Distributed Generation
Predictive Control of Energy Storage
Renewable Integration
Dispatch and control of micro-grids: a multi-time-scale optimization

- Background (MAS vs. MPC)
- Hierarchical MPC Methodology
- GRID-MEND Interface
- Results
Control Design

responsive

Simple

PID

predictive

Complex

MAS

MPC

Optimal

Robust
» Market Mechanisms: tasks are matched to agents by generalised agreement
» Multi-agent planning: planning agents have the responsibility for task assignment
» Organizational structure: agents have fixed responsibilities for particular tasks

Manager agent

Contractor agent

Task announcement

Bid evaluation

Award message

Task evaluation

Bid message

Contract established

Task performed
Negotiation: a process involving at least two parties aimed at reaching an agreement that is acceptable by the parties involved

Requires:

a) **Negotiation protocol:** a set of rules which govern the interactions of participants

b) **Negotiation Strategy:** a decision making model

Negotiation can be **single-stage** or multi-stage:

1. Bargaining: promising something in exchange for something else
2. Bidding: offering a service or capability at a specific ‘price’
3. Contracting: committing to provide a service or capability at a specific ‘price’
Each unit has its own local controller
> MAS is not replacing PID!!
Each unit has a strategy for bidding a cost for electricity production given its current state
Manager agent requests bids, and coordinates dispatch
Typical layers of communication:

Ontology is extremely important:
> Avoids miscommunication
> Encodes information into smaller packages
> Organized into classes
  + Measurements, requests, limits...

<table>
<thead>
<tr>
<th></th>
<th>Client</th>
<th>Customer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agent 1</td>
<td>anyone who buys products</td>
<td>???</td>
</tr>
<tr>
<td>Agent 2</td>
<td>a computer in the client-server architecture</td>
<td>anyone who buys products</td>
</tr>
</tbody>
</table>
**Strengths:**

- New units can be added or taken off-line with ease
- Can bid both generation and reserve capacity
- Readily incorporates line-losses and congestion constraints
- May be able to respond quickly for grid voltage/frequency control
- Agents can themselves be MPC or other advanced control

**Weaknesses:**

- Under-utilization of energy storage due to shape of bidding curve vs. State-of-Charge
- Competition among players on the same team
- Requires an infinitely responsive grid to compensate for error
- May keep to many generators in operation (stable cost-curves are declining with output, thus 1st unit is cheapest)
Overview of MPC

- **MPC**: Uses a DYNAMIC model to PREDICT the future response of the plant and OPTIMIZE the control signal.

- **Receding Horizon**: solve an optimal control problem over a finite future horizon of $N$ steps, and implement the control action of the 1$^{st}$ step.

Apply 1$^{st}$ step only, then repeat optimization.
An optimal input trajectory is only optimal if it satisfies constraints

- MPC embeds constraints into the optimization
- Most control strategies (e.g. PID, lead-lag) implement constraints as an after thought (saturation, overshoot)

Ex) Filling a tank with a PI control law

- Good speed of response, good settling time...
- Typically allow for 25% overshoot
- What if we are trying to keep the tank full near its maximum constraint?

- Predictive control will **NOT** propose a trajectory which allows the tank to overflow
- Nor will it allow an input that is not **stabilisable** before the constraint is reached
- The rise time might be **slower**, but it will be **safe**
- Works like auto-tuning maximum control input to the current operating point
Challenges for Optimal Control

1. Unknown demand
   > Forecast

2. Unknown schedule
   > Dispatch

3. Uncertainty of demand
   > Robustness

4. Changing system performance
   > Machine Learning
Hierarchical MPC Overview

- Forecast (Load & prices)
- Economic Dispatch (15min)
- On-Line Optimization (<1min)
- Threshold
  - ON
  - OFF
- MPC (<1s)
- LC 1
- LC 2
- LC 3
Multiple Time-Scales

- **Forecast**
  - Temperature
  - Loads
  - Utilities
  - 24 Hours

- **Dispatch**
  - Generators
  - Heaters/Chillers
  - Energy Storage
  - 24 Hours

- **Threshold**
  - Time
  - Demand
  - SOC
  - 15 min to 1 Hour

- **Control**
  - Re-optimize DER
  - Adjust generator set-points
  - Apply MPC
  - 60 Seconds

- **Balance**
  - Distribute un-met load between grid and ES
  - <1 sec

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Step 1: Forecast Temperature

- Average of yesterday’s temperature & historical profile for current season or month
- Avoid Discontinuity: blend current temperature to forecasted temperature over 8 hours
Step 2: forecast loads

- Use 2-D surface fits of historical data (electricity, heating, cooling)
- Use forecasted temperature and time of day to interpolate load
- Apply same technique to average yesterday’s load & the historical load
- Use different 2-D surface for weekdays & weekend/holidays
Step 1) Start with 2 concave cost curves for each generator

> From these concave cost curves we can map the optimal schedule of generator output vs. demand
Step 2) Simultaneously solve for all generators/storage/grid

> Temporarily ignore the lower boundary constraint
> Enforce the ramping constraint
> Give a quadratic value to the final SOC of any storage
> Use Fit A for cost (zero generation = zero cost)

**Feed-forward Approach**

**H-MPC Approach**

**General Solution:** 5 generators @1 hour resolution requires evaluating $1.33\times10^{36}$ QP problems, each with 360 states

**Feed-Forward Solution:** Solve 32 optimizations with 1-5 states at each time step (24 hours = 768 total optimizations)

**H-MPC Solution:** solve 768 QP optimizations with 15 states plus 2 QP optimizations with 360 states.
Step 3.1) Take the generation profile from step 2 (demand + charging/discharging of storage), and treat this as the demand profile.

Step 3.2) Find the optimal generator configuration at each time step (1 step at a time) to produce this amount of generation

- Enforce lower boundary constraints
- Use Fit B for cost (non-zero y-intercept), but test every feasible combination of generators
- Do not enforce ramping constraints

Step 4) Combine the two optimization approaches with some filters to determine a ‘near’ optimal dispatch (on/off) schedule

- Consider both lower bounds & ramping constraints
- Filters include frequency of start-ups, minimum on-line periods, and minimum off-line periods
The cost of using stored energy is zero
The cost of charging energy storage is seen in the cost of the generators

1. The simple energy balance

\[ Generation - \Delta ES = Demand \]
\[ \Delta ES = ES_{t+1} - ES_t \]

2. With charging/discharging inefficiency

\[ Generation - \Delta ES \cdot \eta_- + \varphi \cdot (\eta_+ - 1) = Demand \]  \[ \varphi \geq \Delta ES, \quad \varphi \geq 0 \]
\[ \eta_- = \left( BS_{\text{Voltage}} - BS_{R,\text{discharge}} \cdot \frac{BS_{C,\text{discharge}} \cdot BS_{\text{Capacity}}}{BS_{\text{Voltage}}} \right)/BS_{\text{Voltage}} \leq 1 \]
\[ \eta_+ = BS_{\text{Voltage}}/\left( BS_{\text{Voltage}} + BS_{R,\text{charge}} \cdot \frac{BS_{C,\text{charge}} \cdot BS_{\text{Capacity}}}{BS_{\text{Voltage}}} \right) \geq 1 \]

3. With self-discharge

\[ Generation - \{ES_{t+1} - (1 - \delta)ES_t\} \cdot \eta_- + \varphi \cdot \eta_+ = Demand \]

4. With soft-boundary constraints

> Add costs (quadratic term only) when ES < 10% and when >90%
Summary of Dispatch Features

» **List of attributes**
  > Utilizes quadratic rather than linear cost functions for each generator
  > Determines best use of energy storage by optimizing over time horizon
  > Respects lower operating constraints of generators & start-up costs
  > Computation scales linearly with # of intervals ($t \cdot 2^n$ rather than $2^{n \cdot t}$)

» **Current Functionality**
  > Considers electricity+heat+cooling together
  > Incorporates charging/discharging inefficiencies
  > Incorporates self-discharging (losses) of energy storage

» **Future functionality**
  > Ambient temperature dependence of generator limits/cost
  > Co-production of steam (for steam turbine) or hydrogen
  > Spinning reserve
  > Active/reactive power
  > Transmission constraints & line losses
Multiple Time-Scales

- **Forecast**
  - Temperature
  - Loads
  - Utilities
  - 24 Hours

- **Dispatch**
  - Generators
  - Heaters/Chillers
  - Energy Storage
  - 24 Hours

- **Threshold**
  - Time
  - Demand
  - SOC
  - 15 min to 1 Hour

- **Control**
  - Re-optimize DER
  - Adjust generator set-points
  - Apply MPC
  - 60 Seconds, 1 sec

- **Balance**
  - Distribute un-met load between grid and ES
  - <1 sec
Uncertainty & error in prediction

> Just because your prediction says you should turn a generator on (or off), does not mean you should

> Setting thresholds, upper and lower boundaries, and waiting for the load to pass this threshold before taking action is one way to adjust for errors in prediction

> Thresholds can also be set by time or by SOC for a storage system

Some of this is currently implemented, but robustness of HMPC can still be improved with better determination of thresholds
Every ~60 sec: re-optimize generator output

- Horizon is the time interval of the dispatch (15 min)
- Boundaries for generators determined from dispatch
  + Ex) may need generator #1 to be ramping up continuously
- SOC of storage targets an end condition determined by dispatch (end of 1\textsuperscript{st} dispatch interval)
  + penalties for over or under charging (larger penalty for under charging)
- Send targets to MPC controller

Every ~1 sec: MPC controller sends updated set-point to generators
A. Grid Only
   > Purchase any additional power necessary to balance supply & demand
   > Excess power is dumped onto grid

B. Storage Only
   > Balance demand by charging/discharging storage

C. Grid & Storage
   > Dispatch determines a target amount of charging/discharging for current step
   > If charging:
   > If discharging:

<table>
<thead>
<tr>
<th>Over-production</th>
<th>Under-production</th>
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<tbody>
<tr>
<td>Over-production</td>
<td></td>
</tr>
<tr>
<td>1) Reduce discharging</td>
<td>1) Reduce power sold to grid</td>
</tr>
<tr>
<td>2) Reduce grid purchases</td>
<td>2) Increase grid purchases</td>
</tr>
<tr>
<td>3) Sell power back to grid</td>
<td>3) Discharge more storage</td>
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</tbody>
</table>
Hierarchical MPC Overview

Forecast (Load & prices)

Economic Dispatch (15min)

On-Line Optimization (<1min)

MPC (<1s)

GRID MEND

Threshold

ON

OFF

LC 1

LC 2

LC 3

MPC

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Specifying Generators

SIMO Response

Continuous-Time Model
\[ x' = Ax + Bu \]

| A | 235e-22 -0.0013 |
| B | [0.002229;0.00] |
| C | [1 0 0 0;0] |
| D | [0;0] |

Note: GRID-MEN

[kW]

Values represent normalized output 1 = 100%

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</table>

Add Row | Delete Row | Revert | Finished

% of Capacity

0 0.2 0.4 0.6 1

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» Same idea for electric & gas utilities
» Also can create district heating/cooling utilities
## Solar Power Setup

**Name:** CSP_x3  
**Location:** Vermont  
**Size (kW):** 3  
**Size (m²):** 15.7895  

### Solar Tracking
- **Fixed**  
- **Single Axis**  
- **Dual Axis**

### Solar Type
- **Flat Panel**  
- **Concentrated**

### DC–AC Conversion

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<th>Component</th>
<th>Value</th>
<th>Min</th>
<th>Max</th>
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<td>DC rating</td>
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<td>1.0500</td>
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<tr>
<td>Inverter/Transformer</td>
<td>0.9200</td>
<td>0.8800</td>
<td>0.9800</td>
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<tr>
<td>Mismatch</td>
<td>0.9800</td>
<td>0.9700</td>
<td>0.9950</td>
</tr>
<tr>
<td>Diodes/connection</td>
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<td>DC wiring</td>
<td>0.9800</td>
<td>0.9700</td>
<td>0.9900</td>
</tr>
<tr>
<td>AC wiring</td>
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<td>0.9930</td>
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<tr>
<td>Soiling</td>
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<tr>
<td>System availability</td>
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<td>0.9950</td>
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<tr>
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</table>

### Efficiency

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<th>Value</th>
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<th>Max</th>
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<tbody>
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<td>Charging Efficiency (%)</td>
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</tr>
<tr>
<td>Discharging Efficiency (%)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

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Running a Test

Communicates with LabView to simulate generator response

Uses user-supplied SS model