Integrating Automatic and Manual Reserves in Optimal Power Flow via Chance Constraints

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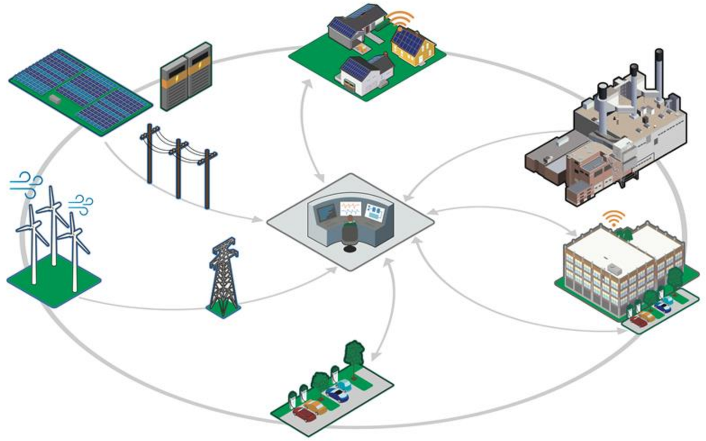
OPTIMAL POWER FLOW

- Least-costly dispatch
- Supply electricity net demand
- Technical limits:
  - Production
  - Network equipment



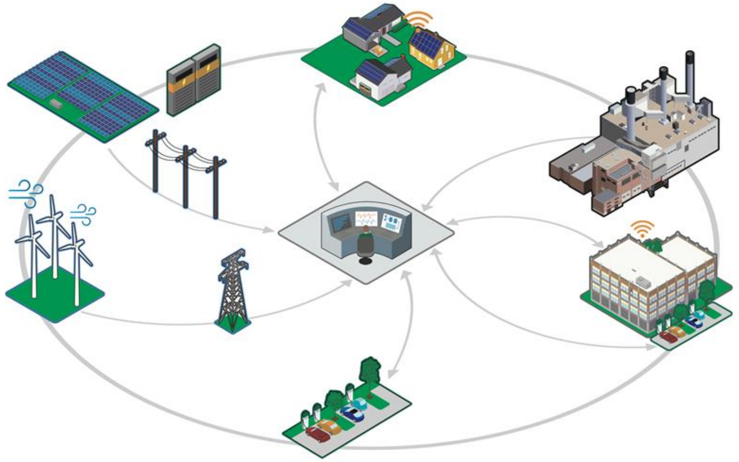
$$
\begin{aligned}
\min_{p_g} \quad & \sum_{g \in \mathcal{G}} c_g p_g \\
\text{s.t.} \quad & \sum_{g \in \mathcal{G}} p_g = \sum_{n \in \mathcal{N}} d_n \\
& \underline{p}_g \leq p_g \leq \overline{p}_g, \quad \forall g \in \mathcal{G} \\
& -\overline{f}_l \leq \sum_{n \in \mathcal{N}} B_{ln} \left(\sum_{g \in \mathcal{G}} p_g - d_n \right) \leq \overline{f}_l, \quad \forall l \in \mathcal{L}
\end{aligned}
$$

- Operating cost
- System's balance
- Power output dispatch limits
- Line-flow capacity

OPTIMAL POWER FLOW under UNCERTAINTY

Uncertainty in 

electricity demand and **renewable energy generation**



- Uncertain net demand: $d_n + \omega_n$
- Reserve deployment: $p_g + r_g(\omega)$
- To counterbalance error: $\sum_{g \in \mathcal{G}} r_g(\omega) = \sum_{n \in \mathcal{N}} \omega_n = \Omega$
- To anticipate downward and upward reserve capacity: $-r_g^d \leq r_g(\omega) \leq r_g^u$

Two-stage Framework (TS)

$$\min_{p_g, r_g^u, r_g^d, r_g(\omega)} \quad \sum_{g\in\mathcal{G}} c_g p_g + c_g^u r_g^u + c_g^d r_g^d$$

$$\text{s.t.} \quad \sum_{g\in\mathcal{G}} p_g = \sum_{n\in\mathcal{N}} d_n$$

$$\underline{p}_g + r_g^d \leq p_g \leq \overline{p}_g - r_g^u, \quad \forall g \in \mathcal{G}$$

$$r_g^d, r_g^u \geq 0, \quad \forall g \in \mathcal{G}$$

- First-stage constraints

$$\sum_{g\in\mathcal{G}} r_g(\omega) = \sum_{n\in\mathcal{N}} \omega_n = \Omega$$

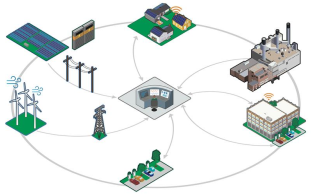
$$-r_g^d \leq r_g(\omega) \leq r_g^u, \quad \forall g \in \mathcal{G}$$

$$-\overline{f}_l \leq \sum_{n\in\mathcal{N}} B_{ln} \left(\sum_{g\in\mathcal{G}} (p_g + r_g(\omega)) - d_n - \omega_n \right) \leq \overline{f}_l, \quad \forall l \in \mathcal{L}$$

- Second-stage constraints

$p_g,\ r_g^u,\ r_g^d \rightarrow$ first-stage variables

$r_g(\omega) \rightarrow$ second-stage variables



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How does it work?

Real-time Operation

TS ***Framework***

p_g

$r_g^d,\ r_g^u$

Uncertainty Realization ω

Reserve deployment ***Optimization Problem***

r_g

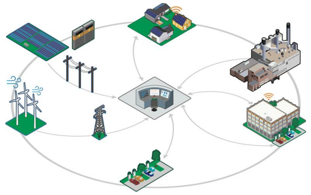
Action

Manual Adjustment

Satisfying technical constraints

Manual reserve

Computationally demanding!!!
Unrealistic



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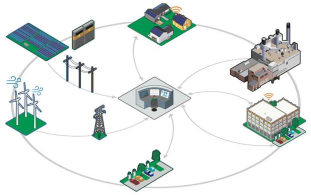
Real-time Operation

Spectrum of Uncertainty Realizations

unrealistic — **Manual**

Automatic

***Automatic Generation Control* - AGC**



Affine Control Policy (AGC)

$$
\begin{aligned}
\min_{p_g, \beta_g, r_g^u, r_g^d} \quad & \sum_{g \in \mathcal{G}} c_g p_g + c_g^u r_g^u + c_g^d r_g^d \\
\text{s.t.} \quad & \sum_{g \in \mathcal{G}} p_g = \sum_{n \in \mathcal{N}} d_n \\
& \underline{p}_g + r_g^d \leq p_g \leq \overline{p}_g - r_g^u, \quad \forall g \in \mathcal{G} \\
& r_g^d, r_g^u \geq 0, \quad \forall g \in \mathcal{G} \\
& \\
& \sum_{g \in \mathcal{G}} \beta_g = 1 \\
& - r_g^d \leq \beta_g \Omega \leq r_g^u, \quad \forall g \in \mathcal{G} \\
& - \overline{f}_l \leq \sum_{n \in \mathcal{N}} B_{ln} \left(\sum_{g \in \mathcal{G}} (p_g + \beta_g \Omega) - d_n - \omega_n \right) \leq \overline{f}_l, \quad \forall l \in \mathcal{L}
\end{aligned}
$$

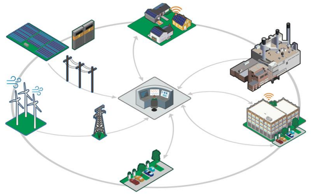
$$p_g, \beta_g, r_g^u, r_g^d \rightarrow \text{first-stage variables}$$

- Reserve deployment follows an affine control policy (AGC):

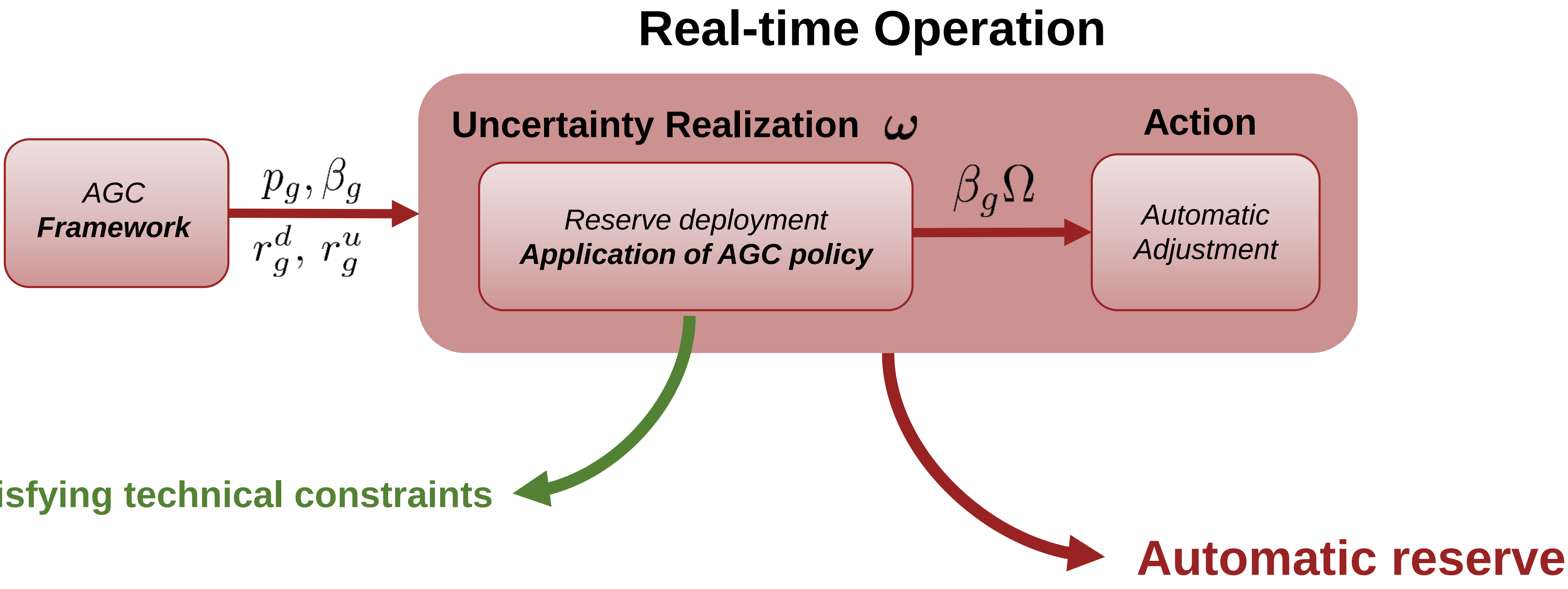
$$r_g(\omega) = \beta_g \sum_{n \in \mathcal{N}} \omega_n = \beta_g \Omega$$

- AGC counterbalances forecast errors:

$$\sum_{g \in \mathcal{G}} \beta_g = 1$$

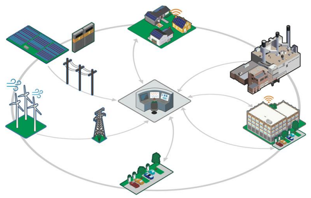


How does it work?



Conservative approach!!!

Linear decision rule replacing second-stage variables



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Real-time Operation

Spectrum of Uncertainty Realizations

unrealistic	**Manual**
conservative	**Automatic**

Why does SO have to meet technical constraints in low-probability and high-impact events?

Real-time Operation

Spectrum of Uncertainty Realizations

unrealistic	Manual
conservative	Automatic
Chance-constrained Programming	Automatic

Technical constraints are not satisfied for this range of uncertainty realizations

Chance-constrained Program (AGC+CC)

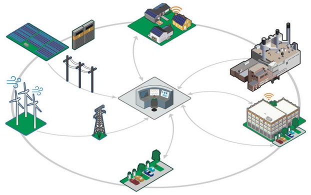
$$
\begin{aligned}
\min_{p_g, r_g^u, r_g^d, r_g(\omega)} \quad & \sum_{g \in \mathcal{G}} c_g p_g + c_g^u r_g^u + c_g^d r_g^d \\
\text{s.t.} \quad & \sum_{g \in \mathcal{G}} p_g = \sum_{n \in \mathcal{N}} d_n \\
& \underline{p}_g + r_g^d \leq p_g \leq \overline{p}_g - r_g^u, \quad \forall g \in \mathcal{G} \\
& r_g^d, r_g^u \geq 0, \quad \forall g \in \mathcal{G}
\end{aligned}
$$

$$
\sum_{g \in \mathcal{G}} \beta_g = 1
$$

$$
\mathbb{P} \left(\begin{array}{l} -r_g^d \leq \beta_g \Omega \leq r_g^u, \quad \forall g \in \mathcal{G} \\ -\overline{f}_l \leq \sum_n B_{ln} \left(\sum_{g \in \mathcal{G}} (p_g + \beta_g \Omega) - d_n - \omega_n \right) \leq \overline{f}_l, \quad \forall l \in \mathcal{L} \end{array} \right) \geq 1 - \epsilon
$$

$$
p_g, \beta_g, r_g^u, r_g^d \rightarrow \text{first-stage variables}
$$

- Technical constraints are satisfied with a given (high) probability.
- Solutions more economical, since extreme events are discarded.



How does it work?

Real-time Operation

AGC+CC
Framework

p_g, β_g

r_g^d, r_g^u

Uncertainty Realization ω

Reserve deployment
Application of AGC policy

$\beta_g \Omega$

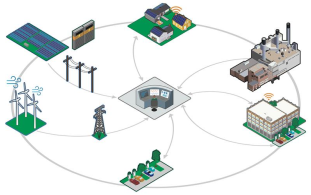
Action

Automatic Adjustment

Costly scenarios are discarded

Critical nature of power systems

The system is left vulnerable



Real-time Operation

Spectrum of Uncertainty Realizations

unrealistic	Manual	
conservative	Automatic	
vulnerability	Automatic	
	Automatic	Manual

in-between solution

Integration of automatic and manual

Integrating Automatic and Manual (AGC+M)

- Reserve deployments are combinations of AGC and manual adjustments:

$$r_g(\omega) = \beta_g \Omega + r_g^M(\omega) \qquad \sum_{g \in \mathcal{G}} r_g^M(\omega) = 0$$

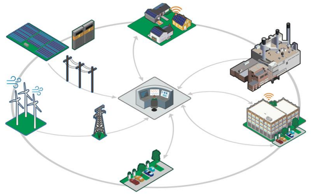
- Guaranteeing robust feasibility.

$$-r_g^d \leq \beta_g \Omega + r_g^M(\omega) \leq r_g^u, \quad \forall g \in \mathcal{G}$$

$$-\overline{f}_l \leq \sum_{n \in \mathcal{N}} B_{ln} \left(\sum_{g \in \mathcal{G}} (p_g + \beta_g \Omega + r_g^M(\omega)) - d_n - \omega_n \right) \leq \overline{f}_l, \quad \forall l \in \mathcal{L}$$

- Most of the time the operation is automatic except in extreme, unlikely events. Manual reserve is computationally expensive. Thus, its probability of occurrence is limited.

$$\mathbb{P}(r_g^M(\omega) = 0, \quad \forall g \in \mathcal{G}) \geq 1 - \epsilon$$



Integrating Automatic and Manual (AGC+M)

$$
\begin{aligned}
\min_{p_g, r_g^u, r_g^d, r_g(\omega)} \quad & \sum_{g\in\mathcal{G}} c_g p_g + c_g^u r_g^u + c_g^d r_g^d \\
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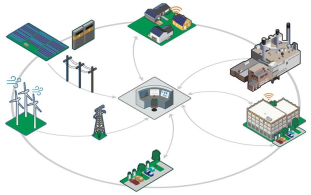
& \underline{p}_g + r_g^d \le p_g \le \overline{p}_g - r_g^u, \quad \forall g\in\mathcal{G} \\
& r_g^d, r_g^u \ge 0, \quad \forall g\in\mathcal{G} \\
& \\
& \sum_{g\in\mathcal{G}} \beta_g = 1, \quad \sum_{g\in\mathcal{G}} r_g^M(\omega) = 0 \\
& -r_g^d \le \beta_g\Omega + r_g(\omega) \le r_g^u, \quad \forall g\in\mathcal{G} \\
& -\overline{f}_l \le \sum_{n\in\mathcal{N}} B_{ln}\left(\sum_{g\in\mathcal{G}}(p_g + \beta_g\Omega + r_g(\omega)) - d_n - \omega_n\right) \le \overline{f}_l, \quad \forall l\in\mathcal{L} \\
& \mathbb{P}(r_g^M(\omega) = 0, \quad \forall g\in\mathcal{G}) \ge 1-\epsilon
\end{aligned}
$$

$p_g, \beta_g, r_g^u, r_g^d \rightarrow$ first-stage variables

$r_g^M(\omega) \rightarrow$ second-stage variables



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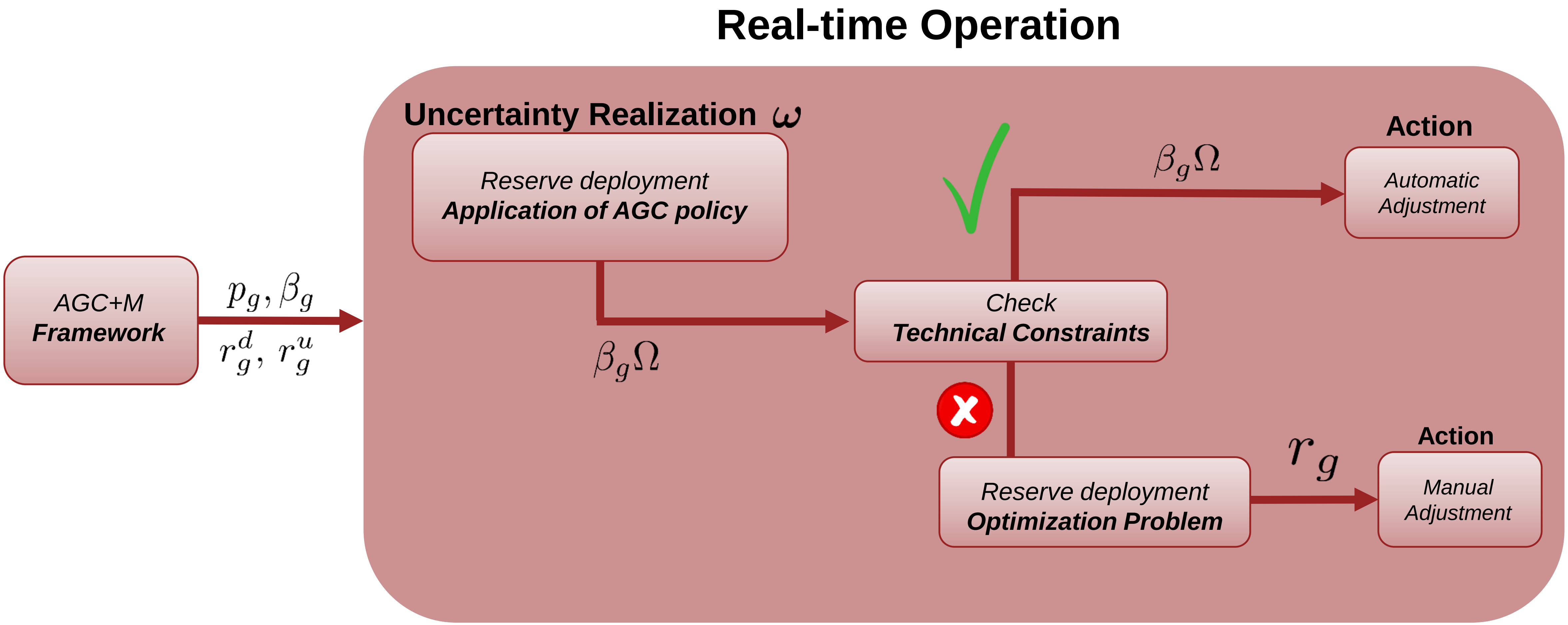
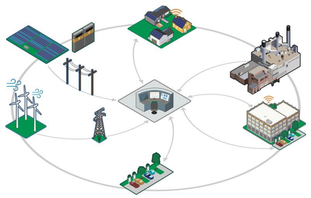
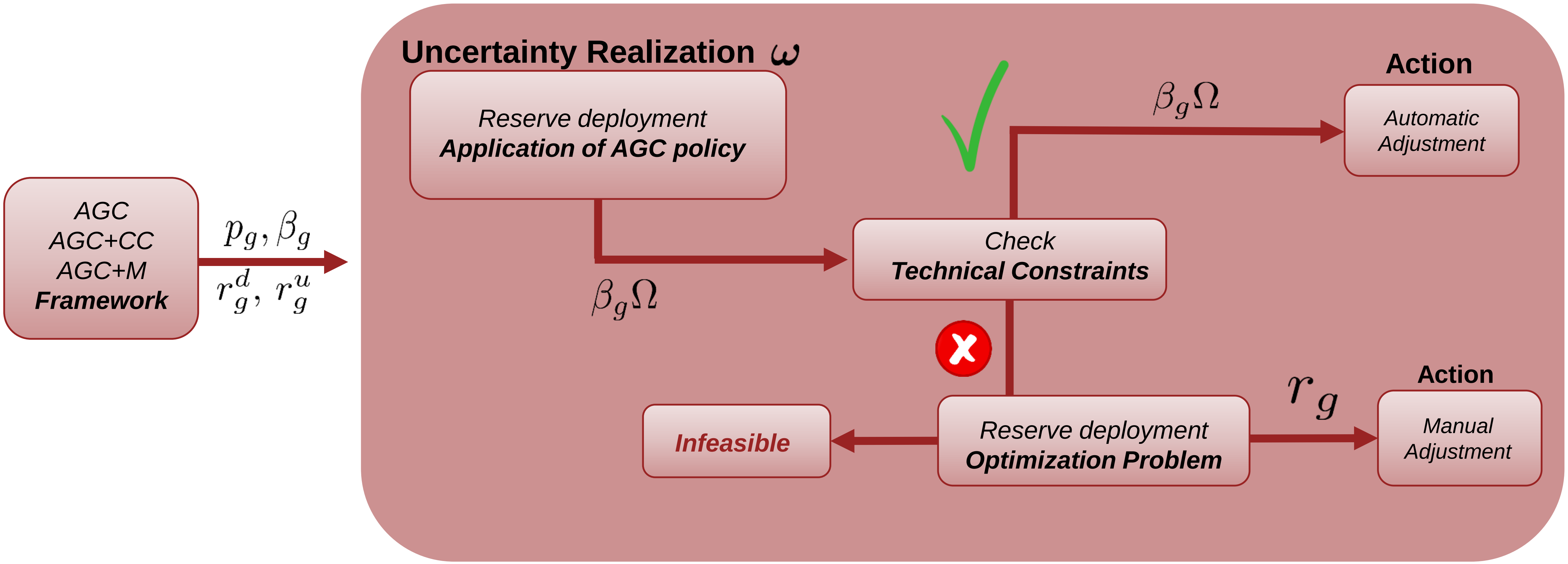
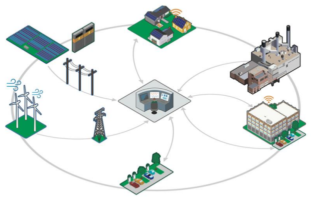




Evaluation Procedure

Real-time Operation





Numerical Experiments

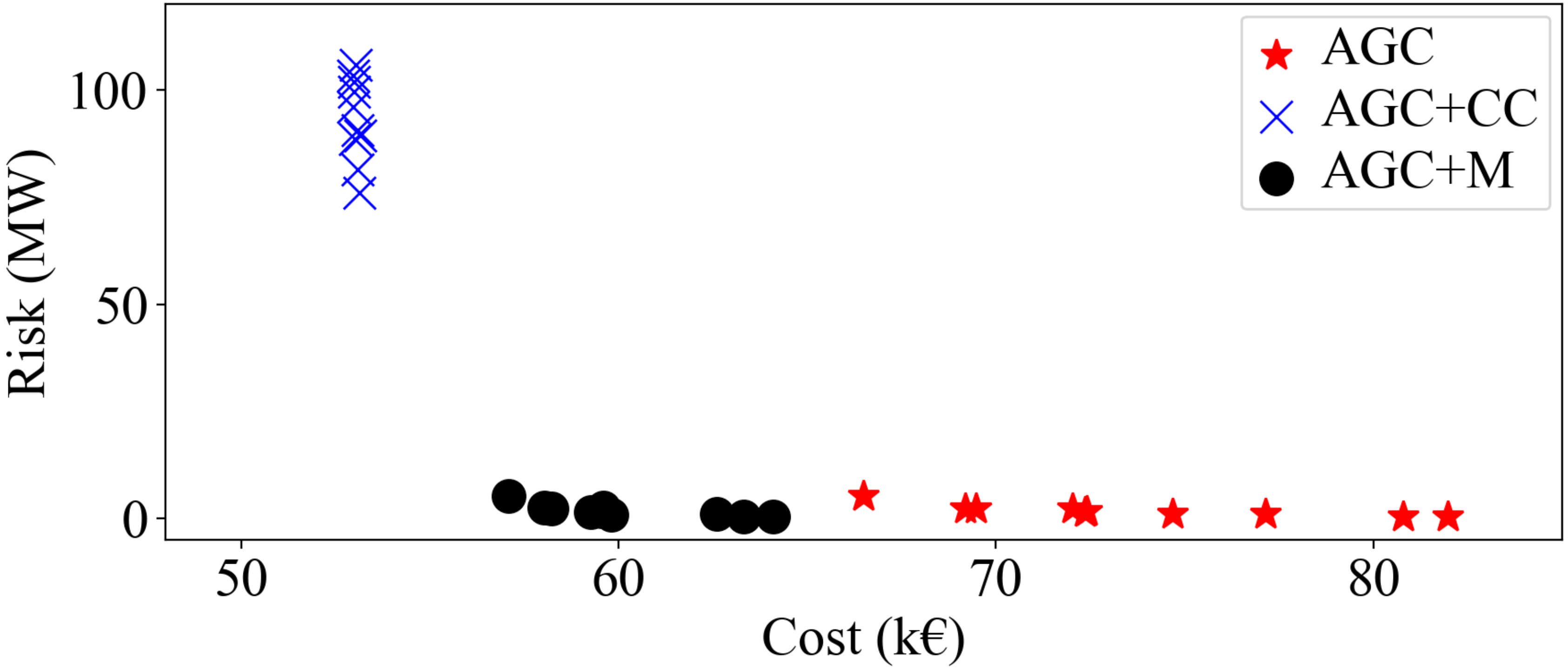
- IEEE-118 bus system.
- Real-time operation over 100.000 scenarios.

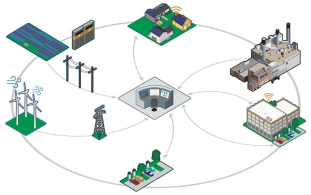
$$\epsilon = 5\%$$

- Different metrics are evaluated.:
  - The number of scenarios where AGC is sufficient to handle the forecast errors satisfying technical constraints. $|\mathcal{S}_A|$
  - The number of scenarios where manual adjustments are required to meet technical constraints. $|\mathcal{S}_M|$
  - The number of scenarios where AGC and manual reserve are not enough to offset the power imbalances whilst satisfying technical constraints. $|\mathcal{S}_I|$
  - Expected operating cost $\mathbb{E}[C]$ (k€)

	$\lvert\mathcal{S}_{\mathrm{A}}\rvert$	$\lvert\mathcal{S}_{\mathrm{M}}\rvert$	$\lvert\mathcal{S}_{\mathrm{I}}\rvert$	$\mathbb{E}[C]$ (k€)
AGC	99.56%	0.16%	0.28%	73.65
AGC+CC	94.12%	0.17%	5.71%	53.04
AGC+M	94.30%	5.41%	0.29%	60.15

Numerical Experiments





Thanks!
Any question?

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