Optimizing Primary Frequency Response

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Primary frequency response

- Background:
  - Compulsory provision
  - Fixed droop for all conventional generators
  - Response characteristic has drastically decreased over the past decades:
    - 37.5 MW/mHz → 30.7 MW/mHz
  - Increasing penetration of renewable generation will further decrease this response

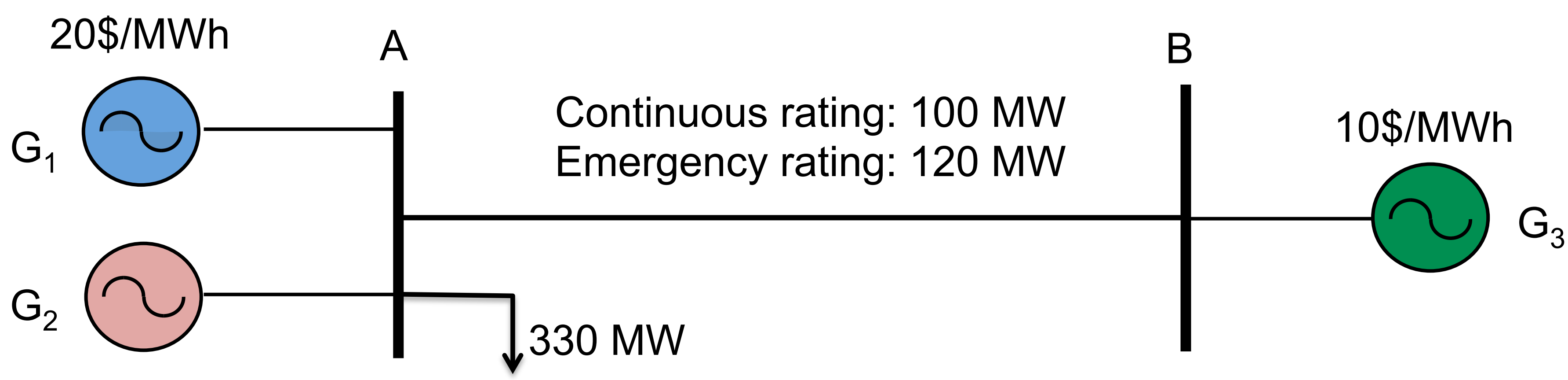
Objectives

- Improve reliability by accurately assessing the needs for primary frequency response
- Reduce the cost of providing primary reserve
  - Significant cost savings even for moderate wind penetration levels

Approach

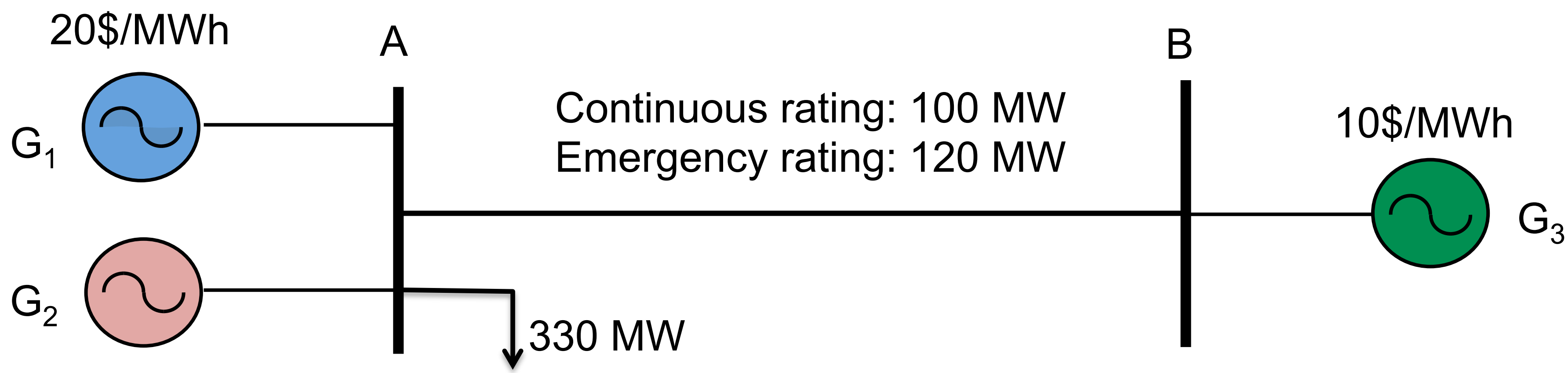
- Optimally allocate primary reserve between all generating units
  - Optimize individual droop coefficients
  - Co-optimize each generator's contribution to primary reserve with its energy production
  - No generator contingency should:
    - Cause an excessive frequency deviation
    - Overload a line or transformer
- Preventive Security Constrained OPF (PSCOPF)
  - Consider generator contingencies

Example



All generators have the same rating

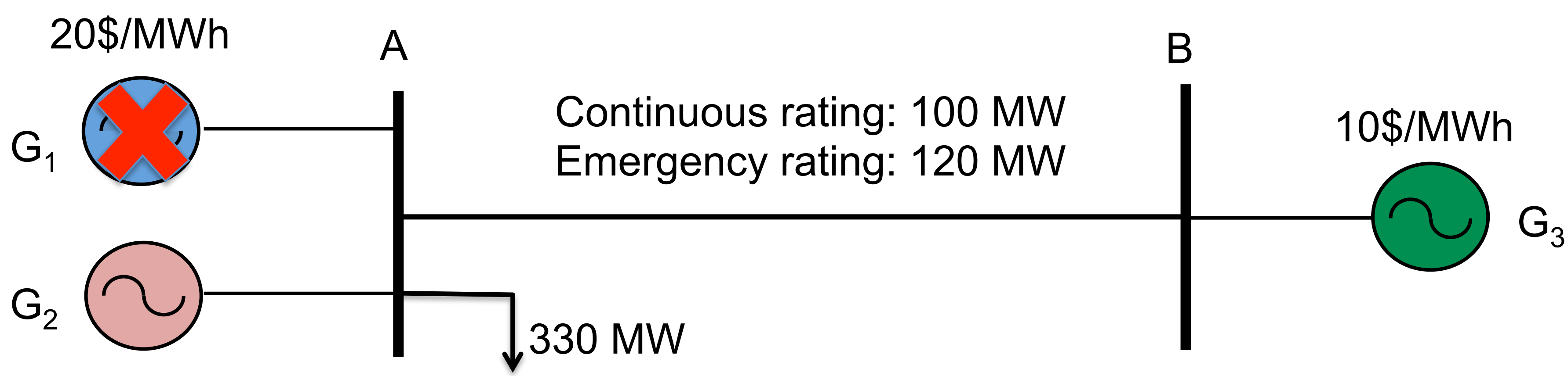
OPF without generator contingency constraints



Output of G_3 is limited by continuous rating of line A-B:

State	G_1	G_2	G_3
Pre-contingency dispatch (MW)	115	115	100

Generator contingency with identical droops

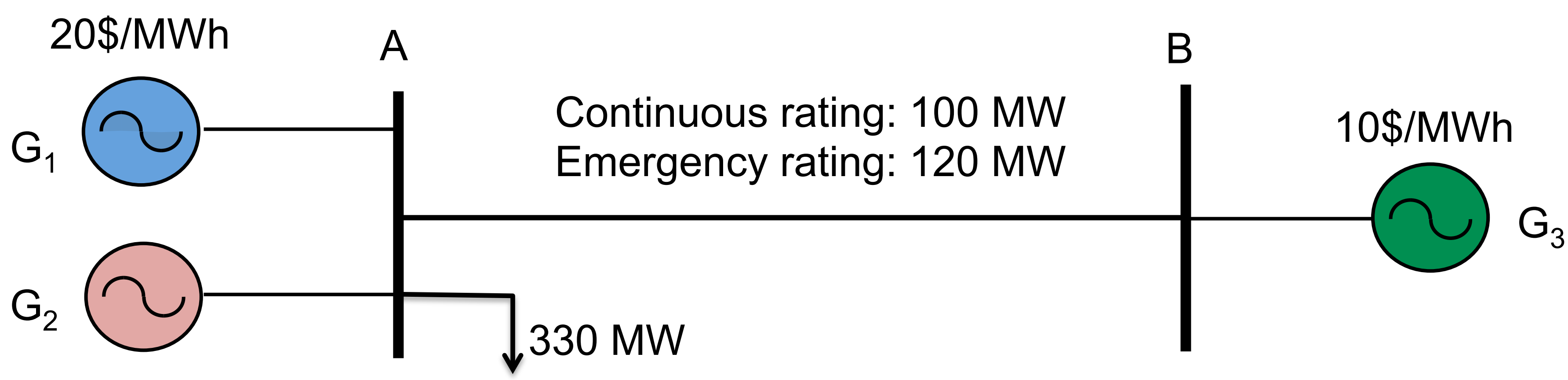


If G_2 and G_3 have the same droop and the same size:

State	G_1	G_2	G_3
Pre-contingency dispatch (MW)	115	115	100
Response (MW)	--	57.5	57.5
Post-contingency dispatch (MW)	--	172.5	157.5

Exceeds the emergency rating of line A-B

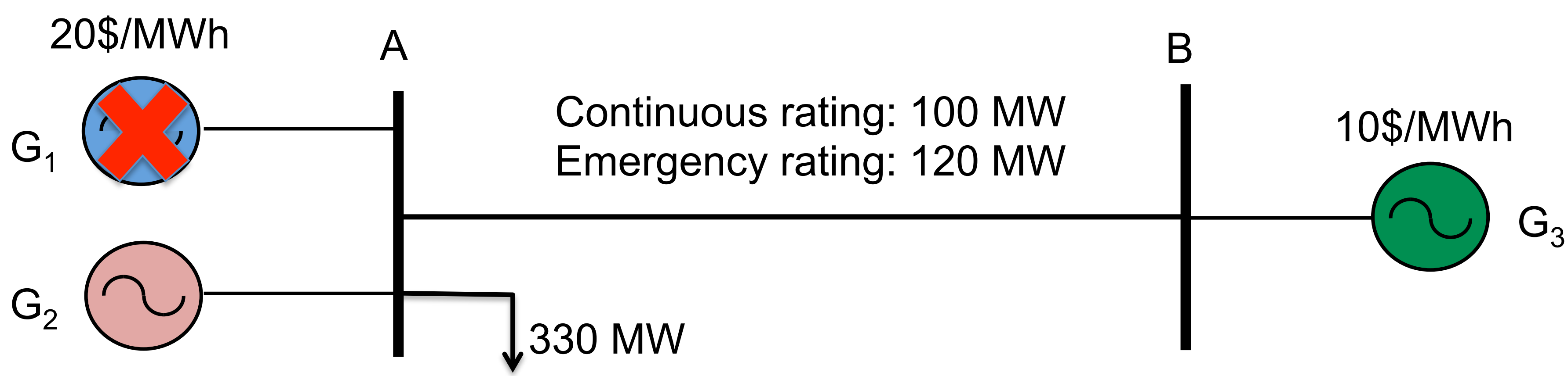
PSCOPF with generator contingency constraints



The dispatch takes into account the emergency rating of line A-B:

State	G_1	G_2	G_3
Pre-contingency dispatch (MW)	140	140	50

Generator contingency with identical droops

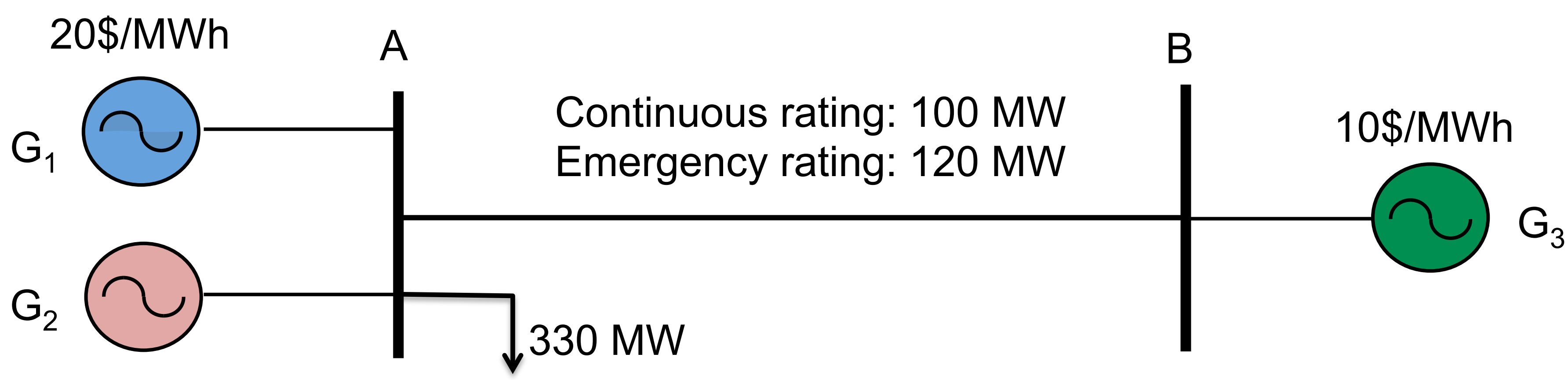


Security constrained dispatch with identical droops:

State	G_1	G_2	G_3
Pre-contingency dispatch (MW)	140	140	50
Response (MW)	--	70	70
Post-contingency dispatch (MW)	--	210	120

Within the emergency rating of line A-B

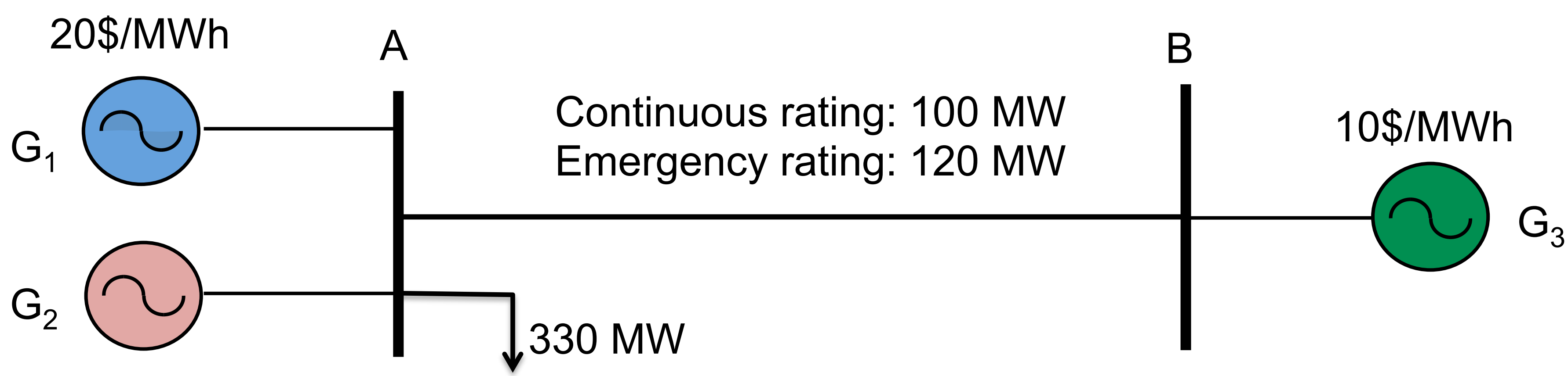
OPF vs. PSCOPF



State	G_1	G_2	G_3	Cost ($/h)
OPF dispatch (MW)	115	115	100	5,600
PSCOPF dispatch (MW)	140	140	50	6,100

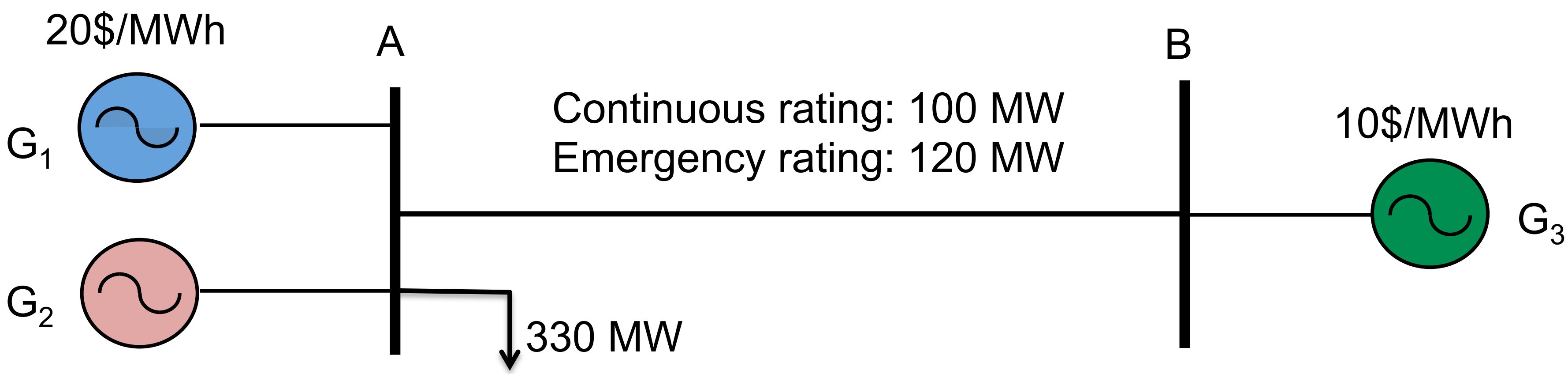
Cost of security: $6,100 - $5,600 = $500

Reducing the security cost



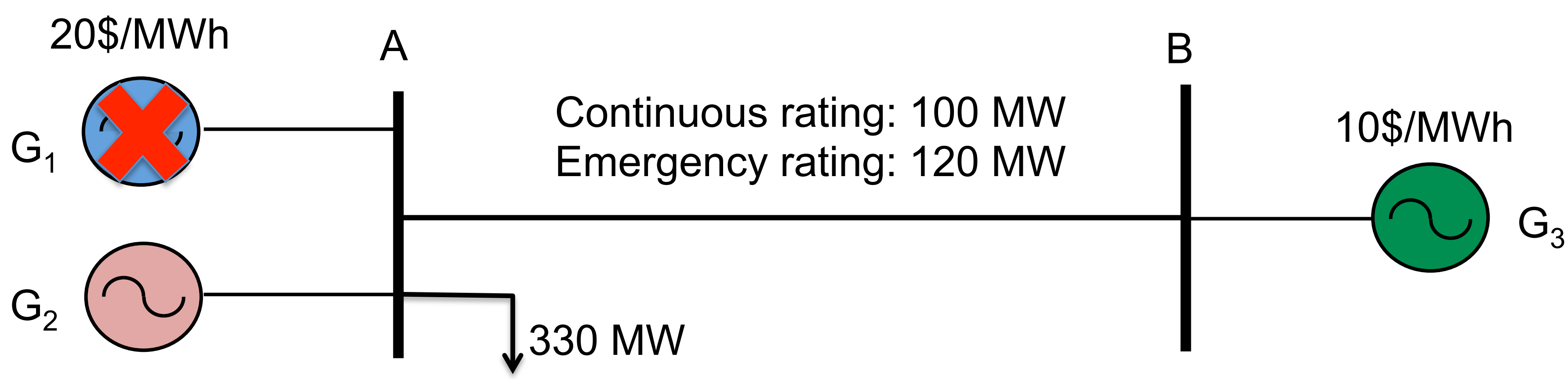
- Increase the output of G_3 in the pre-contingency state
- Decrease the output of G_3 in the post-contingency state
  - Avoid exceeding the emergency rating of the line
- Increase the primary response of G_1 and G_2
  - Avoid excessive frequency drop
- Optimize the droop of each generator

PSCOPF with droop optimization



State	G_1	G_2	G_3
Pre-contingency dispatch (MW)	120	120	90
Droop	2%	2%	6%

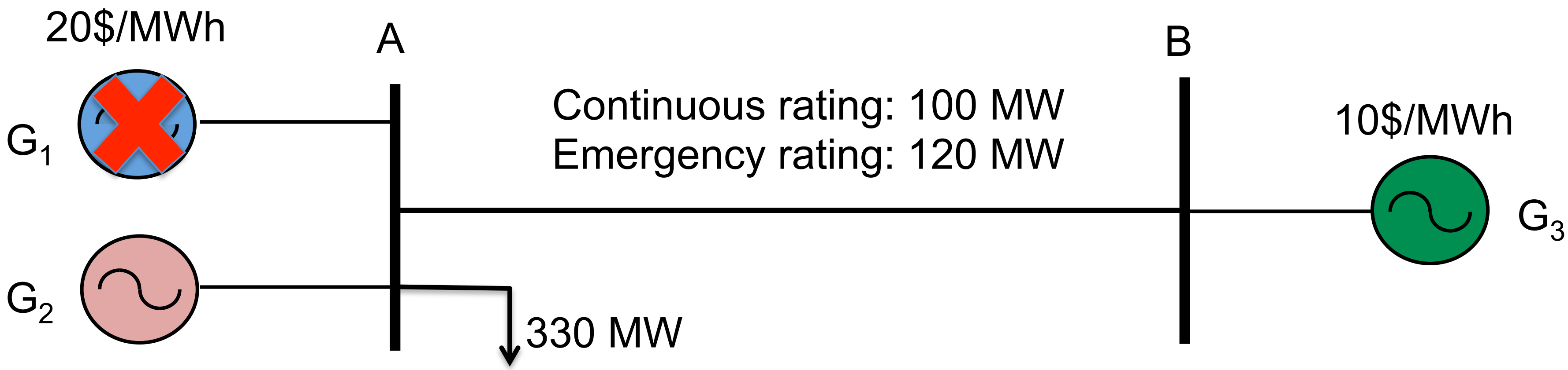
PSCOPF with droop optimization



State	G_1	G_2	G_3
Pre-contingency dispatch (MW)	120	120	90
Droop	2%	2%	6%
Response (MW)	--	90	30
Post-contingency dispatch (MW)	--	210	120

Large pre-contingency output but low response from G_3

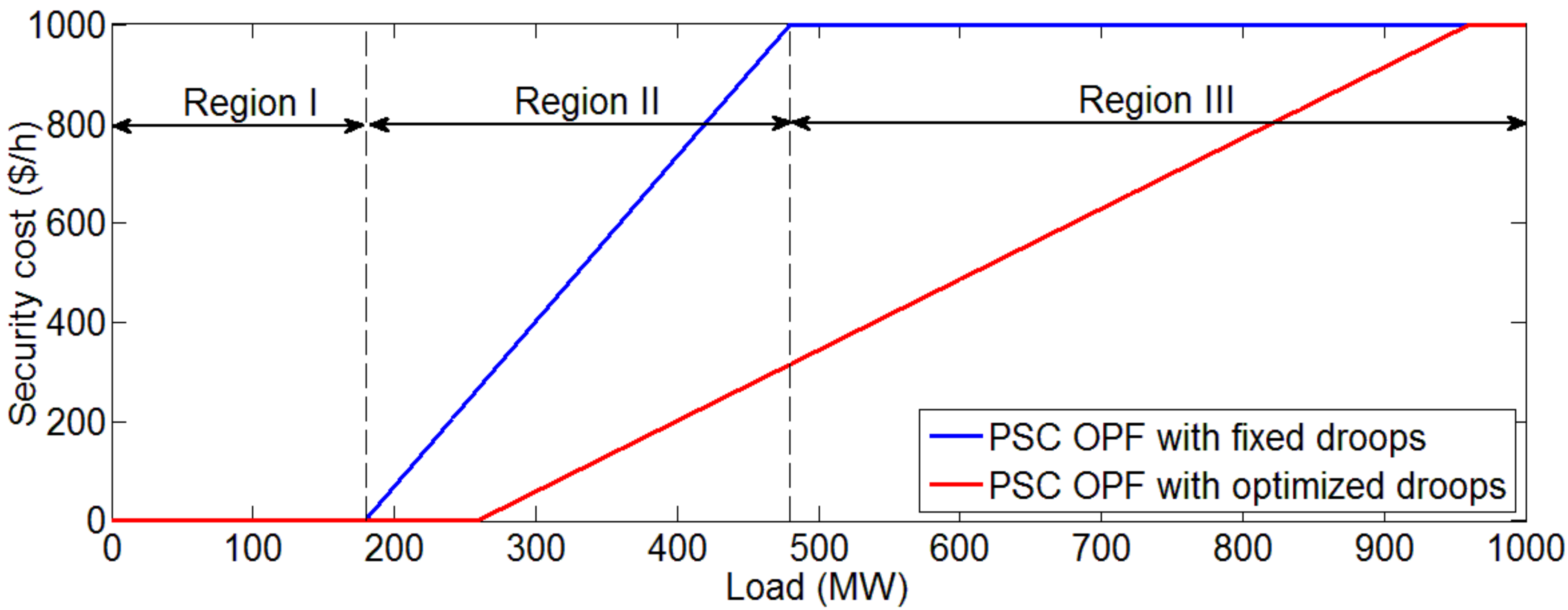
Comparison



Case	State	G_1	G_2	G_3	Cost
Without droop optimization	Pre-contingency	140	140	50	$ 6,100
	Response	--	70	70	
With droop optimization	Pre-contingency	120	120	90	$ 5,700
	Response	--	90	30	

Droop optimization reduces the total cost while ensuring the same level of security as PSCOPF with fixed droops

Cost savings



The savings depend on the load, but are limited by the acceptable range of droop coefficients: 2 to 6%

PSCOPF formulation

Objective function:

$$\min_{P_{g0}} \sum_g C_g(P_{g0})$$

Dispatch constraints:

$$\sum_g \mathbb{1}_{ng} P_{gc} + P_n^{\mathrm{w}} + \sum_k \mathbb{1}_{nk} P_{kc} = P_n^{\mathrm{d}}, \ \forall n, c$$

$$\mathbb{1}_{gc} P_g^{\min} \le P_{gc} \le \mathbb{1}_{gc} P_g^{\max}, \ \forall g, c$$

$$0 \le P_n^{\mathrm{w}} \le P_n^{\mathrm{f\_w}}, \ \forall n$$

$$P_{kc} = B_k \sum_n \mathbb{1}_{nk} \theta_{nc}, \ \forall k, c$$

$$-P_{kc}^{\max} \le P_{kc} \le P_{kc}^{\max}, \ \forall k, c$$

$$\theta^{\min} \le \theta_{nc} \le \theta^{\max}, \ \forall n > 1, c$$

$$\theta_{1c} = 0, \ \forall c$$

Primary response constraints:

$$P_{gc_g} \ge z_{gc_g} P_g^{\max}, \ \forall g, c_g$$

$$P_{gc_g} \le \mathbb{1}_{gc_g}(P_{g0} - D_g \Delta f_{c_g}), \ \forall g, c_g$$

$$P_{gc_g} \ge \mathbb{1}_{gc_g}(P_{g0} - D_g \Delta f_{c_g}) - M z_{gc_g} \ \forall g, c_g$$

PSCOPF formulation

$$\min_{P_{g0}} \sum_g C_g(P_{g0})$$

$$\sum_g \mathbb{1}_{ng} P_{gc} + P_n^{\text{w}} + \sum_k \mathbb{1}_{nk} P_{kc} = P_n^{\text{d}}, \ \forall n, c$$

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Droop coefficients: New discretized decision variables

Primary response constraints

Solving this PSCOPF

- Non-linear problem because the droop coefficients are decision variables
  - Product of binary and continuous variables
- Non-convex problem
  - Use a Benders-like decomposition
  - No guarantee of optimality
  - Test results show that the loss of optimality is acceptable

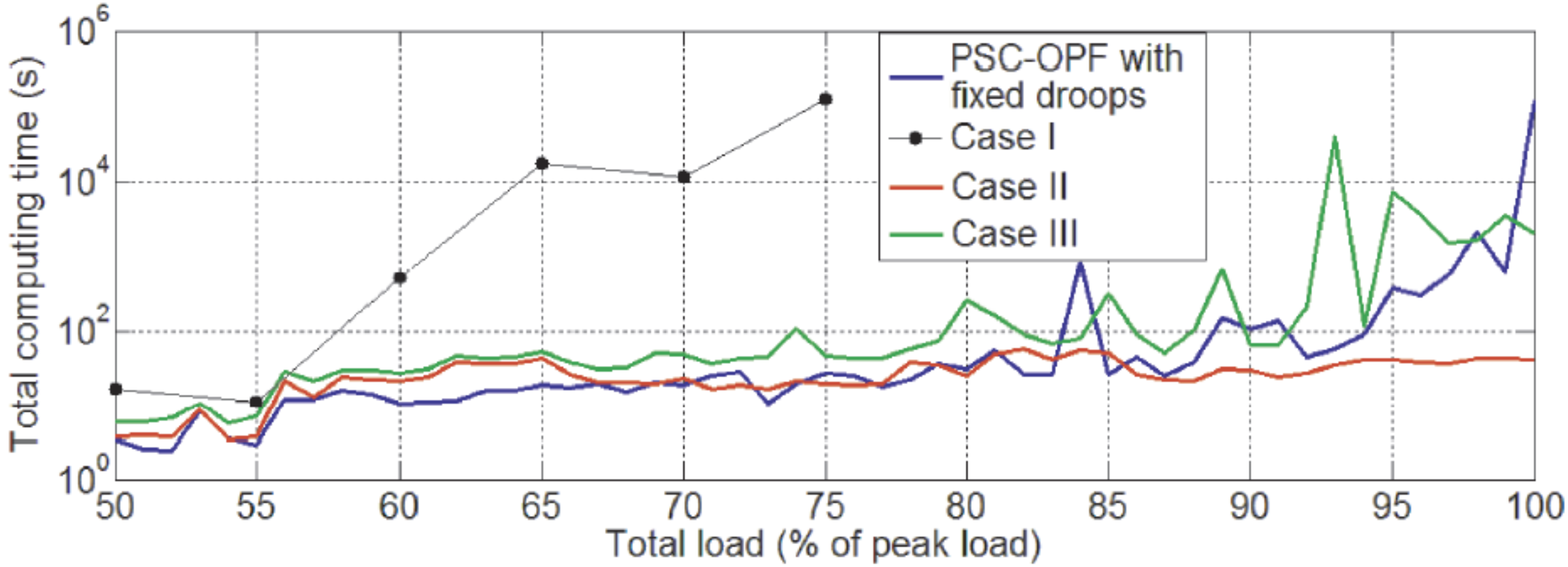
Test System and Data

- Modified versions of the one- and three-area Reliability Test System
- Yearly load and simulated wind generation profiles
- Day-ahead UC decisions are optimized using a deterministic UC model
- Optimization is performed using the CPLEX 12.1 solver in GAMS 24.0.2 on a 2.5 GHz Intel Xeon processor with 16 GB RAM

Cases

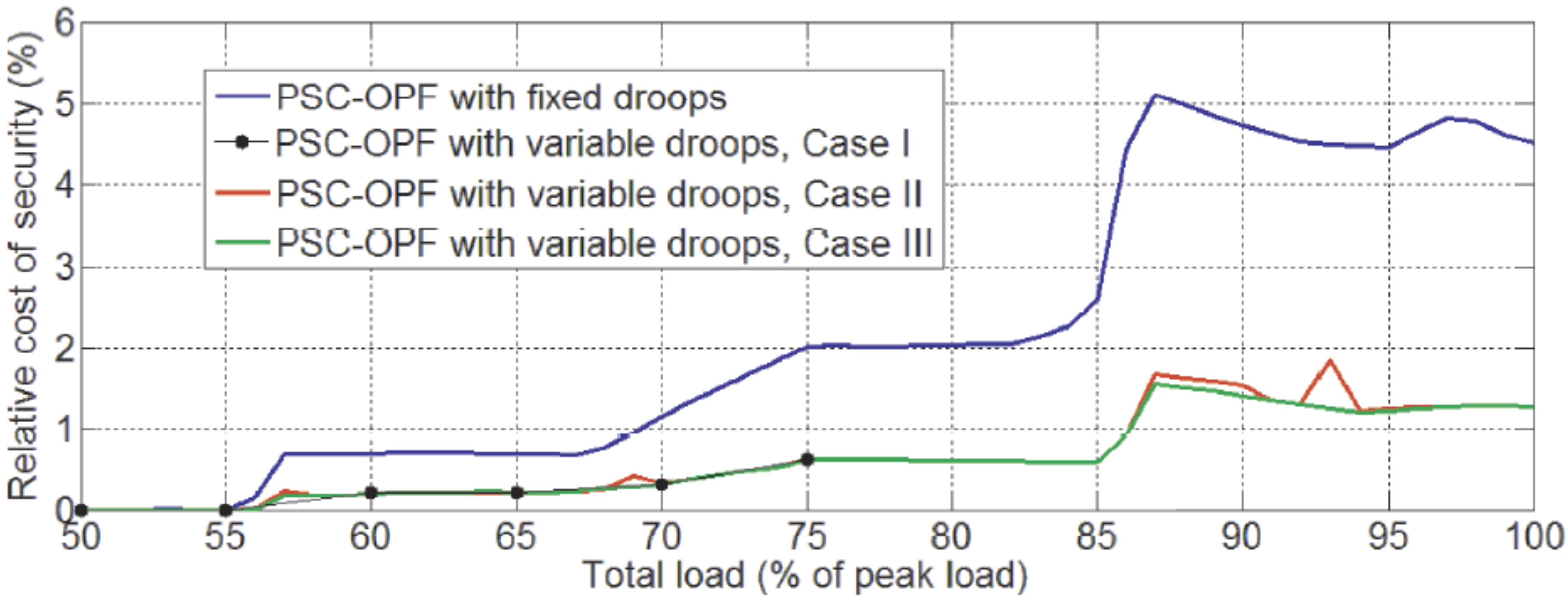
- Case 0: PSC OPF with fixed droops
- Case I:PSC OPF with droops optimization but without Benders' decomposition
- Case II: PSC OPF with droops optimization but with Benders' decomposition
- Case III: Determine the optimal droops using Benders decomposition, then re-solve the PSC OPF with these droops fixed.

Computational performance



Tests performed on the one-area RTS

Cost of security

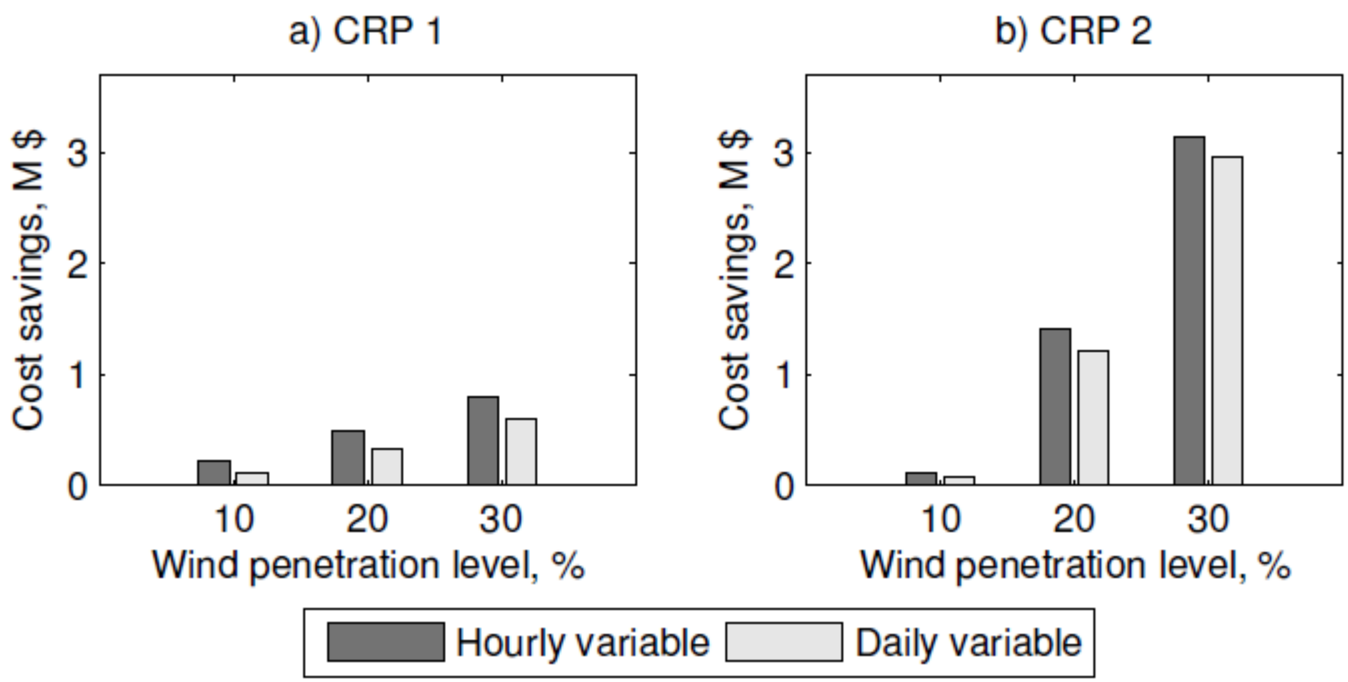


Tests performed on the one-area RTS

Cost savings over a year

- Three-area RTS
- Case III technique is used for year-long simulations
- Hourly and daily droop optimization
- Three wind penetration levels: 10, 20, 30%
- Two contingency reserve policies (CRP):
  - CRP1 (state-of-the-art): (N-1) reserve requirement is arbitrarily shared between three areas
  - CRP2 (potential policy): Each area provides a third of the (N-1) reserve requirement

Savings over a year



- Cost savings increase with the wind penetration
- Hourly variable droop optimization provides more flexibility for procuring primary response and achieves larger savings
- The proposed methodology is especially valuable for CRP2

Conclusions

- Optimizing droops enables more flexible allocation of primary response
- Cost savings achieved with the proposed methodology increase with wind penetration
- The proposed methodology is computationally tractable and compatible with PSCOPF

References

- Motivation for modelling generation contingencies in PSCOPF:

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- Evidence of reducing primary response:

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[6] R. Doherty, G. Lalor, and M. O'Malley, "Frequency Control in Competitive Electricity Market Dispatch," *IEEE Transactions on Power Systems,* Vol. 20, No. 3, pp. 1588-1596, 2005.