Operating Reserve Quantification Considering System Uncertainties and Day-ahead Optimal Dispatching of a Microgrid with Active PV Generators

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Part I: Background: Problem, Objective and Methods

Part II: Operating Reserve (OR) Quantification to Cover Uncertainty
1. Power Forecasting with Artificial Neural Networks (ANN)
2. Net Demand Uncertainty Analysis
3. Power Reserve Quantification

Part III: Operating Power Reserve Dispatching Strategies

Part IV: Day-ahead Unit Commitment Problem with Dynamic Programming
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3. Optimization Strategies
4. Application: Case Study and Simulation Results

Part V: A User-friendly EMS and Operational Planning Supervisor

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I. Background: Problem, Objective and Methods

I.1 Problem: Uncertainty and Power Reserve

**Uncertainty**: Intermittent renewable energy sources (RES) power is difficult to predict.

**To cover the risk**: Additional Operating Reserve (OR) is needed.

**Massive RES** increases the uncertainty in power system and OR is mandatory to maintain the system security level.

- Today the consumption/production balancing and OR provision are performed by conventional generators.

![Diagram](image)

- Pref is given by the system operators (power dispatch)

- **Problem**: how to precisely quantify the OR and locate it into the generators, without losing the system security level.
Microgrid supervision can be analyzed and classified in different timing scales and functions.
I. Background: Problem, Objective and Methods

I.3 Objectives and Methods

- Predictive Analysis for Uncertainty: PV power and load forecasting
- Operating Reserve Quantification: Loss of load probability (LOLP)
- OR Dispatching Strategies on Generators
- Day-ahead Optimization Planning: Unit commitment problem with dynamic programming
- A User-friendly EMS and Operational Planning Supervisor

PV Active Generator (PV AG): PV panels combined with a storage system to provide ancillary services.
II. Operating Reserve (OR) Quantification to Cover Uncertainty

II.1 Data Predictive Analysis and Forecasting

- Data management: Collect, Mining, and Predictive Analysis
- PV Power and Load Forecasting with ANN

*PV power forecasting With Artificial Neural Networks (ANN)*

Day ahead Predicted Temperature

\[ \tilde{T}_h, \ldots, \tilde{T}_{h+24} \]

Last 24h sensed irradiance

\[ \tilde{I}_{h-24}, \ldots, \tilde{I}_{h-1} \]

Last 24h sensed PV Power

\[ P_{V_{h-24}}, \ldots, P_{V_{h-1}} \]

PV Forecast

\[ ANN \]

\[ \tilde{P}_{V_h}, \ldots, \tilde{P}_{V_{h+24}} \]

\[ D+1 \]

\[ D \]

Load forecasting with ANN

24h ahead Predicted Temperature

\[ \tilde{T}_h, \ldots, \tilde{T}_{h+24} \]

Last 48h Sensed Load

\[ L_{h-48}, \ldots, L_{h-1} \]

Load Forecast

\[ ANN \]

\[ \tilde{L}_h, \ldots, \tilde{L}_{h+24} \]

\[ D+1 \]

\[ D \]
II. Operating Reserve (OR) Quantification to Cover Uncertainty

II.2 Net Demand (ND) Uncertainty Analysis

- The real ND is composed of the forecasted ND and an error: $ND_h = \tilde{ND}_h + \varepsilon_h^{ND}$
- First Method: Day-ahead Net Demand Errors Forecast;
- Second Method: Calculation from the PV Power and the Load Forecast Errors Estimation.

### Mean average and Standard deviation

- $\mu_h^{ND}$: Mean value
- $\sigma_h^{ND}$: Standard deviation

Equations (8) and (9)

$$\mu_h^{ND} = \mu_h^L - \mu_h^{PV}$$

$$\left(\sigma_h^{ND}\right)^2 = \left(\sigma_h^L\right)^2 + \left(\sigma_h^{PV}\right)^2$$
II. Operating Reserve (OR) Quantification to Cover Uncertainty

II.3 Uncertainty Assessment and Power Reserve Quantification

- ND uncertainty assessment for each ½ hour

$$B = F^{-1}\left(x|\mu^{ND}_h, \sigma^{ND}_h\right) = \left\{B : F\left(B|\mu^{ND}_h, \sigma^{ND}_h\right) = x\right\}$$

$$x = F\left(B|\mu^{ND}_h, \sigma^{ND}_h\right) = \frac{1}{\sigma^{ND}_h \sqrt{2\pi}} \int_{-\infty}^{B} e^{-\frac{(\tau-\mu^{ND}_h)^2}{2(\sigma^{ND}_h)^2}} d\tau$$
II. Operating Reserve (OR) Quantification to Cover Uncertainty

II.4 Operating Power Reserve Quantification

- **Power reserve quantification**

  \[ LOLP = x \% \]

\[ LOLP_h = \text{prob}(L_h - P_h > 0) = \int_{PR}^{+\infty} pdf(\tau) d\tau \]

- **Day-ahead forecasted PV, load and power reserve**

<table>
<thead>
<tr>
<th>Time (half hour)</th>
<th>Forecast PV (kW)</th>
<th>Forecast Load (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8h</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>10h</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>13h</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>16h</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>19h</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>22h</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>1h</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>4h</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>7h</td>
<td>30</td>
<td>60</td>
</tr>
</tbody>
</table>

- **Targets**

  - Day-ahead dynamic power reserve quantification.
III. Operating Power Reserve Dispatching

III. Strategies: OR Provision by MGT and PV AG

- **Strategy 1:** OR on three MGTs only

- **Strategy 2:** OR on three MGTs and thirteen PV AGs

Each PV AGs equally contributed the OR.
IV. Day-ahead Unit Commitment Problem with Dynamic Programming

IV.1 Scheme of Day-ahead Optimal Power Reserve Planning

- Focus on the design of the MCEMS under particular constraints.
- Uint commitment problem (UCP) with dynamic programming (DP) is developed in order to reduce the economic cost and CO₂ equivalent emissions.
IV.2 Non-linear Constraints

- **Security**: Reserve power assessment with $x\%$ of LOLP;

- **Power balancing**: 
  $$\psi(t) = P_L(t) + P_{res}(t) - \sum_{n=1}^{N} P_{AG\_n}(t) - \sum_{i=1}^{M} (\delta_i(t) \cdot P_{MGT\_i}(t)) = 0$$

- **Maximization of renewable energy usage**: considering the battery capacity limitation (more PV power, larger battery storage!)

- **MGT** corresponding inequality constraint: 
  $$50\%P_{M\_\text{max}_i}(t) \leq P_{M\_i}(t) \leq 100\%P_{M\_\text{max}_i}(t)$$
IV. Day-ahead Unit Commitment Problem with Dynamic Programming

IV.3 Unit Commitment Problem (UCP) with Dynamic Programming

- **UCP**: Optimal Operational of a cluster of MGTs (since the PV power is prior source)

  \[ x(t) = [P_{MGT_1}(t), P_{MGT_2}(t), \ldots, P_{MGT_i}(t)] \]

  \[ u(t) = [\delta_1(t), \delta_2(t), \ldots, \delta_i(t)] \]

- **Optimization Objectives**:
  1. Economic criteria: minimize total fuel cost;
  2. Environmental criteria: minimize CO2 emission;
  3. Best compromise criteria: make a compromise.

- **Dynamic Programming (DP)**

  Systematically evaluates a large number of possible decision in a multi-step problem considering the "transition costs".
IV.4 Case Study and Simulation Results (1)

In this case: rated load (110 kW), rated PV power (55 kW) and the OR (with 1% of LOLP) coming from the net demand uncertainty assessment.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Optimized criteria</th>
<th>Cost (€)</th>
<th>Pollution (kg)</th>
<th>OR on AG (%)</th>
<th>E_{battery-Max} (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without PV Power</td>
<td>None</td>
<td>219</td>
<td>1392</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Environmental</td>
<td>212</td>
<td>1196</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Economic</td>
<td>210</td>
<td>1263</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Strategy 1:</td>
<td>None</td>
<td>183</td>
<td>1156</td>
<td>0</td>
<td>80.2</td>
</tr>
<tr>
<td></td>
<td>Environmental</td>
<td>181</td>
<td>1067</td>
<td>0</td>
<td>80.2</td>
</tr>
<tr>
<td></td>
<td>Economic</td>
<td>178</td>
<td>1120</td>
<td>0</td>
<td>80.2</td>
</tr>
<tr>
<td>Strategy 2:</td>
<td>None</td>
<td>182</td>
<td>1098</td>
<td>40</td>
<td>54.1</td>
</tr>
<tr>
<td></td>
<td>Environmental</td>
<td>179</td>
<td>991</td>
<td>40</td>
<td>54.1</td>
</tr>
<tr>
<td></td>
<td>Economic</td>
<td>177</td>
<td>1061</td>
<td>40</td>
<td>54.1</td>
</tr>
</tbody>
</table>

- **Power reserve dispatching, one day ahead**

Without PV power

- MGT1: 39%
- MGT2: 14%
- MGT3: 47%
- AG=0: 10%

Strategy 1

- MGT1: 71%
- MGT2: 10%
- MGT3: 19%

Strategy 2

- MGT1: 40%
- MGT2: 18%
- MGT3: 12%
- AG: 30%

40% of OR is on PV AG!
IV. Day-ahead Unit Commitment Problem with Dynamic Programming

IV.4 Results (2): MGTs Load Ratio and System Security

- **Strategy 1:** OR on MGTs

- **Strategy 2:** OR on MGTs and PV AG
## Strategy 1: OR on MGTs

### Results (3): Battery State of Charge

<table>
<thead>
<tr>
<th>Day</th>
<th>Unit Commitment Problem with Dynamic Programming</th>
</tr>
</thead>
<tbody>
<tr>
<td>8h</td>
<td><img src="image1.png" alt="Graph 1" /></td>
</tr>
<tr>
<td>10h</td>
<td><img src="image2.png" alt="Graph 2" /></td>
</tr>
<tr>
<td>13h</td>
<td><img src="image3.png" alt="Graph 3" /></td>
</tr>
<tr>
<td>16h</td>
<td><img src="image4.png" alt="Graph 4" /></td>
</tr>
<tr>
<td>19h</td>
<td><img src="image5.png" alt="Graph 5" /></td>
</tr>
<tr>
<td>22h</td>
<td><img src="image6.png" alt="Graph 6" /></td>
</tr>
<tr>
<td>1h</td>
<td><img src="image7.png" alt="Graph 7" /></td>
</tr>
<tr>
<td>4h</td>
<td><img src="image8.png" alt="Graph 8" /></td>
</tr>
<tr>
<td>7h</td>
<td><img src="image9.png" alt="Graph 9" /></td>
</tr>
</tbody>
</table>

### Strategy 2: OR on MGTs and PV AG

- **80.2 kWh**
- **54.1 kWh**

### Graphs

- PMGT1 (kW)
- PMGT2 (kW)
- PMGT3 (kW)
- PAG (kW)
Objective: to conceptualize the overall system operation and to provide a complete set of user-friendly GUI to properly model and study the details of PV AG, load demand, and MGTs.
Data Collect and System Uncertainty Analysis

- Historical Data Collect for ANN Training
- Day-ahead Data Download: Weather Information, Load, and PV Power Data
- PV Power and Load Demand Forecast by Using Well Trained ANN

PV Power Uncertainty
- Load Demand Uncertainty
- Net Demand Uncertainty
- OR Quantification

Dispatching Strategies
- PV AGs and MGTs Power References

Real Time Data Obtain:
- Weather Data Download
- Load Data Download
- PV Power Data Download

Forecasting With ANN:
- PV Power Forecasting
- Load Forecasting

Training Results Display Area

Forecasting Results Display Area

System Uncertainties Assessment for OR Quantification

- PV Power Uncertainty
- Load Demand Uncertainty
- Net Demand Uncertainty
- OR Quantification

OR Dispatching Strategies:
- High PV Power Scenario
- Low PV Power Scenario
- OR in MGTs Only
- OR in MGTs and PV AGs

Dispatching Results Display Area

Probabilistic OR Assessment:
- LOLP, EENS
- Risk-constrained OR Calculation

OR Computer:
- x % of LOLP

Uncertainties Display Area: PV Power, Load, and ND (First and second method)

Operational and OR Dispatching

- Initialization
  - Forecasted PV
  - Forecasted Load
  - OR

PV AGs

MGTs

Uncertainty Assessment
- PV Power Uncertainty
- Load Uncertainty

ND Uncertainty Assessment:
- First Method
- Second Method

Optimization Results Display Area

DP for UCP Optimization Criterias:
- None
- Economic
- Environmental
- Best Compromise
V.3 Microgrid Simulator Interface Design with Matlab GUI

Demonstration

Probabilistic Power Reserve Quantification and Dispatching Strategies in a Microgrid Including Active PV Generators

Microgrid integration of a prosumer and micro gas turbines (MGTs)
VI. Conclusion

Conclusions

- PV power variability and load demand variability are analyzed.
- The ANN algorithms are developed for the PV power and the load forecast.
- A probabilistic method for the OR calculation based on two different kind of ND forecasted uncertainty assessment methods is proposed.
- The dynamic joint operational and OR dispatching strategies are developed.
- Day-ahead optimal operational and OR planning with DP is proposed by considering different constraints and different optimization strategies.
- A User-friendly EMS and Operational Planning Supervisor is developed.

Prospects

- “Big data” for distributed RES uncertainty analysis and a better forecasting results
- Optimization method to improve the battery efficiency
- Build a global EMS to incorporate the predicted uncertainty ranges into the scheduling, load following, and into the regulation processes.
Related Publications


Thank you for your attention!