserve from the supply side at 30% of the bids of energy
- Reserve from EVs at 2 $/MW
- Exercise price at 5 $/MWh
Summary

• Presented the necessary adaptations to a typical US-style short-term forward electricity markets including EVs fleet aggregators
• The operating constraints of the EVs are explicitly modeled
• Represents adequately the collective operation of the EVs to attain benefits while reducing operating costs
• Several ancillary services and their deployment are represented: V2G, Reserve capacity as additional charge and interruption of scheduled charging/discharging
Conclusions

• If no coordination is implemented, only a limited amount of EVs can be successfully integrated in the system

• Implementing an approach such as the proposed, allows the integration of large volumes of EVs without needing to invest in generation assets

• The participation of the aggregator(s) as service providers determined by the services bids
Conclusions

• Charging process is scheduled at the cheapest periods
• Services from EVs are scheduled only if these are competitive with those from conventional sources
• V2G is attractive to avoid synchronization of expensive generation
• Reserve is in the form of interruption of charging is attractive, but it can only be offered when EVs are charging → light loads…
• Reserve as additional charge are attractive, but only when their supply equivalent is expensive