# Reserve Scheduling in AC Power Grids

## In Presence of Uncertain Renewable Power Generation

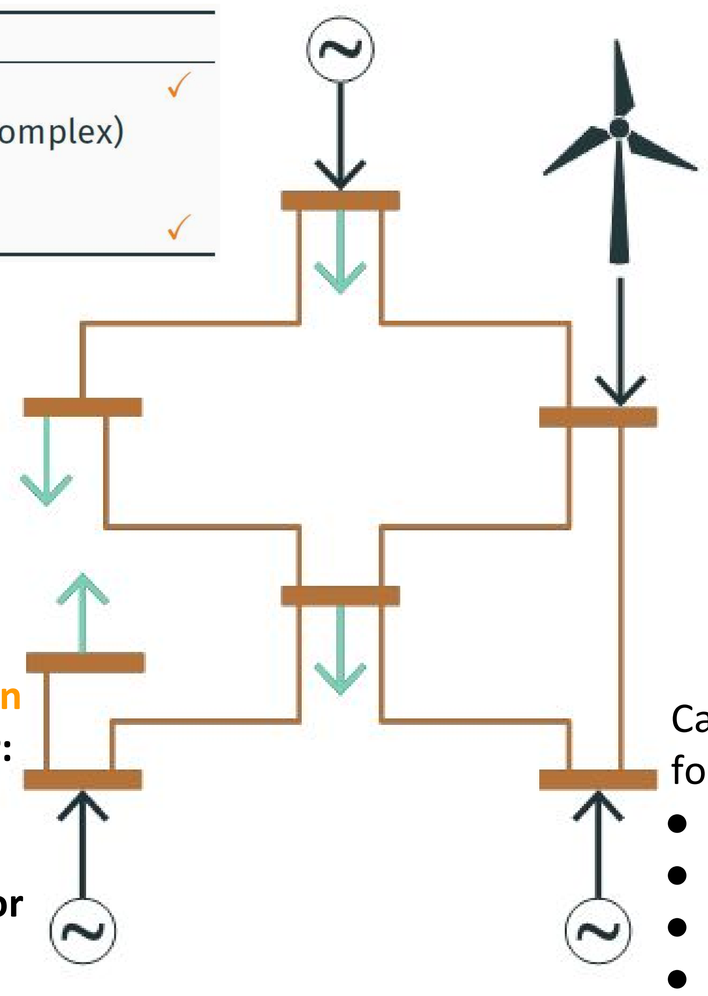
### Modelling Frameworks for Power System Analysis

| DC | | vs | | AC |
|---|---|---|---|---|
| yes | | **assumptions** | | no ✓ |
| ✓ | convex (linear) | **problem type** | | non-convex (complex) |
| ✓ | control input | **decision variable** | | network state |
| | reasonable | **fidelity** | | high ✓ |

- Model power system as network of
  - Buses: generators and loads
  - Lines: cables and transformers
- Cost of generation and operating limits given
- Powerflows represent steady-state behaviour
- Wind power is uncontrollable and uncertain

**In the presence of uncertain wind power generation**

- **Controllable generators providing reserve power:**
  - **Upspinning (less wind power generation)**
  - **Downspinning (more wind power generation)**
  - **Distribution of reserve for Automatic Generator Control**



### Reserve Scheduling (RS) Problem Statement

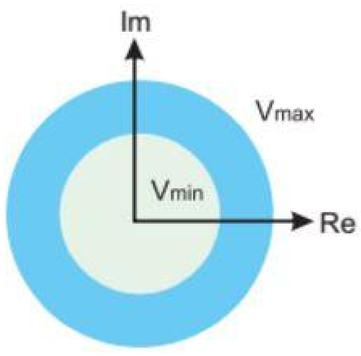
**Find a control strategy** that minimizes the cost of power production while ensuring reliable operation

- Objective is the cost of generated power (quadratic and linear) **and reserve cost (linear)**
- Subject to following constraints:
  - Generation limits
  - Transportation limits
  - Bus limits
  - Demand satisfaction
- **Reserve Scheduling Problem: Finding optimal setting for Automatic Generator Control while ensuring reliable operation**

Can we find a more optimal way to control generators for an AC power grid with uncertain wind power?

- How to incorporate the uncertainty of wind power?
- How to formulate the optimization problem?
- How to solve the resulting optimization?
- How to verify the quality of the solutions?

### AC Modelling for Optimal Power Flow (OPF) Problem



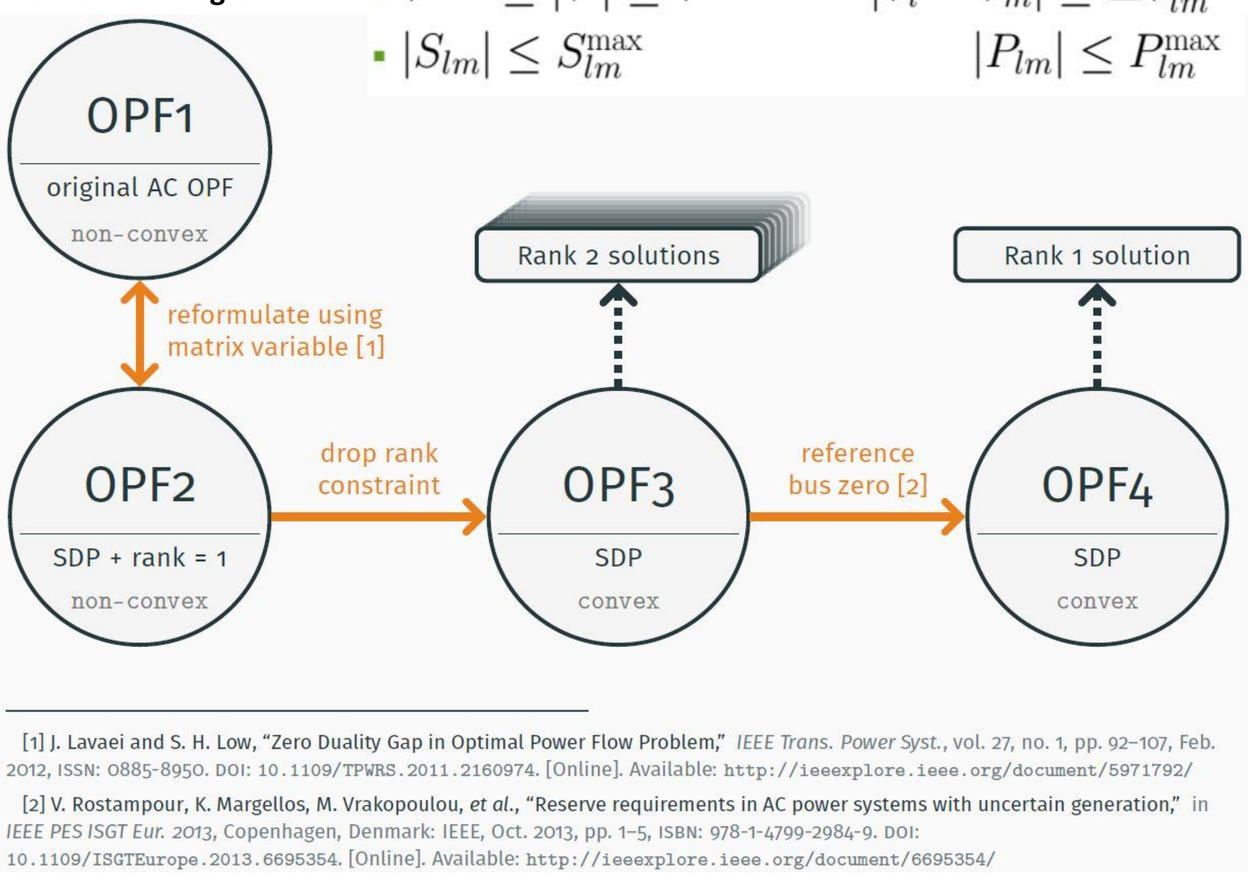

**Decision vector:** $\mathbf{V}_b, \mathbf{P}_g, \mathbf{Q}_g$

**Objective:** $\min_{\mathbf{V},\mathbf{P}_g,\mathbf{Q}_g}$ (sum of production cost)

**Subject to:**

- power balance constraint
- $P^{\min} \le P_g \le P^{\max}$ $\quad Q^{\min} \le Q_g \le Q^{\max}$
- $V^{\min} \le |V| \le V^{\max}$ $\quad |V_l - V_m| \le \Delta V_{lm}^{\max}$
- $|S_{lm}| \le S_{lm}^{\max}$ $\quad |P_{lm}| \le P_{lm}^{\max}$

**Nonconvex Program?**

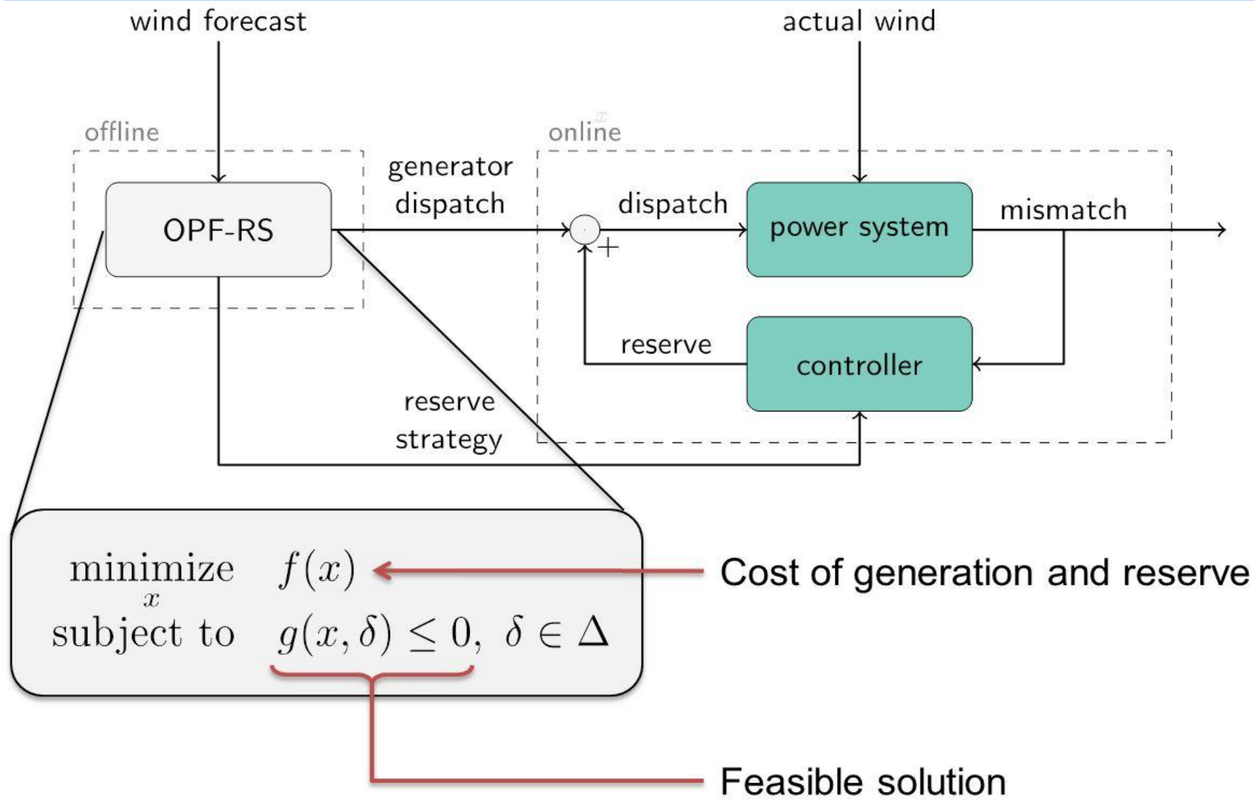




[1] J. Lavaei and S. H. Low, "Zero Duality Gap in Optimal Power Flow Problem," *IEEE Trans. Power Syst.*, vol. 27, no. 1, pp. 92–107, Feb. 2012, ISSN: 0885-8950. DOI: 10.1109/TPWRS.2011.2160974. [Online]. Available: http://ieeexplore.ieee.org/document/5971792/

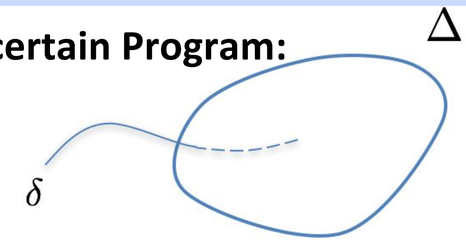
[2] V. Rostampour, K. Margellos, M. Vrakopoulou, *et al.*, "Reserve requirements in AC power systems with uncertain generation," in *IEEE PES ISGT Eur. 2013*, Copenhagen, Denmark: IEEE, Oct. 2013, pp. 1–5, ISBN: 978-1-4799-2984-9. DOI: 10.1109/ISGTEurope.2013.6695354. [Online]. Available: http://ieeexplore.ieee.org/document/6695354/


### Uncertainty in the OPF-RS problem



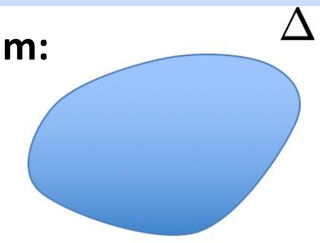

### Dealing With Uncertainty in Large-Scale SDPs

**Uncertain Program:**




$$\begin{aligned} \underset{x}{\text{minimize}} \quad & f(x) \\ \text{subject to} \quad & g(x,\delta) \le 0,\ \delta \in \Delta \end{aligned}$$

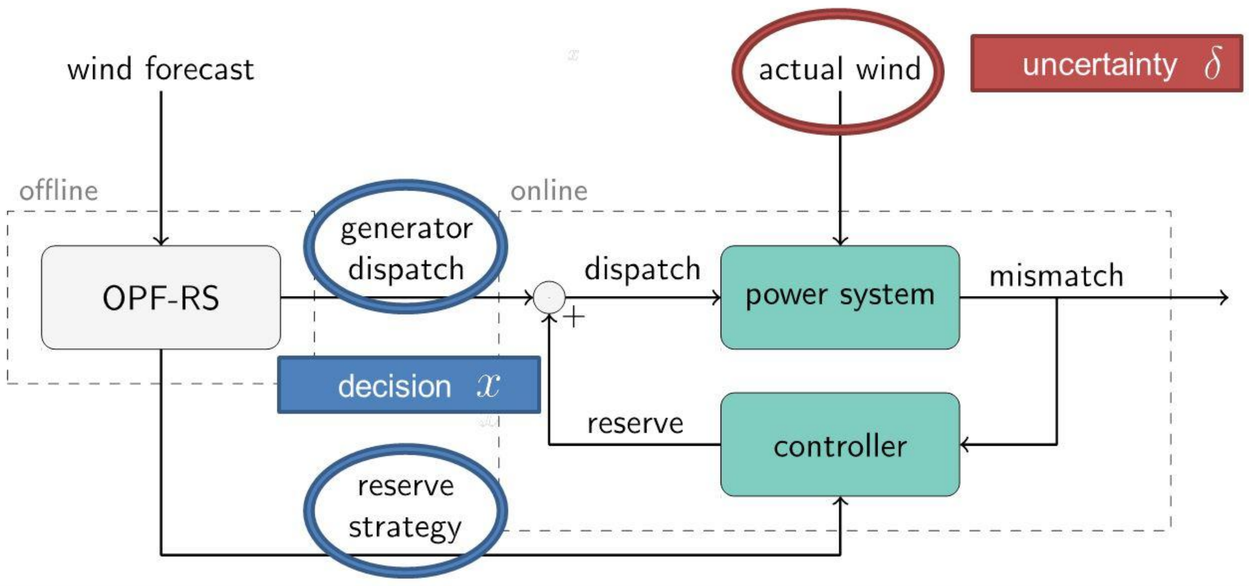
**Robust Program:**



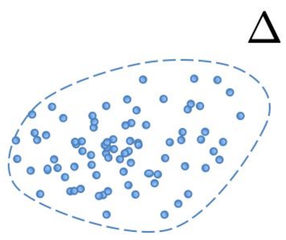

$$\begin{aligned} \underset{x}{\text{minimize}} \quad & f(x) \\ \text{subject to} \quad & g(x,\delta) \le 0, \text{ for all } \delta \in \Delta \end{aligned}$$

No Violation allowed, leads to conservatism

### Implementation of OPF-RS problem




**Scenario Program:**




- Extract samples of uncertainty

$$\mathcal{S} := \{\delta_1, \delta_2 \cdots, \delta_{N_s}\} \in \Delta^{N_s}$$

- Formulate robust program for samples

$$\begin{aligned} \underset{x}{\text{minimize}} \quad & f(x) \\ \text{subject to} \quad & g(x,\delta) \le 0, \quad \text{for all } \delta \in \mathcal{S} \end{aligned}$$

- Optimal solution has at most $\varepsilon$ violation probability

$$\mathbb{P}\big[\delta \in \Delta : g(x^\star, \delta) > 0\big] < \varepsilon$$ with confidence of at least $1 - \beta$

- Theoretical connection between $\varepsilon$ and $N_s$
  - More samples, lower violation probability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