Non-Intrusive Load Monitoring for Demand Response in Future Power Grid

Weicong Kong
Supervisors: Prof. Z.Y. Dong, Prof. David Hill and Dr. Jin Ma
School of Electrical and Information Engineering

Introduction
Background
- Global ambition of integrating renewable energy sources (RES) into energy consumption sector
- Challenges of RES intermittent nature such as power balancing and stability are prominent
- Demand Response (DR) is one of the most proposed solutions to accommodate higher RES penetration
- Lack of accurate load models which can describe the DR potential of DR program participants

Summary
- We investigate the feasibility of modelling and assessing DR potential for residential electricity customers by using current smart meter infrastructure
- We also demonstrate how to model home appliances with Hidden Markov Model (HMM) and fit the HMM by using kmeans algorithm
- Finally, promising results of appliance identification by merely providing (1Hz Smapling) aggregate load profile with learned HMMs are shown.

Case Study
Disaggregate Load Profile with 7 Major Home appliances
- 7 major home appliance load profiles including air-conditioner, dishwasher, clothes dryer, oven, refrigerator, clothes washer and water heater are included [1]
- Kmeans algorithm is applied to learn the hidden Markov model of each appliance
- Randomly construct a sequence of total household power consumption reading using domestic load profile generator [2]
- Apply approximate inference to find the appliance operation sequence which best explain the sequence of reading observation (maximum likelihood).

Results
- Comparison diagram below shows that NILM estimated successfully identifies most appliance operations and even simultaneous operations
- Comparison diagram on the right shows the energy breakdown from the NILM. Even there are minor mis-classification to non-operated appliances, the percentages of energy consumption for individual appliances are closed to real values.

Demand Response for Future Grid
Utilising Smart Meters To Evaluate Real-time Demand Response Potential
- Smart meters provide half hourly readings of total household electricity consumption
- Different appliances have different potential to participate in demand response programs. E.g., air conditioners have greater potential than electric stoves
- Can we assess real-time total demand response potential by utilising Advanced Metering Infrastructure (AMI)?

Modelling NILM
Hidden Markov Model
- Each appliance can be modelled as a Hidden Markov Model with k hidden states
- Using a dishwasher load profile as an example, we can represent a dishwasher’s load profile as a hidden Markov model with 4 states (piecewise constants) by running kmeans algorithm

<table>
<thead>
<tr>
<th>NILM Percentage of Energy Consumption</th>
<th>Original Percentage of Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing-machine (W)</td>
<td>39%</td>
</tr>
<tr>
<td>Dishwasher (D)</td>
<td>34%</td>
</tr>
<tr>
<td>Iron (I)</td>
<td>11%</td>
</tr>
<tr>
<td>Oven (O)</td>
<td>6%</td>
</tr>
<tr>
<td>Air-conditioner (A)</td>
<td>3%</td>
</tr>
</tbody>
</table>

Identifying DR Potential
- The answer is true: we can use prior knowledge of appliance load profiles to identify whether high DR potential appliances are in operation from the aggregate total load profile. This solution is also known as Non-Intrusive Load Monitoring (NILM).

Factors included in HMM
- HMMs employed to predict appliance load profile from NILM data
- Each appliance is modelled as a HMM

Z1 = 5W, Z2 = 249W, Z3 = 588W, Z4 = 1141W
(Fore simplicity, only the probabilities of remaining the same state at the next time step are shown.)

- With that, a sequence of power readings for an appliance can be represented by a Hidden Markov Model like:

Considering there are N appliances at a household, and we only have observation of a sequence of aggregate power consumption readings, the NILM problem can be represented as a Factorial Hidden Markov Model as shown below:

<table>
<thead>
<tr>
<th>State</th>
<th>Hidden Markov Model</th>
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<tbody>
<tr>
<td>S1</td>
<td>0.9944</td>
</tr>
<tr>
<td>S2</td>
<td>0.9934</td>
</tr>
<tr>
<td>S3</td>
<td>0.9961</td>
</tr>
<tr>
<td>S4</td>
<td>0.9966</td>
</tr>
</tbody>
</table>