A Multi-Period OPF Approach to Improve Voltage Stability using Demand Response

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Power System Stability

- Frequency instability
  - Associated with an imbalance between load and generation
  - Demand response based on temporal shifting of load

[Short, Infield, & Freris '07], [Molina-Garcia, Bouffard, & Kirschen '10], [Mathieu, Koch, & Callaway '12], [Zhang, Lian, Chang, & Kalsi '13]

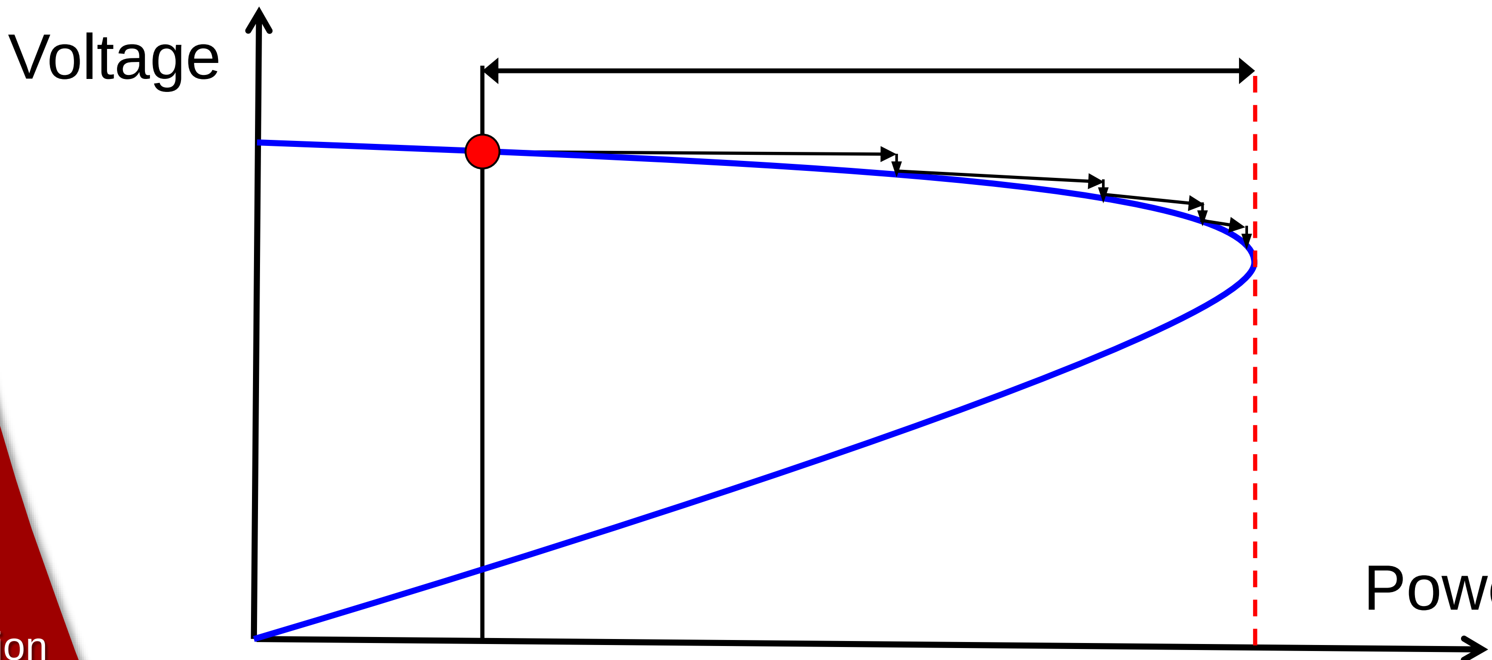
- Voltage instability
  - Associated with operation that nears the limits of the network's power transfer capability
  - Demand response based on spatial shifting of load

How to control flexible loads in order to improve voltage stability after a disturbance?

Voltage Stability

- Distance to the "nose point" of the PV curve
  - Often computed using continuation methods, which are difficult to embed within an optimization problem
  - A voltage stability metric based on power flow sensitivities is based on the smallest singular value of the power flow Jacobian

[Tiranuchit & Thomas '88], [Lof, Smed, Andersson, & Hill '92]



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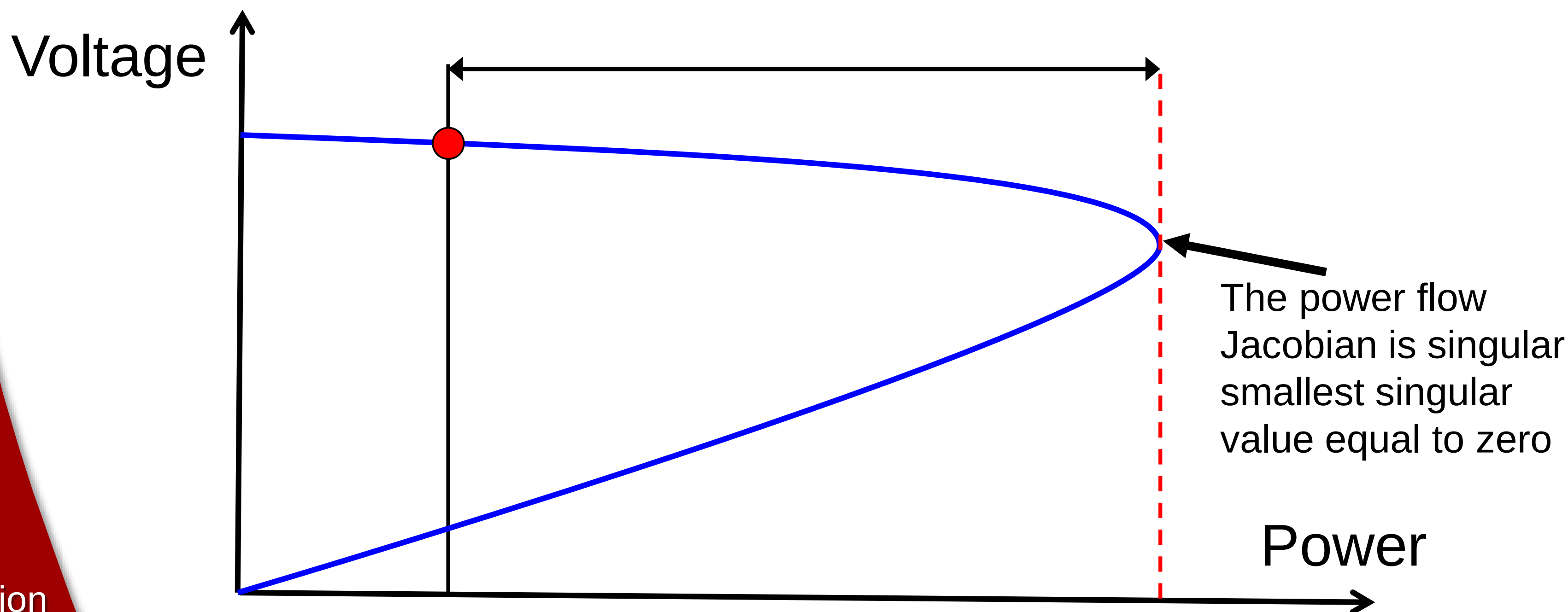
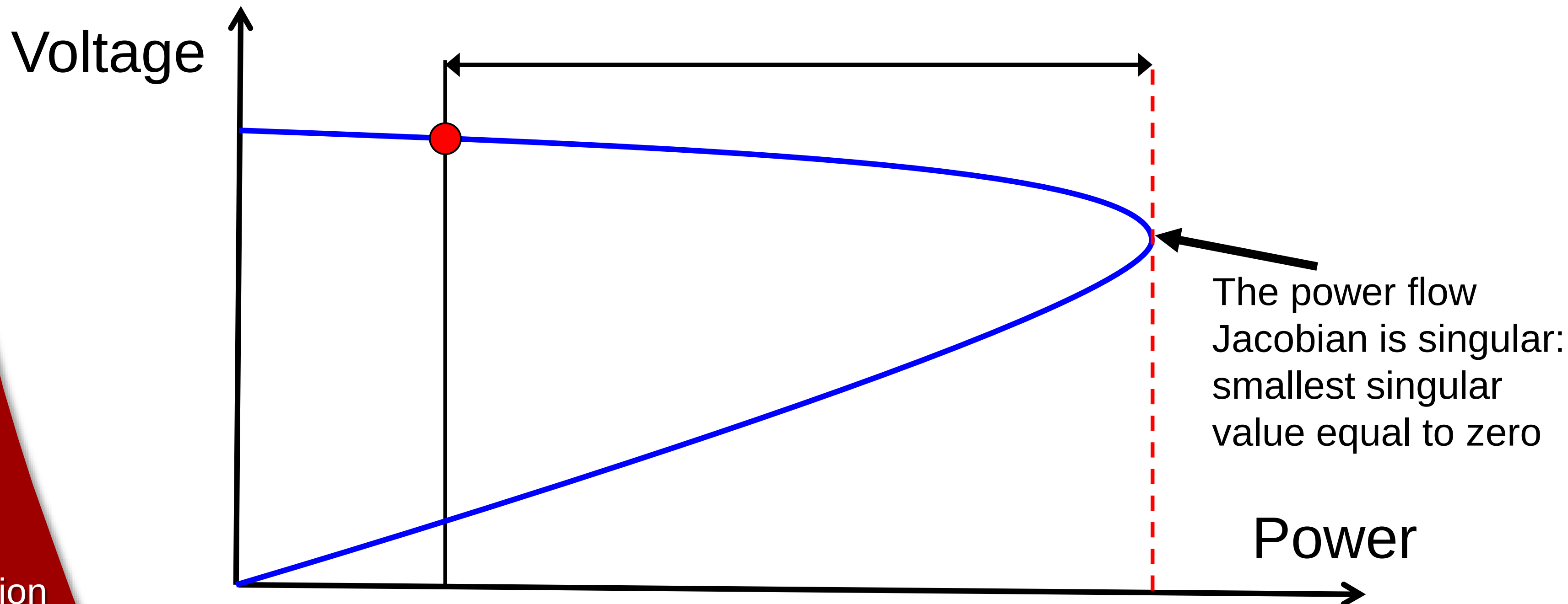
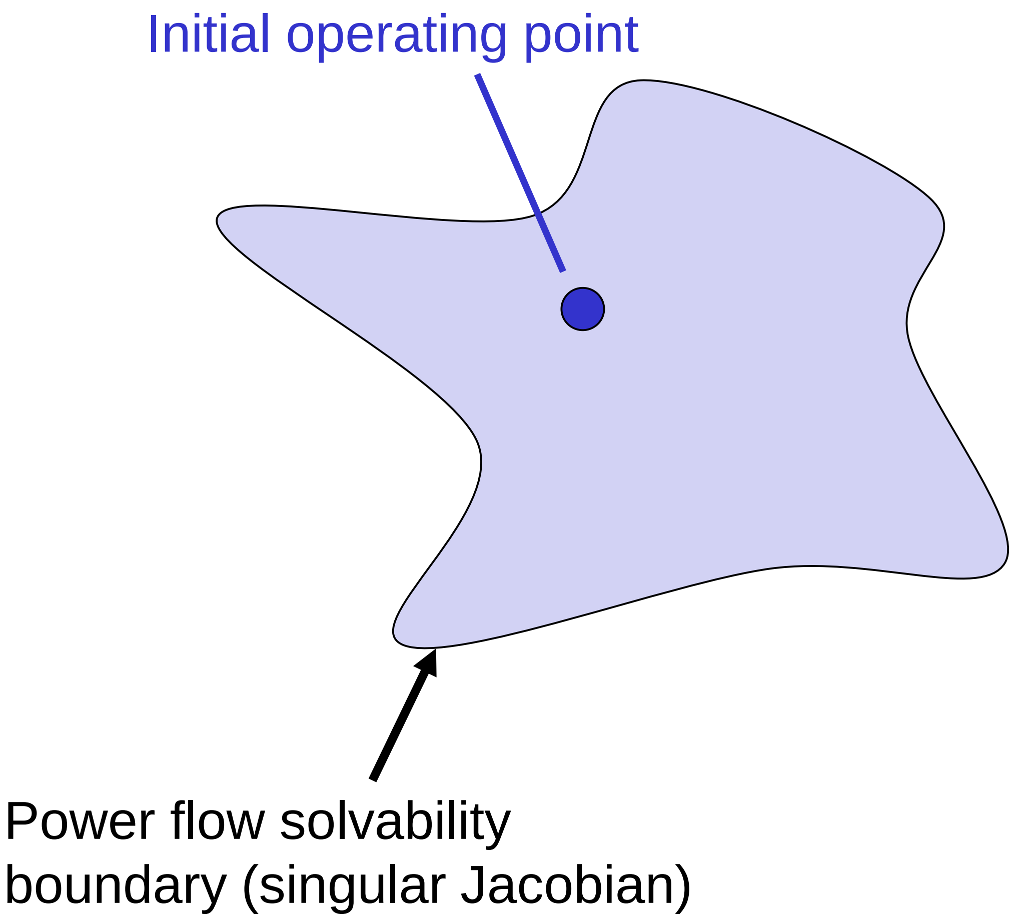


Our Approach

- Maximize the smallest singular value of the power flow Jacobian via control of flexible load demands
- Spatial shifting of loads with total demand held constant over time to maintain frequency stability



Multi-Period Approach



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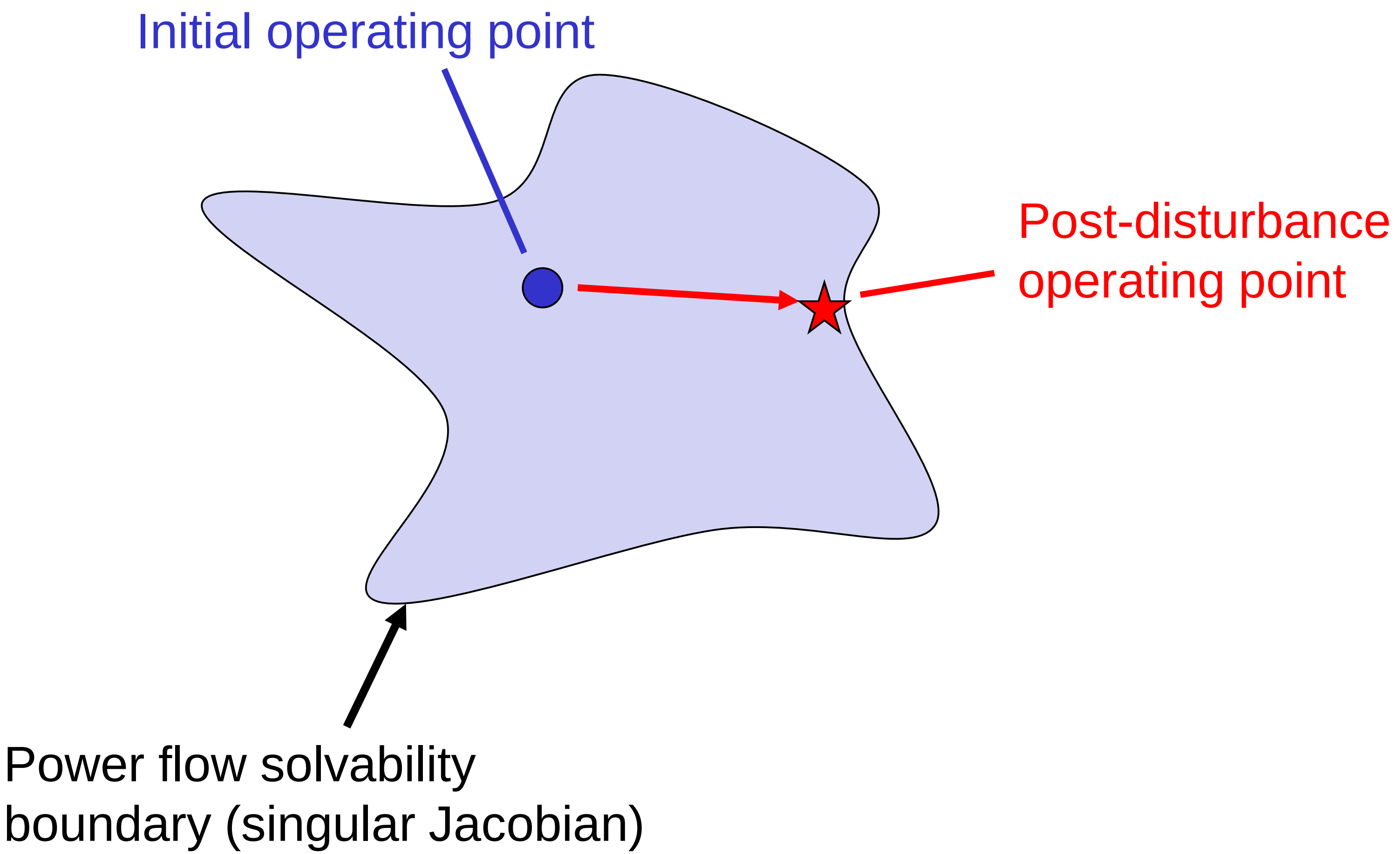
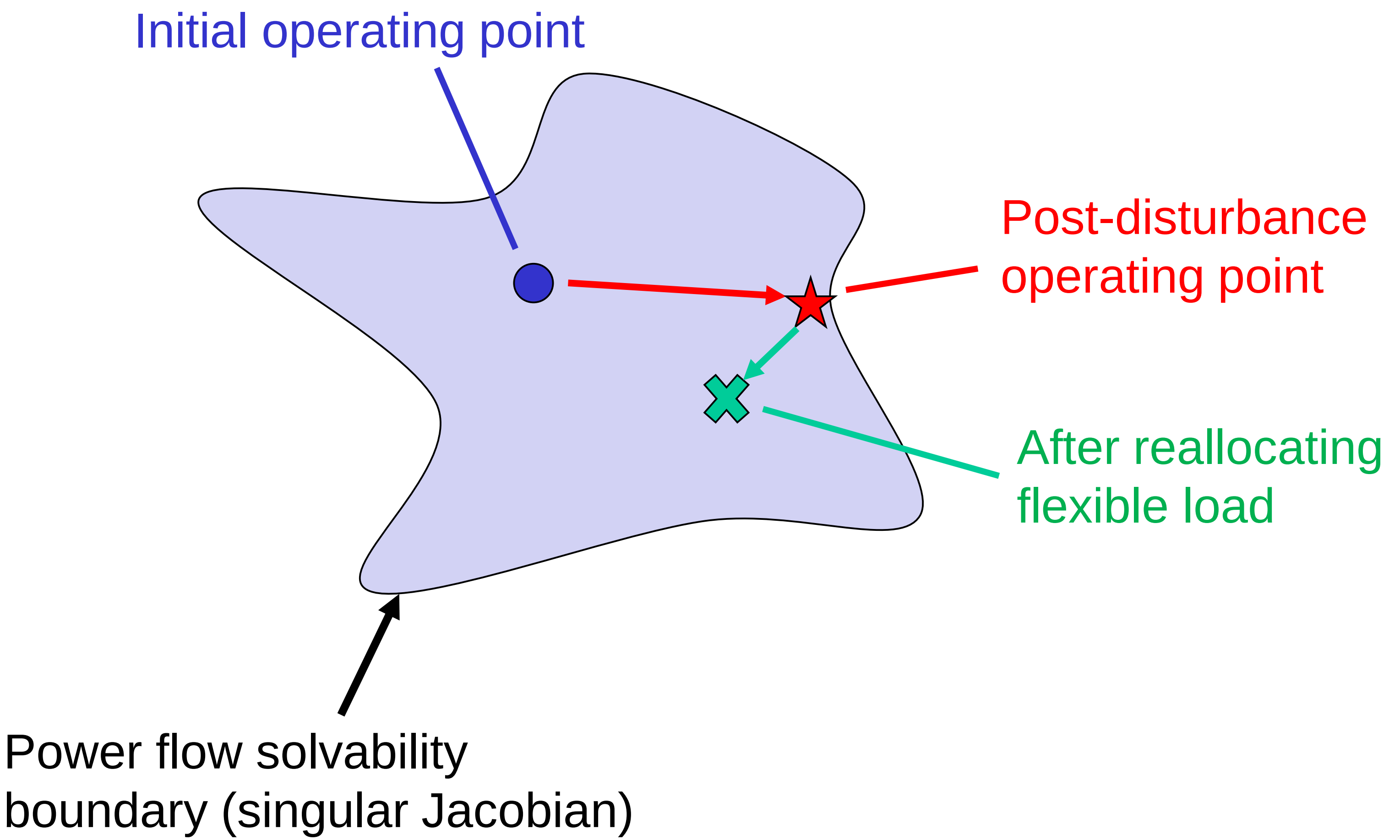
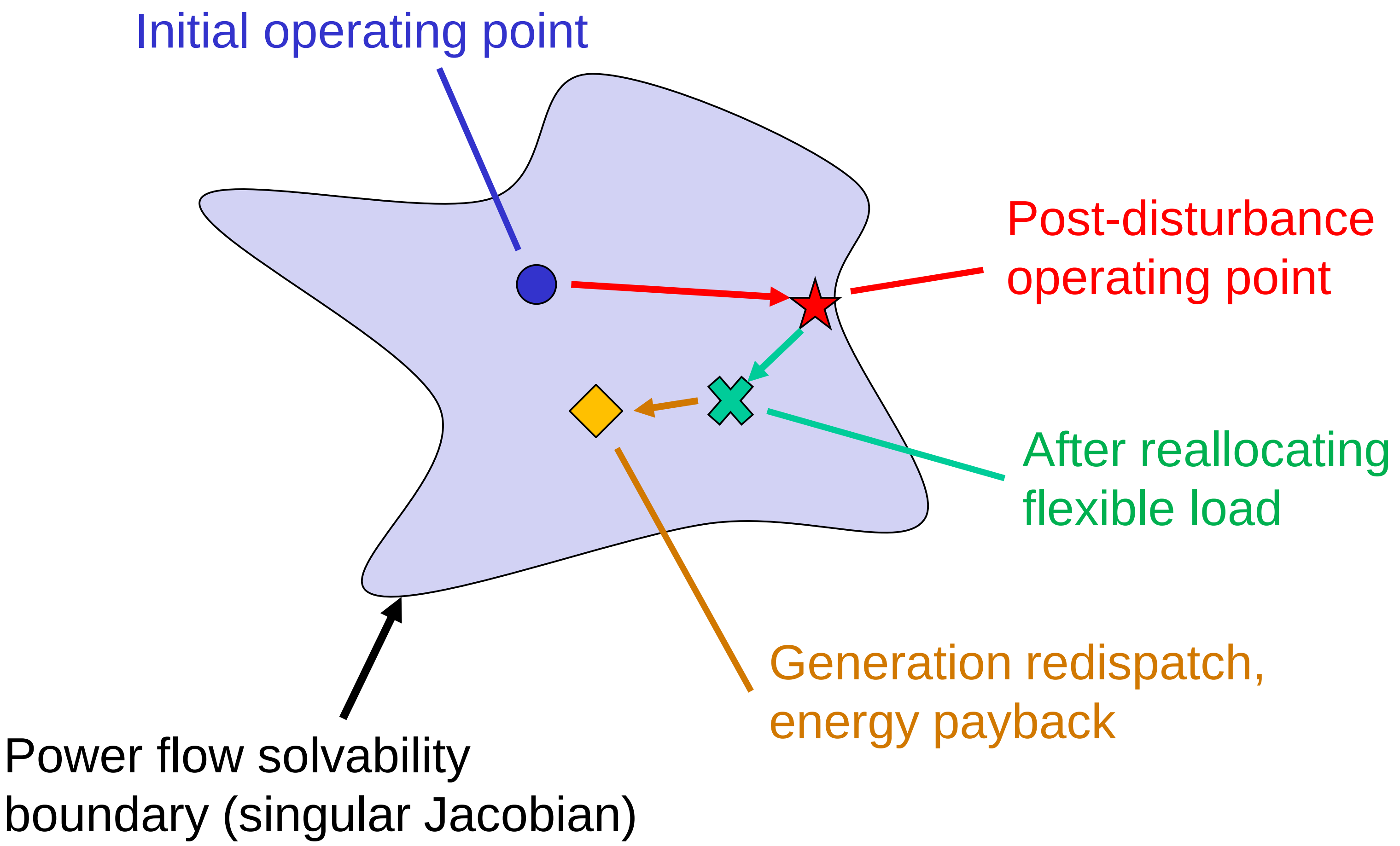


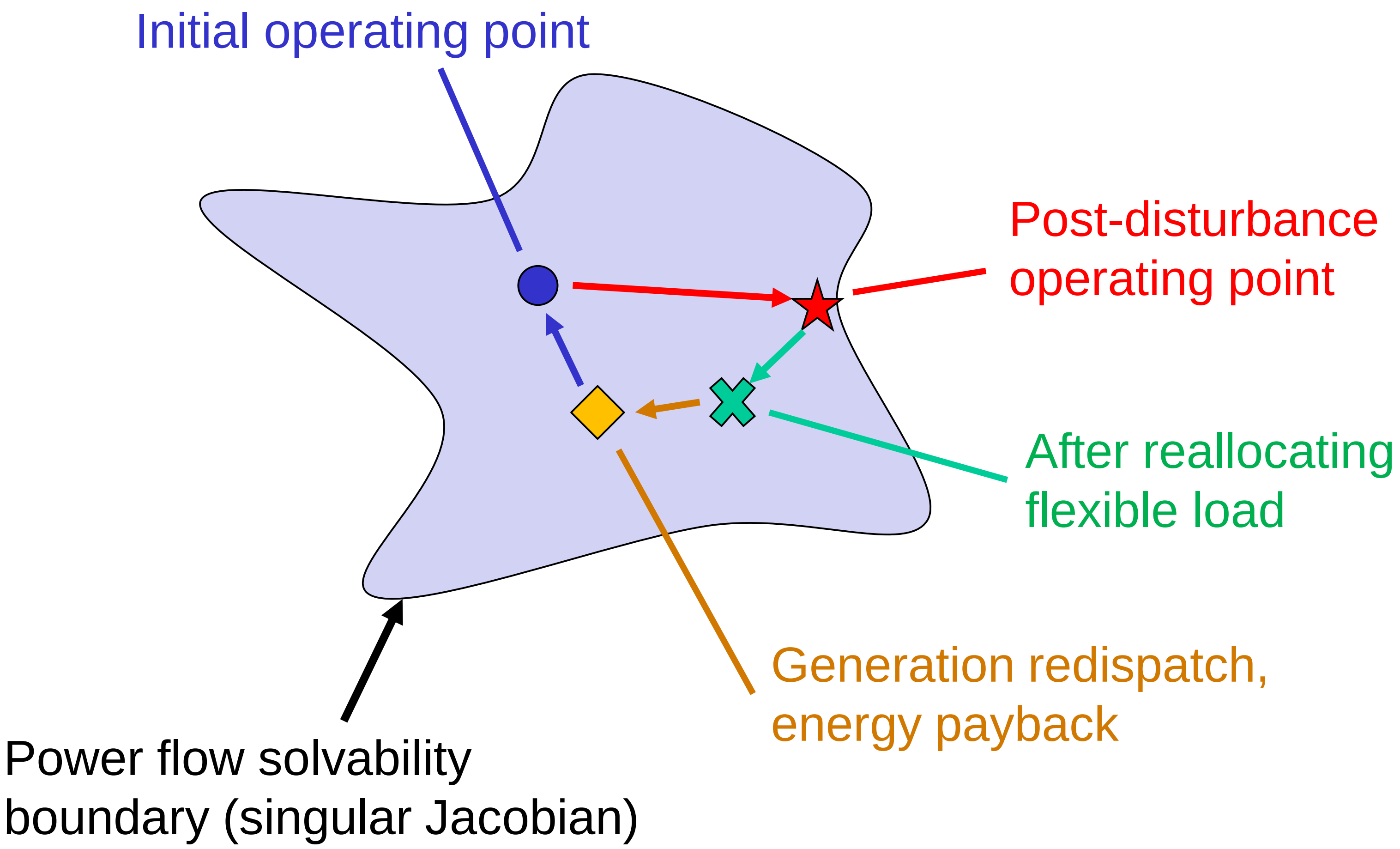
Multi-Period Approach



Multi-Period Approach



Multi-Period Approach



Introduction

Problem Formulation

Assumptions

- Load models
  - Constant power factor
  - Flexible loads at some or all PQ buses
  - Total demand from flexible loads held constant at each period
- Generator models
  - Modeled as PV buses immediately after the disturbance
  - Active power generation redispatched in subsequent periods

We first show the single-period formulation, and then extend to a multi-period setting.

Smallest Singular Value Maximization

$$\max \quad \lambda_0$$

subject to

$$\mathbf{J}(\theta, V)^\intercal \mathbf{J}(\theta, V) - \lambda_0 \mathbf{I} \succeq 0$$

$\lambda_0 \leq$ smallest singular value of the power flow Jacobian

$$\sum_{i \in \mathcal{S}_{DR}} P_{d,i} = P_{d,total}$$

Total flexible load demand is constant

$$\mathcal{F}(x) = 0$$

AC power flow equations

$$\mathcal{G}(x) \geq 0$$

Operational limits

$$x = \{P_g, Q_g, P_d, Q_d, V, \theta\}$$

Directly solving this problem is challenging

Similar to the formulations in [Berizzi et al. ‘01], [Cañizares et al. ‘01]

Solution via Successive Linearization

- Use singular value sensitivities and a linearization of the AC power flow equations

- Sensitivity of the singular values λ_i for the Jacobian $\mathbf{J}(\xi)$ with respect to a parameter in $\xi = \begin{bmatrix} \theta_1 & \ldots & \theta_n & V_1 & \ldots & V_n \end{bmatrix}^\intercal$:

$$\frac{\partial \lambda_i}{\partial \xi} = w_i^\intercal \frac{\partial \left(\left(\mathbf{J}(\xi) \right)^\intercal \mathbf{J}(\xi) \right)}{\partial \xi} u_i$$

Left eigenvector

Right eigenvector

The approximate change in λ_0 is

$$\Delta \lambda_0 = \sum_{i=1}^{n} \left[w_0^\intercal \frac{\partial \left(\left(\mathbf{J}(\xi) \right)^\intercal \mathbf{J}(\xi) \right)}{\partial \theta_i} u_0 \right] \Delta \theta_i + \left[w_0^\intercal \frac{\partial \left(\left(\mathbf{J}(\xi) \right)^\intercal \mathbf{J}(\xi) \right)}{\partial V_i} u_0 \right] \Delta V_i$$

Similar to the approach in [Avalos, Cañizares, & Anjos '08]

Incremental Formulation

$$\max \quad \Delta\lambda_0$$

subject to

Take a step that seeks to increase the smallest singular value

$$\Delta\lambda_0 = \sum_{i=1}^{n} \left[w_0^\intercal \frac{\partial\left(\left(\mathbf{J}\left(\xi\right)\right)^\intercal \mathbf{J}\left(\xi\right)\right)}{\partial\theta_i} u_0 \right] \Delta\theta_i + \left[w_0^\intercal \frac{\partial\left(\left(\mathbf{J}\left(\xi\right)\right)^\intercal \mathbf{J}\left(\xi\right)\right)}{\partial V_i} u_0 \right] \Delta V_i$$

The singular value sensitivity

$$\sum_{i \in \mathcal{S}_{DR}} \Delta P_{d,i} = 0$$

Total flexible load demand is constant

$$f(\Delta x) = 0$$

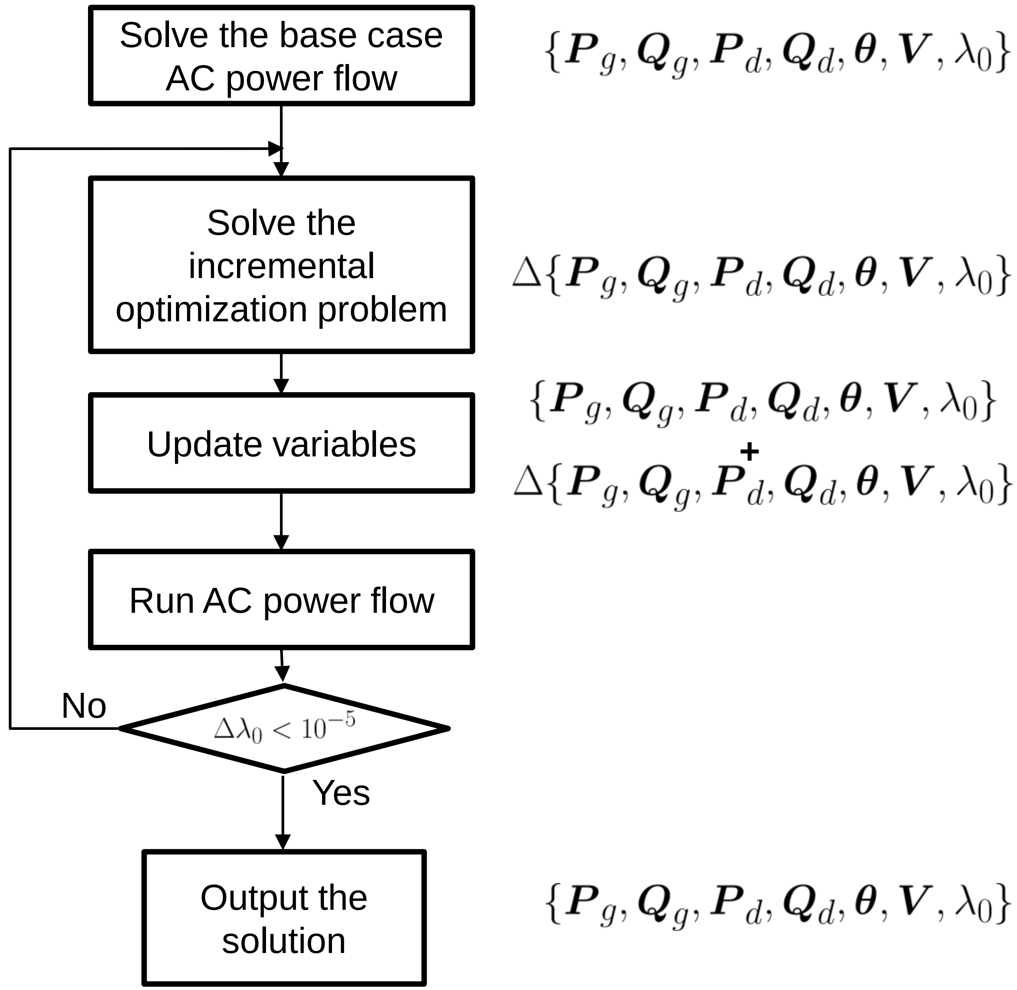
Linearized AC power flow equations

$$g(\Delta x) \geq 0$$

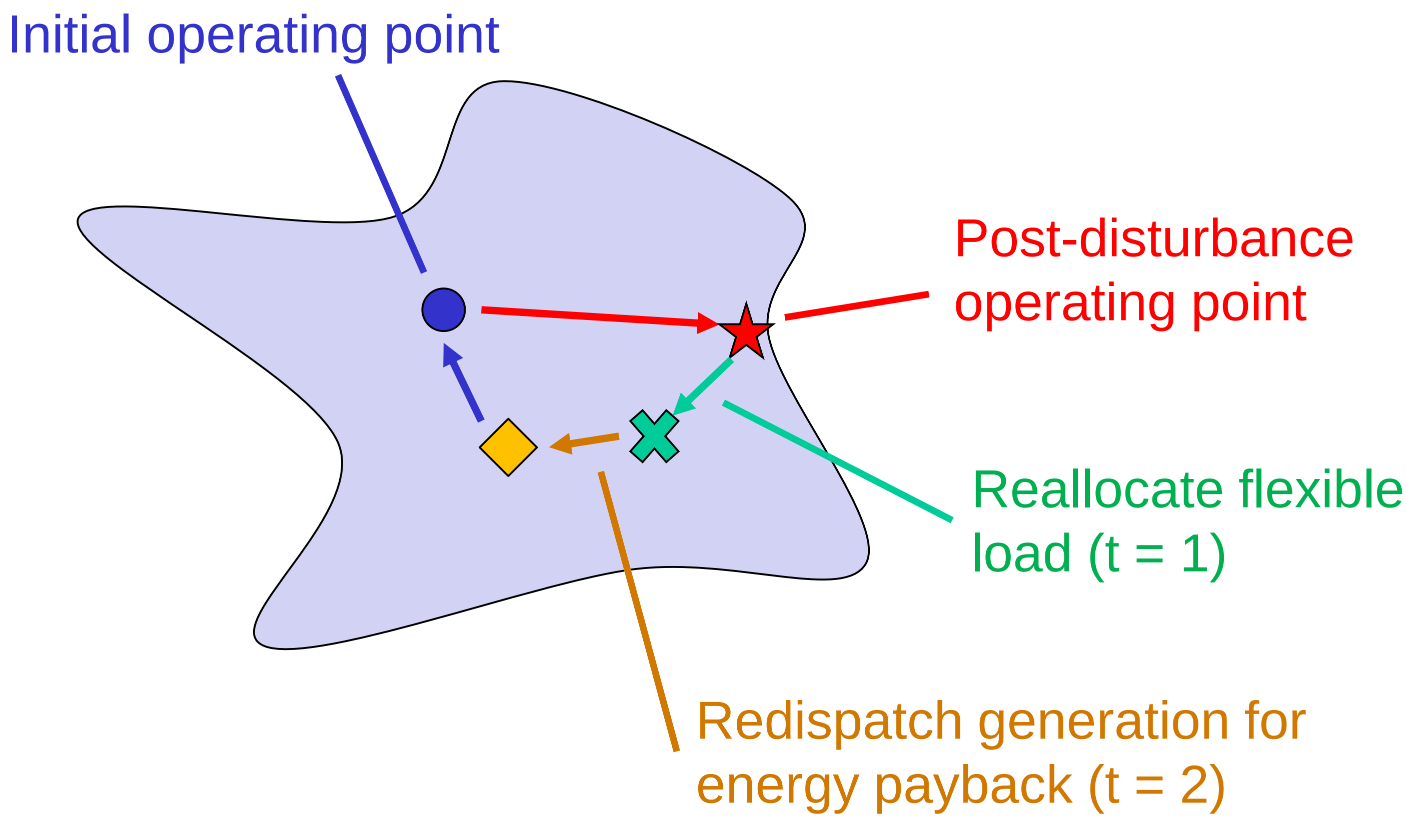
Linearized operational constraints

See [Yao, Mathieu, & Molzahn '17] for the full formulation.

Successive Linearization Algorithm

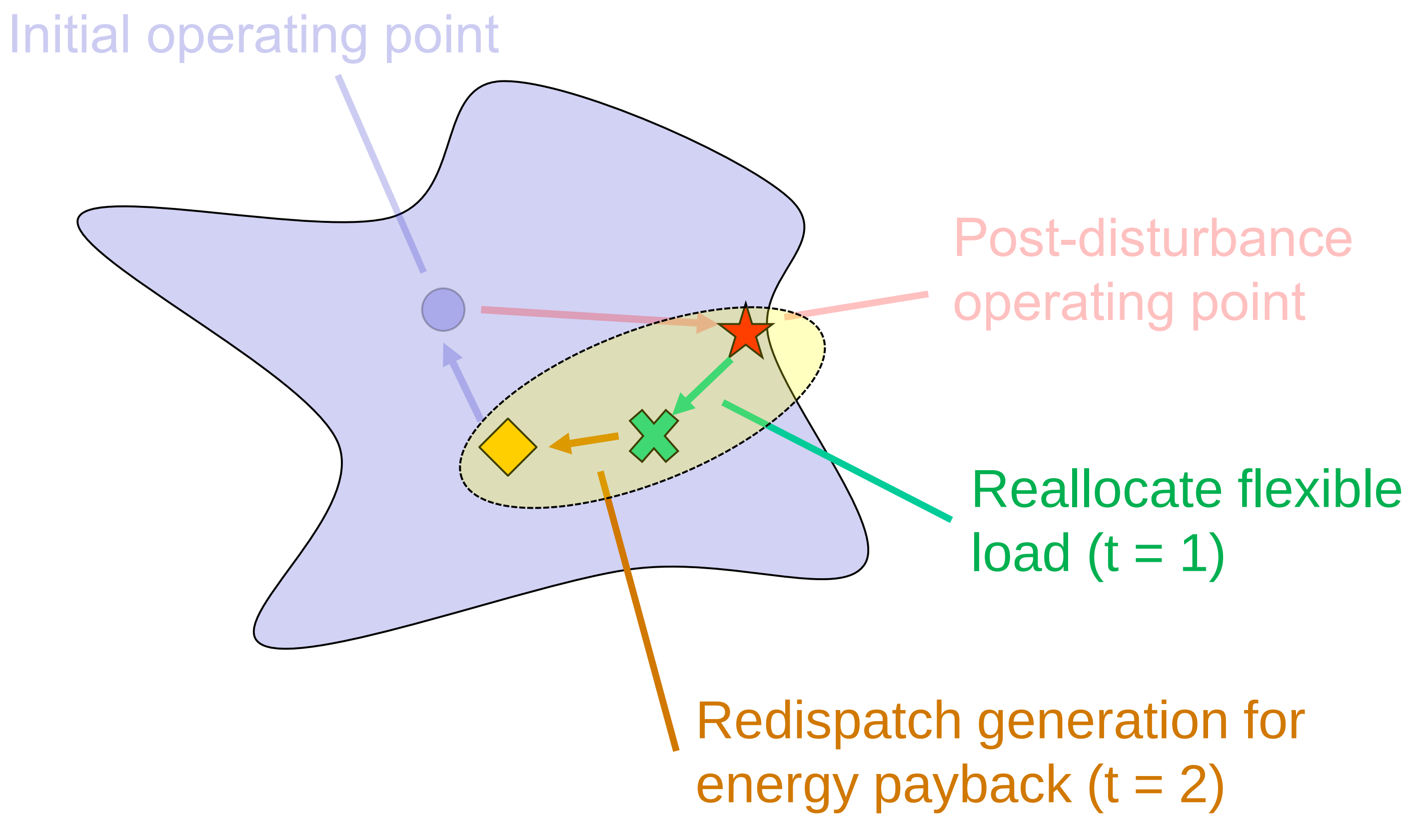


Recall the Multi-Period Approach



Formulation

Recall the Multi-Period Approach



Optimize flexible loads in these steps

Multi-Period Formulation

$$\min_{\mathbf{x}(t)} \quad -\alpha\,\lambda_0(1) + \beta\,\mathcal{C}\left(P_G(2)\right)$$

Optimize a weighted sum of the smallest singular value and the generation redispatch cost for energy payback

subject to

$$\mathbf{J}\,(t)^{\intercal}\mathbf{J}\,(t) - \lambda_0(t)\,\mathbf{I} \succeq 0$$

$\lambda_0(t) \leq$ smallest singular value of the power flow Jacobian

$$\sum_{i \in \mathcal{S}_{DR}} P_{d,i}(1) = P_{d,total}$$

Total flexible load demand is constant

$$P_{d,i}(1) + P_{d,i}(2) = P^{\circ}_{d,i}, \;\; \forall i \in \mathcal{S}_{DR}$$

Power demand shifted from flexible loads is “paid back”

$$\mathcal{F}\left(x(t)\right) = 0, \quad \mathcal{G}\left(x(t)\right) \geq 0$$

AC power flow equations and operational limits

t=1: Smallest singular value maximization

t=2: Energy payback for flexible loads

Multi-Period Formulation

$$\min_{\mathbf{x}(t)} \quad -\alpha\,\lambda_0(1) + \beta\,\mathcal{C}\left(P_G(2)\right)$$

Optimize a weighted sum of the smallest singular value and the generation redispatch cost for energy payback

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Power demand shifted from flexible loads is “paid back”

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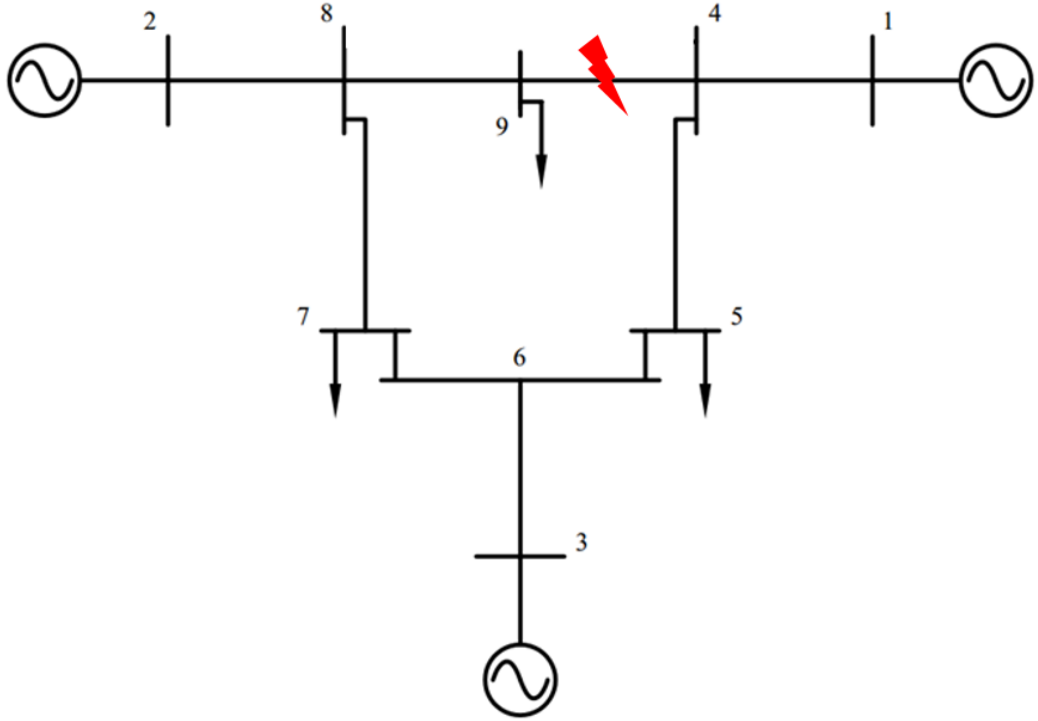
AC power flow equations and operational limits

Solve using a successive linearization algorithm

Test Cases

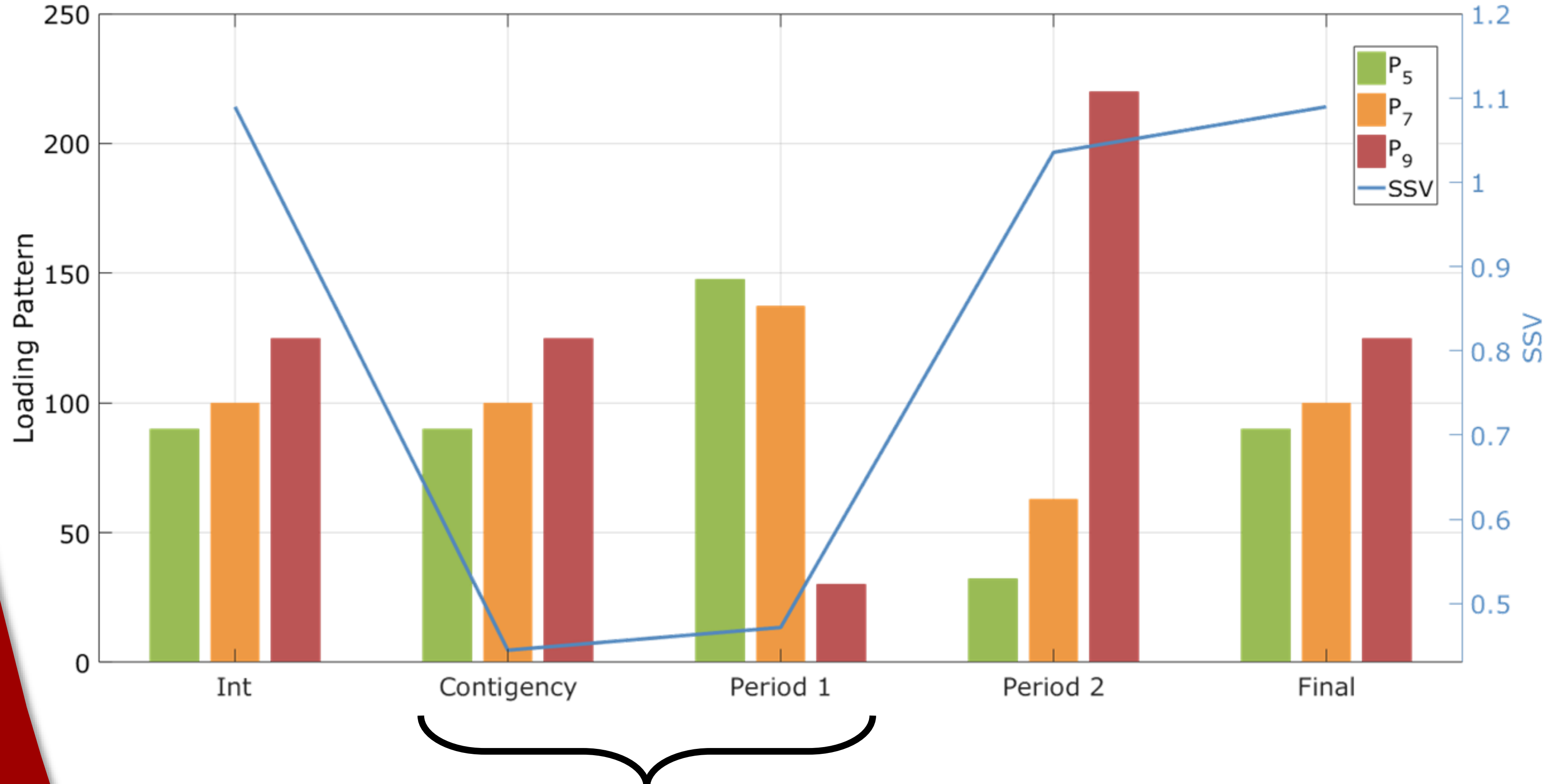
Nine-Bus Test Case



Smallest Singular Value: 1.0895 → 0.4445

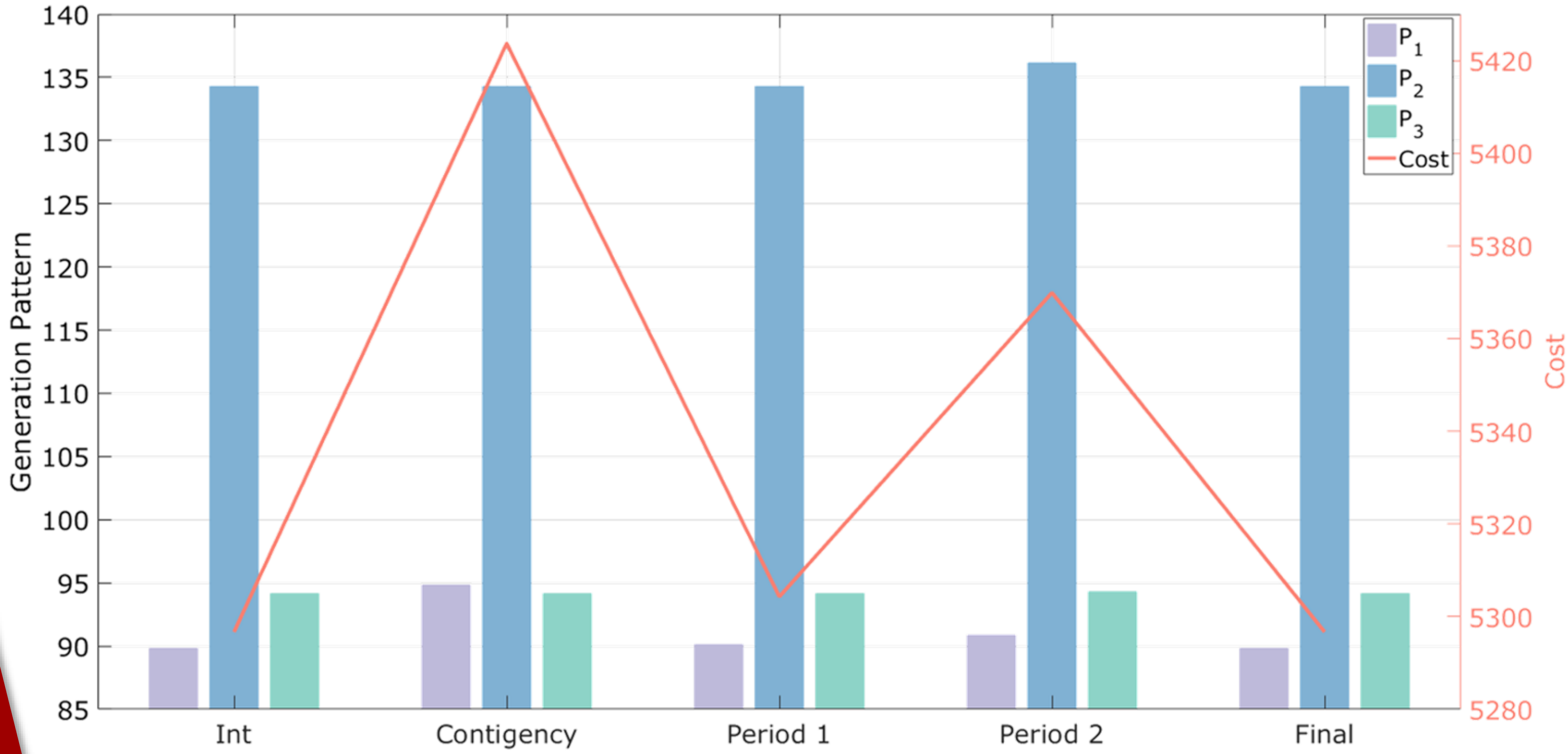
59% decrease

Results: Smallest Singular Value



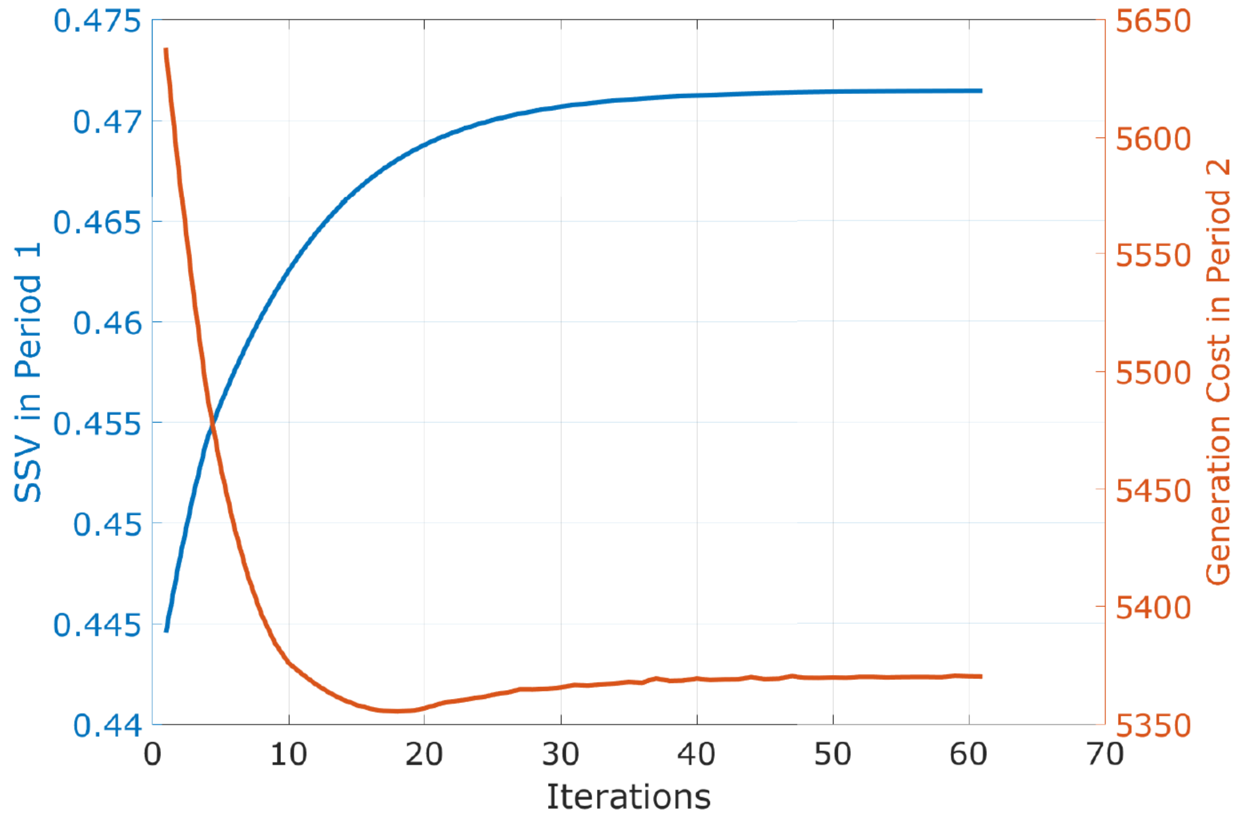
6.1% improvement in the smallest singular value from spatially shifting controllable loads

Results: Generation Cost



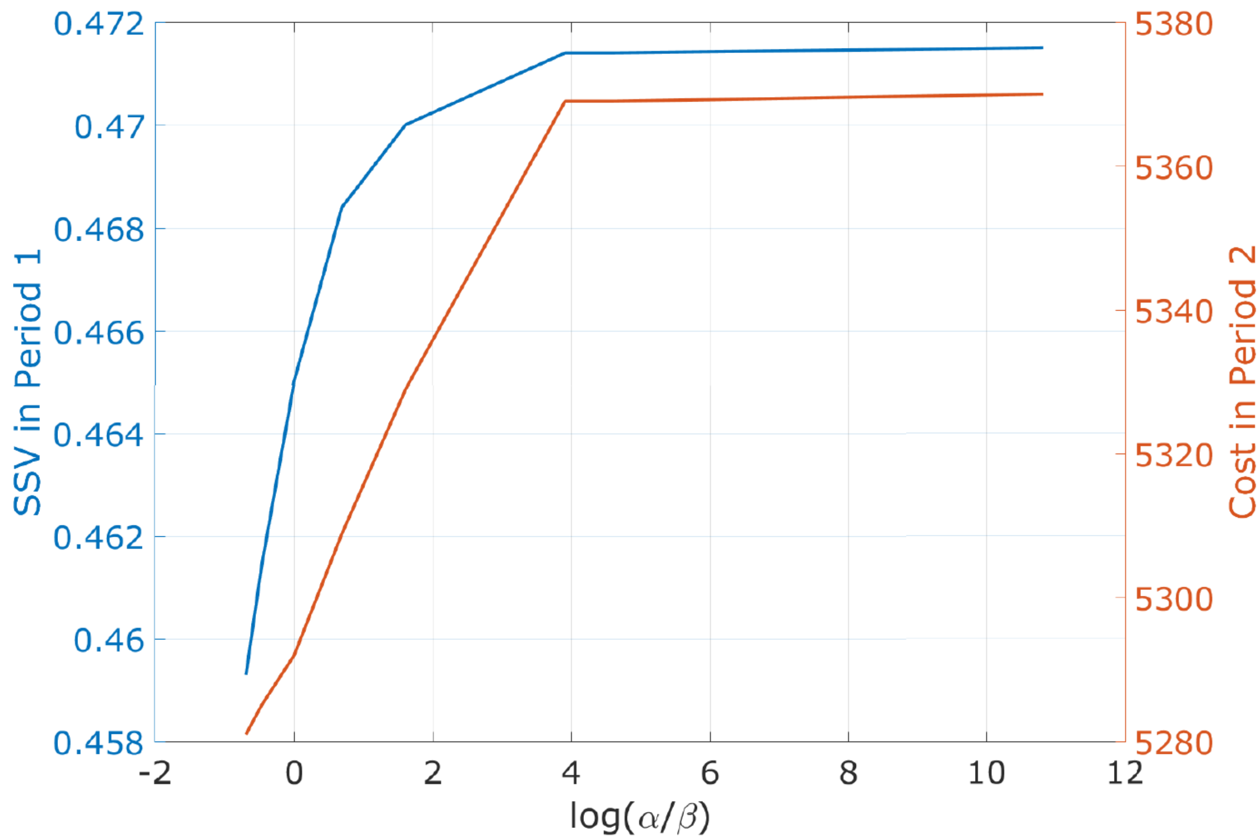
0.8% increase in generation cost from spatially shifting controllable loads

Convergence Rate



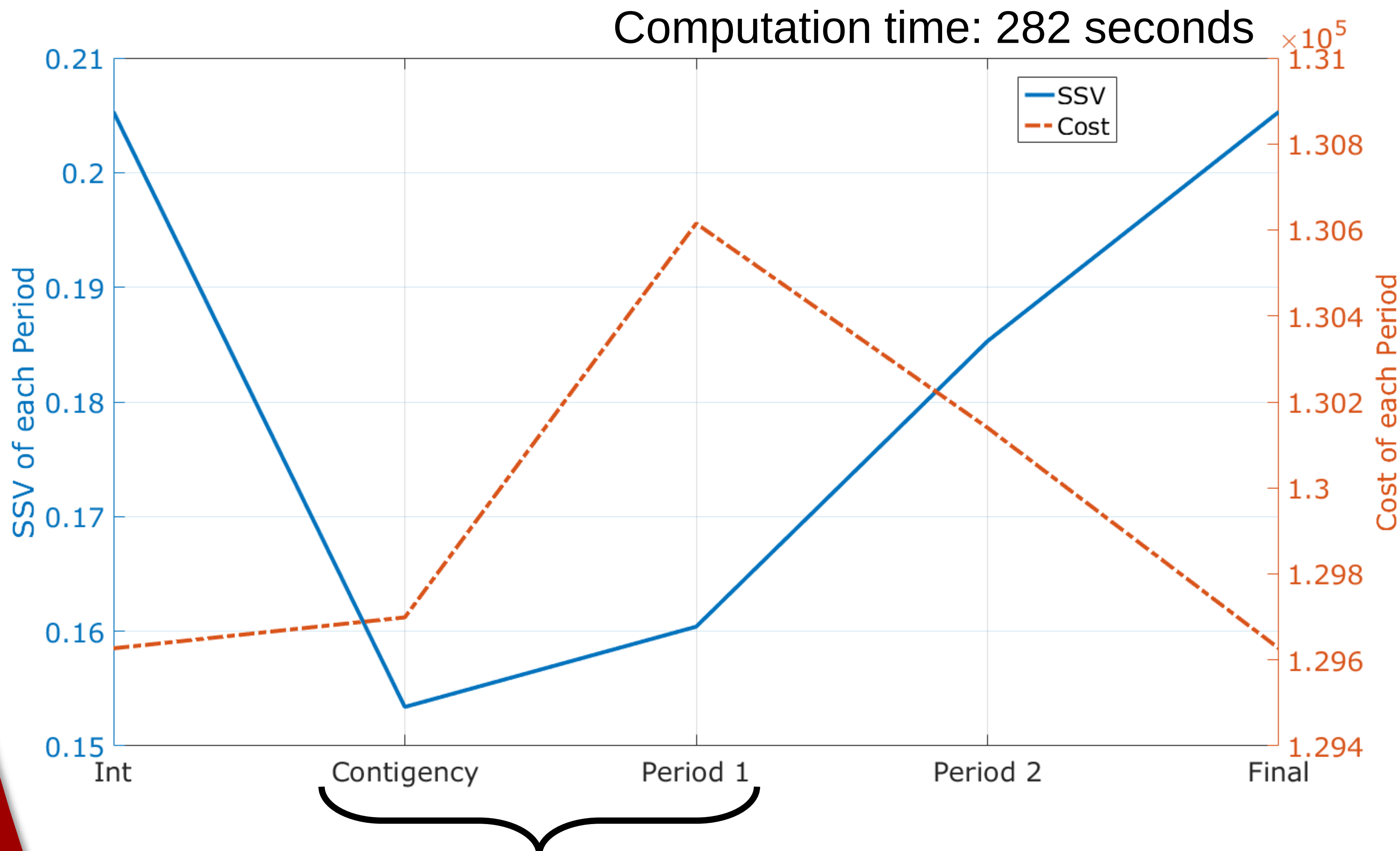
The successive linear programming algorithm typically converges in a few tens of iterations

Trade-Off Between Smallest Singular Value and Generation Cost



The weights in the objective function effectively control the trade-off between higher generation cost and improved voltage stability margins

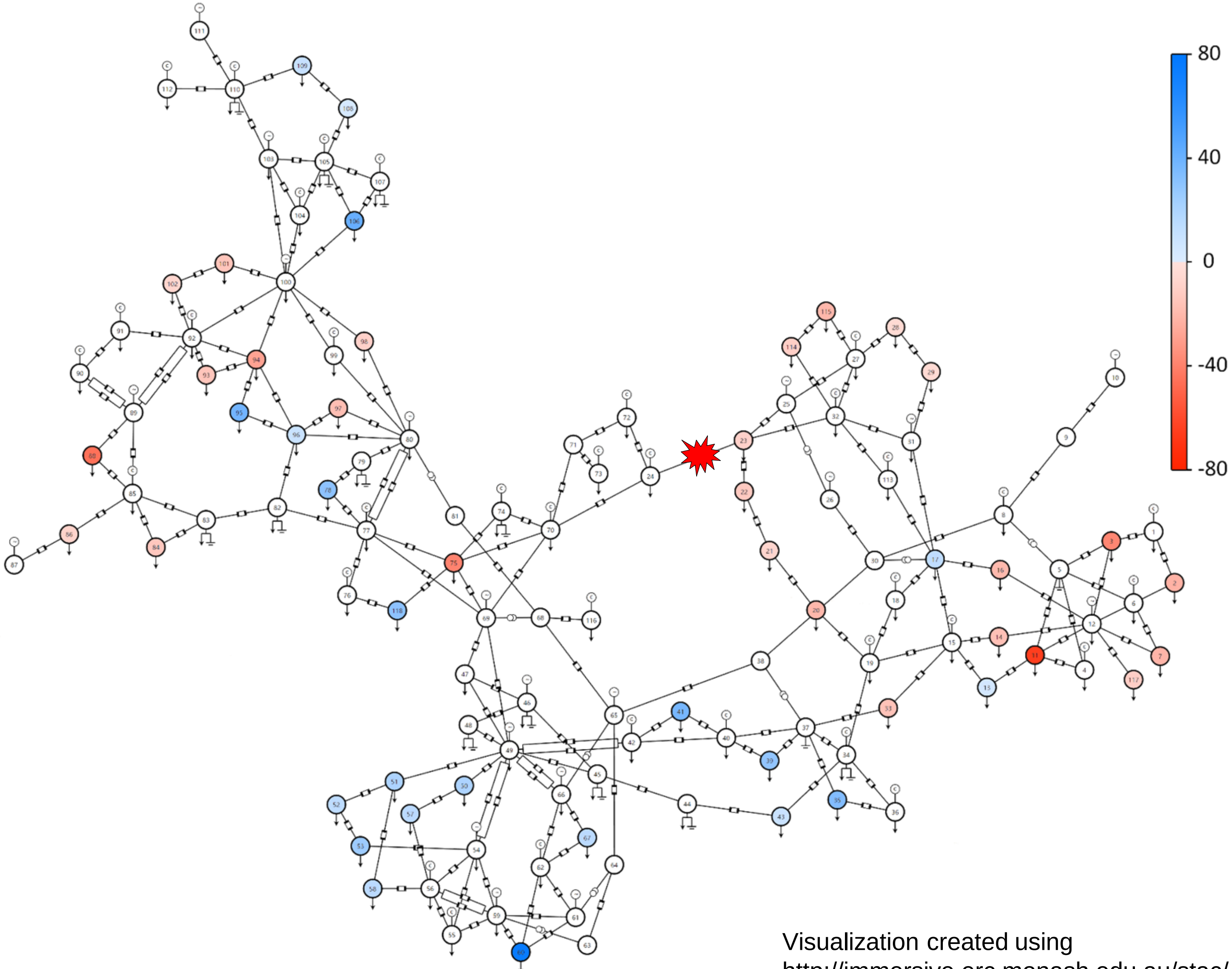
IEEE 118-Bus Test Case



4.6% improvement in the smallest singular value

0.2% increase in the total generation cost

IEEE 118-Bus Test Case



Visualization created using
http://immersive.erc.monash.edu.au/stac/

Conclusion

Conclusion

- Spatial shifting of load can improve voltage stability margins after a disturbance
- To determine appropriate load control, we formulated a multi-period optimization problem and applied a successive linearization solution algorithm
- Future work:
  - Incorporating more detailed load models (ZIP loads)
  - Improving computational speed
  - Characterizing closeness to global optimality using convex relaxation techniques

Questions?

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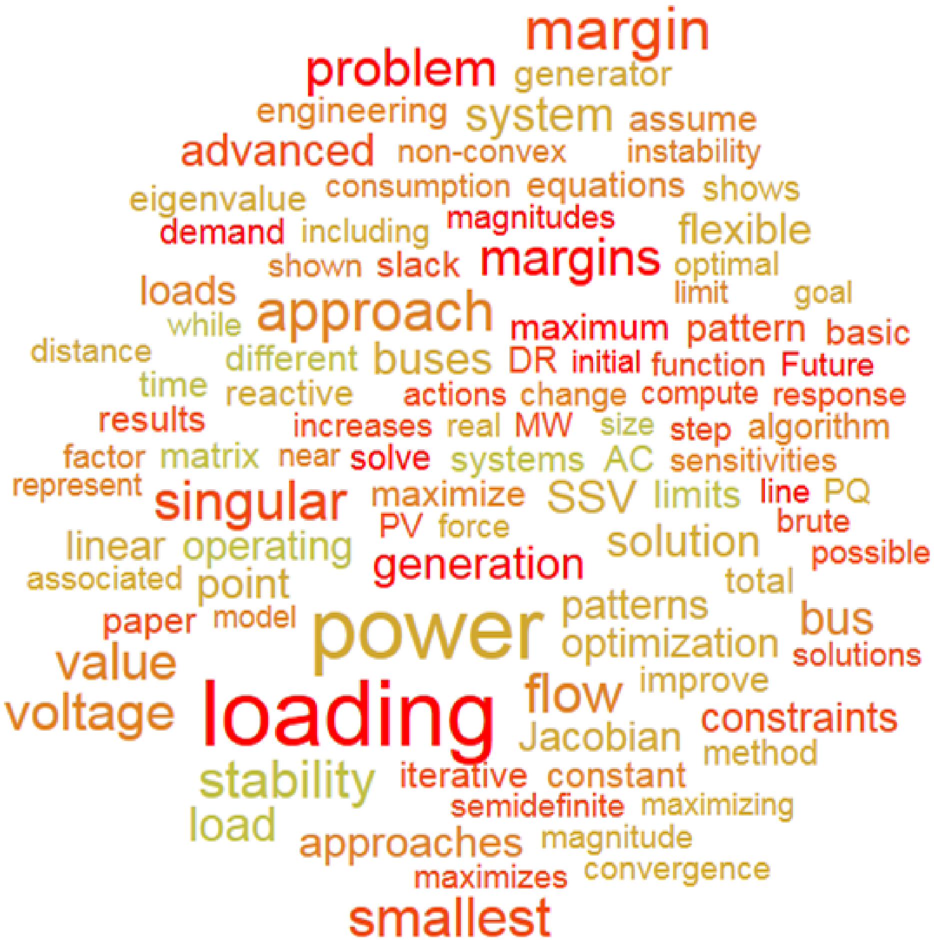

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