Leveraging Consumers’ Flexibility for the Provision of Ancillary Services

Giulia De Zotti
Agenda

- Introduction
- Key concepts in smart power systems
- Consumers’ flexibility for services provision
- Unlocking consumers’ flexibility potential: an innovative framework
- Concluding remarks
Introduction

Context and motivation

Power system operation in the past

- Conventional generation units
- Passive consumers

Almost predictable and controllable

Transmission (high voltage)  Distribution (medium voltage)  Distribution (low voltage)
Introduction
Context and motivation

Power system operation today
- Renewable energy sources
- Active and dynamic consumers

Stochastic and less controllable

Transmission (high voltage) Distribution (medium voltage) Distribution (low voltage)
Introduction
Context and motivation

Challenges for the power system operation

1. Increasing complexity
   - Stochasticity
   - Non-linearity
   - Dynamics

2. Higher need of stability
   - Higher demand of ancillary services (AS)

3. Uncertainty in AS provision
   - Operating under rated capacity
   - Conventional generation units retirement
   - International targets
     - Denmark: Strategy 2050*

* DEA, 2017
Introduction

Thesis objectives

Objectives

- Green solution for the AS provision
- Role of electrical consumers

Research questions

1. How can we estimate the potential of consumers’ flexibility in providing AS?
2. Which framework can help to optimally exploit consumers’ flexibility for AS provision at different voltage levels?
Introduction

Contributions

Research contributions and papers

1. Consumers’ flexibility potential
   - Aggregate flexibility
   - Stochastic nature of consumers’ behaviour
   - Different consumers’ dynamics

2. Framework to leverage consumers’ flexibility
   - AS4.0 hypothetical design
   - AS4.0 modelling and simulations

Key concepts in smart power systems
Ancillary services (AS) guarantee service continuity and security from the distribution to the transmission level.

- **Primary regulation**: Local automatic, Seconds
- **Secondary regulation**: Centralised automatic, Minutes
- **Tertiary regulation**: Manual, Hours

**Ancillary services provision**

- Compulsory provision
- Bilateral contracts
- Tendering process
- AS spot market
Key concepts in smart power systems
Services provision through demand response

Demand response programs

In demand response (DR), consumers alter their consumption according to the necessity of the grid.
Key concepts in smart power systems
Services provision through demand response

Demand response programs

In **demand response** (DR), **consumers alter their consumption** according to the necessity of the grid.

**Explicit DR program**
- **Two-way communication**
  - Minimised uncertainty
  - Consumers’ privacy

**Implicit DR program**
- **One-way communication**
  - Consumers’ autonomy
  - Proper price signals
How can we estimate the potential of consumers’ flexibility in providing AS?
# Consumers’ flexibility for services provision
## Analysis of the factors influencing consumers’ response

## Consumers’ flexibility potential

<table>
<thead>
<tr>
<th>Assumptions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Different types of</td>
<td>Time varying prices</td>
</tr>
<tr>
<td>consumers</td>
<td></td>
</tr>
<tr>
<td>Rational consumers</td>
<td>One-way communication</td>
</tr>
</tbody>
</table>

- **Cost minimisation**

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**June 2019**

**DTU**
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Consumers’ flexibility potential

Assumptions

- Different types of consumers
- Rational consumers
- Time varying prices
- One-way communication

Cost minimisation

Model

$$\min_{L_{t,j}} \sum_{i=1}^{r} (\lambda^{\text{base}} + \Delta \lambda_{t}^{u} + \Delta \lambda_{t}^{d}) \sum_{j=1}^{J} (L_{t,j}^{\text{base}} + L_{t,j}^{d} - L_{t,j}^{u})$$
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Consumers’ flexibility potential

Assumptions
- Different types of consumers
- Rational consumers
- Time varying prices
- One-way communication

Cost minimisation
Comfort

Technical constraints
1. Ramping
2. Rebound
3. Activation
4. Flex duration

Model
\[
\min_{L_{t,j}} \sum_{t=1}^{T} (\lambda_{t}^{\text{base}} + \Delta \lambda_{t}^{u} + \Delta \lambda_{t}^{d}) \sum_{j=1}^{J} (L_{t,j}^{\text{base}} + L_{t,j}^{u} - L_{t,j}^{d})
\]
Consumers’ flexibility for services provision
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4. Flex duration

Model

\[
\min_{L_{t,j}} \sum_{t=1}^{T} (\lambda_{t,j}^{\text{base}} + \Delta \lambda_{t}^{u} + \Delta \lambda_{t}^{d}) \sum_{j=1}^{J} \left( L_{t,j}^{\text{base}} + L_{t,j}^{d} - L_{t,j}^{u} \right)
\]

s.t.
- \(-r_{j}^{\alpha} \leq L_{t+1,j}^{\alpha} - L_{t,j}^{\alpha} \leq r_{j}^{\alpha} \quad \forall t, j, \alpha\)
- \(0 \leq L_{t,j}^{d} \leq u_{t,j}^{d} (L_{t,j}^{\max} - L_{t,j}^{\text{base}}) a_{t,j}^{d} \quad \forall t, j\)
- \(0 \leq L_{t,j}^{u} \leq u_{t,j}^{u} (L_{t,j}^{\text{base}} - L_{t,j}^{\min}) a_{t,j}^{u} \quad \forall t, j\)
- \((t-1)R_{j} + R_{j} \sum_{t'=(t-1)R_{j}+1}^{(t+1)R_{j}} (L_{t',j}^{d} - L_{t',j}^{u}) = 0 \quad \forall t : [t \in T, (tR_{j} \leq \tau)], j\)
- \(u_{t,j}^{d} + u_{t,j}^{u} \leq 1 \quad \forall t, j\)
- \(y_{t,j}^{\alpha} - z_{t,j}^{\alpha} = u_{t,j}^{\alpha} - u_{t-1,j}^{\alpha} \quad \forall t, j, \alpha\)
- \(y_{t,j}^{\alpha} + z_{t,j}^{\alpha} \leq 1 \quad \forall t, j, \alpha\)
- \(\sum_{t=1}^{T} y_{t,j}^{\alpha} \leq n_{j}^{\alpha} \quad \forall j, \alpha\)
- \(\sum_{t'=t}^{t+R_{j}} u_{t',j}^{\alpha} \geq d_{j}^{\alpha} y_{t,j}^{\alpha} \quad \forall t : [t \in T, (t + d_{j}^{\alpha} < \tau)], j, \alpha\)
- \(\sum_{t'=t}^{t+R_{j}} z_{t',j}^{\alpha} \geq y_{t,j}^{\alpha} \quad \forall t : [t \in T, (t + d_{j}^{\alpha} < \tau)], j, \alpha\)
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Consumers’ flexibility potential

Assumptions
- Different types of consumers
- Rational consumers
- Time varying prices
- One-way communication

Technical constraints

1. Ramping
   Provision change is limited over time

2. Rebound
3. Activation
4. Flex duration

Model

\[
\begin{align*}
\min_{L_{t,j}^\alpha} & \quad \sum_{t=1}^{\tau} (L_{t,j}^\text{base} + \Delta L_{t,j}^u + \Delta L_{t,j}^d) \\
\text{s.t.} & \quad -r_{j,t}^\alpha \leq L_{t+1,j}^\alpha - L_{t,j}^\alpha \leq r_{j,t}^\alpha \quad \forall t, j, \alpha \\
& \quad 0 \leq L_{t,j}^d \leq u_{t,j}(L_{t,j}^{\text{max}} - L_{t,j}^\text{base}) a_{t,j}^d \quad \forall t, j \\
& \quad 0 \leq L_{t,j}^u \leq u_{t,j}(L_{t,j}^{\text{base}} - L_{t,j}^{\text{min}}) a_{t,j}^u \quad \forall t, j \\
& \quad \sum_{t'(t-1)R_j + 1}^{t-1} (L_{t',j}^d - L_{t',j}^u) = 0 \quad \forall t : [t \in T, (tR_j \leq \tau)], j \\
& \quad u_{t,j}^d + u_{t,j}^u \leq 1 \quad \forall t, j \\
& \quad y_{t,j}^\alpha - z_{t,j}^\alpha = u_{t,j}^\alpha - u_{t-1,j}^\alpha \quad \forall t, j, \alpha \\
& \quad y_{t,j}^\alpha + z_{t,j}^\alpha \leq 1 \quad \forall t, j, \alpha \\
& \quad \sum_{t=1}^{\tau} y_{t,j}^\alpha \leq n_j^\alpha \quad \forall j, \alpha \\
& \quad \sum_{t'=t}^{t+d_j^\alpha} u_{t',j}^\alpha \geq d_j^\alpha y_{t,j}^\alpha \quad \forall t : [t \in T, (t + d_j^\alpha < \tau)], j, \alpha \\
& \quad \sum_{t'=t}^{t+d_j^\alpha} z_{t',j}^\alpha \geq y_{t,j}^\alpha \quad \forall t : [t \in T, (t + d_j^\alpha < \tau)], j, \alpha
\end{align*}
\]
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Consumers’ flexibility potential

Assumptions
- Different types of consumers
- Time varying prices
- Rational consumers
- One-way communication

Technical constraints
1. Ramping
2. Rebound
3. Activation
4. Flex duration

Consumers’ flexibility for services provision

Model
\[
\min_{L_{t,j}^{\alpha}} \sum_{t=1}^{\tau} \left( \lambda_{t,j}^{\text{base}} + \Delta \lambda_{t,j}^{u} + \Delta \lambda_{t,j}^{d} \right) \sum_{j=1}^{J} \left( L_{t,j}^{\text{base}} + L_{t,j}^{d} - L_{t,j}^{u} \right)
\]

s.t.
- \[-r_{j}^{\alpha} \leq L_{t,j}^{\alpha} - L_{t,j}^{\alpha} \leq r_{j}^{\alpha} \quad \forall t, j, \alpha\]
- \[0 \leq L_{t,j}^{d} \leq u_{t,j}^{d} \left( L_{t,j}^{\text{max}} - L_{t,j}^{\text{base}} \right) a_{t,j}^{d} \quad \forall t, j\]
- \[0 \leq L_{t,j}^{u} \leq u_{t,j}^{u} \left( L_{t,j}^{\text{base}} - L_{t,j}^{\text{min}} \right) a_{t,j}^{u} \quad \forall t, j\]
- \[\sum_{\nu=(t-1)R_{j}+1}^{(t-1)R_{j}+R_{j}} \left( L_{\nu,j}^{d} - L_{\nu,j}^{u} \right) = 0 \quad \forall t : \left[ t \in T, (tR_{j} \leq \tau) \right], j\]

- \[u_{t,j}^{d} + u_{t,j}^{u} \leq 1 \quad \forall t, j\]
- \[y_{t,j}^{\alpha} - z_{t,j}^{\alpha} = u_{t,j}^{\alpha} - u_{t-1,j}^{\alpha} \quad \forall t, j, \alpha\]
- \[y_{t,j}^{\alpha} + z_{t,j}^{\alpha} \leq 1 \quad \forall t, j, \alpha\]
- \[\sum_{t=1}^{\tau} y_{t,j}^{\alpha} \leq n_{j}^{\alpha} \quad \forall j, \alpha\]
- \[\sum_{t'=t}^{t+d_{j}^{\alpha}} u_{t',j}^{\alpha} \geq d_{j}^{\alpha} y_{t,j}^{\alpha} \quad \forall t : \left[ t \in T, (t + d_{j}^{\alpha} \leq \tau) \right], j, \alpha\]
- \[\sum_{t'=t}^{t+d_{j}^{\alpha}} z_{t',j}^{\alpha} \geq y_{t,j}^{\alpha} \quad \forall t : \left[ t \in T, (t + d_{j}^{\alpha} \leq \tau) \right], j, \alpha\]
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Consumers’ flexibility potential

Assumptions
- Different types of consumers
- Rational consumers
- Time varying prices
- One-way communication

Cost minimisation
Comfort

Technical constraints
1. Ramping
2. Rebound
3. Activation
4. Flex duration

Amount of times flexibility is activated

Consumers’ flexibility potential

Model

\[
\begin{align*}
\min_{L_{t,j}^\alpha} & \quad \sum_{t=1}^{T} (\lambda_{t,j}^{\text{base}} + \Delta \lambda_{t,j}^{u} + \Delta \lambda_{t,j}^{d}) \sum_{j=1}^{J} (L_{t,j}^{\text{base}} + L_{t,j}^{d} - L_{t,j}^{u}) \\
\text{s.t.} & \quad -r_{t,j}^\alpha \leq L_{t+1,j}^\alpha - L_{t,j}^\alpha \leq r_{t,j}^\alpha \quad \forall t, j, \alpha \\
& \quad 0 \leq L_{t,j}^d \leq u_{t,j}^d (L_{t,j}^{\text{max}} - L_{t,j}^{\text{base}}) a_{t,j}^d \quad \forall t, j \\
& \quad 0 \leq L_{t,j}^u \leq u_{t,j}^u (L_{t,j}^{\text{base}} - L_{t,j}^{\text{min}}) a_{t,j}^u \quad \forall t, j \\
& \quad (t-1)R_j + R_j \sum_{\nu=(t-1)R_j+1}^{(t-1)R_j+R_j} (L_{\nu,j}^d - L_{\nu,j}^u) = 0 \quad \forall t : [t \in T, (tR_j \leq \tau)], j \\
& \quad u_{t,j}^d + u_{t,j}^u \leq 1 \quad \forall t, j \\
& \quad y_{t,j}^\alpha - z_{t,j}^\alpha = u_{t,j}^\alpha - u_{t-1,j}^\alpha \quad \forall t, j, \alpha \\
& \quad y_{t,j}^\alpha + z_{t,j}^\alpha \leq 1 \quad \forall t, j, \alpha \\
& \quad \sum_{t=1}^{T} y_{t,j}^\alpha \leq n_{j}^\alpha \quad \forall j, \alpha \\
& \quad \sum_{\nu=t}^{t+d_j^\alpha} u_{\nu,j}^\alpha \geq d_j^\alpha y_{t,j}^\alpha \quad \forall t : [t \in T, (t + d_j^\alpha \leq \tau)], j, \alpha \\
& \quad \sum_{\nu=t}^{t+d_j^\alpha} z_{\nu,j}^\alpha \geq y_{t,j}^\alpha \quad \forall t : [t \in T, (t + d_j^\alpha \leq \tau)], j, \alpha
\end{align*}
\]
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Consumers’ flexibility potential

Assumptions
- Different types of consumers
- Rational consumers
- Time varying prices
- One-way communication

Technical constraints

1. Ramping
2. Rebound
3. Activation
4. Flex duration

Continuous flexibility duration

Cost minimisation
Comfort

Model

\[
\begin{align*}
\min_{L_{t,j}^\alpha} & \quad \sum_{t=1}^{\tau} \left( \lambda_{t,j}^{\text{base}} + \Delta \lambda_{t,j}^u + \Delta \lambda_{t,j}^r \right) \sum_{j=1}^{J} \left( L_{t,j}^{u^d} + L_{t,j}^{u^u} - L_{t,j}^{u^l} \right) \\
\text{s.t.} & \quad -r_{t,j}^\alpha \leq L_{t+1,j}^\alpha - L_{t,j}^\alpha \leq r_{t,j}^\alpha \quad \forall t,j, \alpha \\
& \quad 0 \leq L_{t,j}^{d} \leq u_{t,j}^{d} (L_{t,j}^{\text{max}} - L_{t,j}^{\text{base}}) a_{t,j}^{d} \quad \forall t,j \\
& \quad 0 \leq L_{t,j}^{u} \leq u_{t,j}^{u} (L_{t,j}^{\text{base}} - L_{t,j}^{\text{min}}) a_{t,j}^{u} \quad \forall t,j \\
& \quad \sum_{t'=t}^{(t-1)R_j+1} (L_{t',j}^{d} - L_{t',j}^{u}) = 0 \quad \forall t : [t \in T, (tR_j < \tau)], j \\
& \quad u_{t,j}^{d} + u_{t,j}^{u} \leq 1 \quad \forall t,j \\
& \quad v_{t,j}^{\alpha} - z_{t,j}^{\alpha} = u_{t,j}^{\alpha} - u_{t-1,j}^{\alpha} \quad \forall t,j, \alpha \\
& \quad v_{t,j}^{\alpha} + z_{t,j}^{\alpha} \leq 1 \quad \forall t,j, \alpha \\
& \quad \sum_{t=1}^{\tau} v_{t,j}^{\alpha} \leq n_{j}^{\alpha} \quad \forall j, \alpha \\
& \quad \sum_{t'=t}^{t+1} \frac{d_{j}^{\alpha}}{t_{j}^{\alpha}} y_{t,j}^{\alpha} \quad \forall t : [t \in T, (t + d_{j}^{\alpha} < \tau)], j, \alpha \\
& \quad \sum_{t'=t}^{t+1} \frac{d_{j}^{\alpha}}{t_{j}^{\alpha}} z_{t,j}^{\alpha} \geq y_{t,j}^{\alpha} \quad \forall t : [t \in T, (t + d_{j}^{\alpha} < \tau)], j, \alpha
\end{align*}
\]
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Consumers’ flexibility potential

Assumptions

- Different types of consumers
- Rational consumers
- Time varying prices
- One-way communication

Technical constraints

1. Ramping
2. Rebound
3. Activation
4. Flex duration

Analyses

1. Consumers’ price responsiveness
2. Rebound effect
3. Outdoor temperature
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

1 Consumers’ price responsiveness

Willingness to change consumption for different prices
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

1 Consumers’ price responsiveness

Willingness to change consumption for different prices
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

1. Consumers’ price responsiveness
Consumers’ flexibility for services provision

Analysis of the factors influencing consumers’ response

 Consumers’ price responsiveness

\[ 0 \leq L_{t,j}^d \leq u_{t,j}^d \left( L_{t,j}^{\text{max}} - L_{t,j}^{\text{base}} \right) a_{t,j}^d \quad \forall t, j \]

\[ 0 \leq L_{t,j}^u \leq u_{t,j}^u \left( L_{t,j}^{\text{base}} - L_{t,j}^{\text{min}} \right) a_{t,j}^u \quad \forall t, j \]
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

**1. Consumers’ price responsiveness**

Not the same reaction toward prices.
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

1. Consumers’ price responsiveness

\[ 0 \leq L^d_{t,j} \leq u^d_{t,j} \left( L_{t,j}^{\text{max}} - L_{t,j}^{\text{base}} \right) a^d_{t,j} \quad \forall t, j \]

\[ 0 \leq L^u_{t,j} \leq u^u_{t,j} \left( L_{t,j}^{\text{base}} - L_{t,j}^{\text{min}} \right) a^u_{t,j} \quad \forall t, j \]

Not the same reaction toward prices.
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

\[
\begin{align*}
\text{min}_x & \quad c^T x \\
\text{subject to:} & \quad Ax \leq b \\
& \quad x \geq 0
\end{align*}
\]

\[
Pr \left( Ax \leq b \right) \geq \beta
\]

Confidence level
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Simulations results

- **Conservative CC case** ($\beta=0.95$) and **high-risk CC case** ($\beta=0.50$)
- 29 different **consumers’ categories**
- Maximum load consumption: **3.85 GWh**
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Simulations results

- Conservative CC case ($\beta=0.95$) and high-risk CC case ($\beta=0.50$)
- 29 different consumers’ categories
- Maximum load consumption: 3.85 GWh

<table>
<thead>
<tr>
<th>Study case</th>
<th>Regulation (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>95 %</td>
<td>0.719</td>
</tr>
<tr>
<td>50 %</td>
<td>0.243</td>
</tr>
<tr>
<td>Difference</td>
<td>-66 %</td>
</tr>
</tbody>
</table>

Finding

The choice of the confidence level significantly affects the flexibility estimation.
The actual confidence level is always higher than the theoretical counterpart.
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

2 Rebound effect (RE)

Perfect rebound
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

2 Rebound effect (RE)

Perfect rebound

Maximum RE duration

Flexibility

Time

Specific time intervals

$R_j$

$\ell_{t,j}$

Time, $t$

Flexibility

Static RE
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Rebound effect (RE)

- Maximum RE duration
- Flexibility
- Time

Perfect rebound

Specific time intervals

Flexibility, $L_{t,j}$

Time, $t$

$R_j$

5

10

Static RE
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

2 Rebound effect (RE)

Perfect rebound

Maximum RE duration

Flexibility, $L_{t,j}^\alpha$

Time, $t$

Static RE

Dynamic RE

Specific time intervals

Maximum RE duration

RE completed

$R_j$

Consumers’ flexibility for services provision
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

2
Rebound effect (RE)

Maximum RE duration

Perfect rebound

Static RE

Dynamic RE

Time, $t$

Flexibility, $L_{t,j}$

$R_j$

Specific time intervals

Maximum 1 hour

RE completed

Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

2
Rebound effect (RE)

Perfect rebound

Maximum RE duration

Flexibility, $L_{t,j}$

Time, $t$

Static RE

Dynamic RE

Maximum RE duration

Specific time intervals

RE completed
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Simulations and results

- Conservative CC case
- 29 different consumers’ categories
- Two days simulations
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Simulations and results

- Conservative CC case
- 29 different consumers’ categories
- Two days simulations

<table>
<thead>
<tr>
<th>Study case</th>
<th>Regulation (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static rebound</td>
<td>600</td>
</tr>
<tr>
<td>Dynamic rebound</td>
<td>874</td>
</tr>
<tr>
<td>Difference</td>
<td>45 %</td>
</tr>
</tbody>
</table>

Finding

It is fundamental for operators to understand which RE dynamics are most likely to happen on the consumers’ side.
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Outdoor temperature

The price responsiveness is multiplied by a correcting parameter.
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Outdoor temperature

The price responsiveness is multiplied by a correcting parameter.

Case study

- Summer season
  - Case I = 1
  - Case II = 1.1
  - Case III = 0.9
Consumers’ flexibility for services provision
Analysis of the factors influencing consumers’ response

Outdoor temperature

The price responsiveness is multiplied by a correcting parameter.

Case study
- Summer season
  Case I = 1
  Case II = 1.1
  Case III = 0.9

- Static and dynamic RE models
- Conservative CC case

Finding
Operators might account for weather conditions in estimating consumers’ flexibility provision.
Unlocking consumers’ flexibility potential

Which framework can help to optimally exploit consumers’ flexibility for AS provision at different voltage levels?
Unlocking consumers’ flexibility potential
General framework for AS provision
Unlocking consumers’ flexibility potential
General framework for AS provision
Unlocking consumers’ flexibility potential
General framework for AS provision

AS4.0: core idea

Power system operators

Electricity consumers

Requirements

- Dynamics
- Non-linearity
- Stochasticity
- Services at TSO and DSO
- Fast
- Cost effective
- Consumers’ autonomy and privacy
- Scalable

1. Time varying prices
2. Adoption of controllers
3. One-way communication

Introduction
Ancillary services
Consumers’ flexibility
AS4.0
Conclusions
Unlocking consumers’ flexibility potential
General framework for AS provision

AS4.0: core idea

Power system operators

Electricity consumers

Requirements

- Dynamics
- Non linearity
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- Services at TSO and DSO
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1. Time varying prices

2. Adoption of controllers

3. One-way communication
Unlocking consumers’ flexibility potential
General framework for AS provision

AS4.0: core idea

Power system operators

Electricity consumers

Requirements

- Dynamics
- Non linearity
- Stochasticity
- Services at TSO and DSO
- Fast
- Cost effective
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1. Time varying prices
2. Adoption of controllers
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Unlocking consumers’ flexibility potential

General framework for AS provision

AS4.0: core idea

Power system operators

Electricity consumers

Requirements

Dynamics
Non linearity
Stochasticity
Services at TSO and DSO
Fast
Cost effective
Consumers’ autonomy and privacy
Scalable

1. Time varying prices
2. Adoption of controllers
3. One-way communication
Unlocking consumers’ flexibility potential
General framework for AS provision

Required models for AS4.0

Three types of models are needed to formulate AS4.0.
Unlocking consumers’ flexibility potential
General framework for AS provision

Required models for AS4.0

Three types of models are needed to formulate AS4.0.

Introduction

Consumers’ flexibility

ANCILLARY SERVICES

AS4.0

CONCLUSIONS

Consumers’ price response model

Consumers’ effective flexibility response

Distribution system control model

Transmission system control model

External power disturbance

Models

Effect on frequency/voltage

Needed flexibility
Unlocking consumers’ flexibility potential

General framework for AS provision

**Required models for AS4.0**

Three types of **models** are needed to formulate AS4.0.

1. **Power system control models**
   - Effect on frequency/voltage
   - Needed flexibility

2. **Consumers’ price response models**
   - Consumers’ responsiveness toward prices
   - Proper price signals

**Introduction**

**Consumers’ flexibility**

**Ancillary services**

**AS4.0**

**Conclusions**

**Consumers’ price response models**

**Unlocking consumers’ flexibility potential**
Unlocking consumers’ flexibility potential
General framework for AS provision

Required models for AS4.0

Three types of models are needed to formulate AS4.0.

1. Power system control models
   - Effect on frequency/voltage
   - Needed flexibility

2. Consumers’ price response models
   - Consumers’ responsiveness toward prices
   - Proper price signals

3. Effective flexibility response models
   - Actual consumers’ behaviour
   - Achieved flexibility
Unlocking consumers’ flexibility potential
General framework for AS provision

Power system control models

- Transmission system control model
- Distribution system control model
- Consumers’ price response model
- Consumers’ effective flexibility response

External power disturbance

 models

Transmission system

Distribution system

Consumers’ flexibility

Conclusions

AS4.0

Consumers’ flexibility

Ancillary services

Introduction

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Unlocking consumers’ flexibility potential
General framework for AS provision

Power system control models

- Load frequency controller (LFC)
- Transmission system
- Power exchange
- Power flow (PF)
- Distribution system
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Power system control models

At the transmission level

Two-area LFC

Study cases:
- Conventional generation units
- AS4.0

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Power system control models

At the transmission level

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Study cases:
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At the distribution level

Consumers' flexibility
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Aggregate consumers’ price response
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Aggregate consumers’ price response

Time varying price formulation

Introduction

Ancillary services

Consumers’ flexibility

AS4.0

Conclusions
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Aggregate consumers’ price response

Data can be used to model consumers’ reaction toward prices.
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Due to data scarcity, models are adopted.

Different models at transmission and distribution levels:

- Size
- Consumers’ composition
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Different models at transmission and distribution levels:
- Size
- Consumers’ composition

At the transmission level

Frequency is not a local issue

Aggregate consumers’ flexibility

1. Model
   - Consumers’ composition
   - Time varying prices
   - Cost minimisation

2. Montecarlo simulation
   - Aggregate flexibility

3. Neural network
   - Time varying prices
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At the transmission level

**Frequency is not a local issue**

- **Model**
- **Montecarlo simulation**
- **Neural network**

**Aggregate consumers’ flexibility**
- Consumers’ composition
- Time varying prices
- Cost minimisation
- Aggregate flexibility
- Time varying prices

At the distribution level

**Voltage is a local issue**

Flexibility at each **DSO bus**

To make it scalable, we cluster DSO buses

- **Model**
- **PI controller**

- Electricity price
- Consumers’ willingness
- Voltage deviation
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Simulations results

Frequency at the transmission level

AS4.0 reduces the frequency deviation by around 50% compared to the conventional method.

<table>
<thead>
<tr>
<th>Time and disturbance injected, (sec, MW)</th>
<th>Maximum frequency deviation, Hz</th>
<th>Deviation reduction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGUs-based AS</td>
<td>AS4.0</td>
<td></td>
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<tr>
<td>[1, 1000]</td>
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<td>0.06</td>
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<tr>
<td>[150, 1000]</td>
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<tr>
<td>[210, 1056]</td>
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<td>-0.11</td>
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<tr>
<td>[240, 1500]</td>
<td>0.12</td>
<td>0.07</td>
</tr>
</tbody>
</table>
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**Simulations results**

**Voltage at the distribution level**

AS4.0 manages to **mitigate** the **voltage** issues at the DSO buses.

**Operational issues at TSO and DSO levels**

The **number of buses** with voltage issues **decreases** over time.
Concluding remarks
Concluding remarks
Conclusions and perspectives for future work

Conclusions

A new approach to AS provision based on:

- time varying electricity prices
- one-way communication
- control techniques

It successfully handled the operational issues at TSO and DSO level

Better performance than the conventional generation units-based method

Perspectives for future work

1. Including additional factors that influence the price responsiveness of consumers (such as type of day, household income, on-site generation and storage)

2. Modelling power system operation in a more realistic manner.

3. Collecting high resolution data of consumers’ price-responsiveness.
Thank you!