A Comparative Analysis of Switchings in Static and Dynamic Power Grids

Master's Thesis Presentation

Adrian Grupp | 28 April 2020

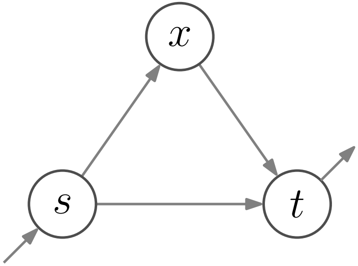
INSTITUTE OF THEORETICAL INFORMATICS – RESEARCH GROUP ALGORITHMICS I

Image Source: svs.gsfc.nasa.gov/30028

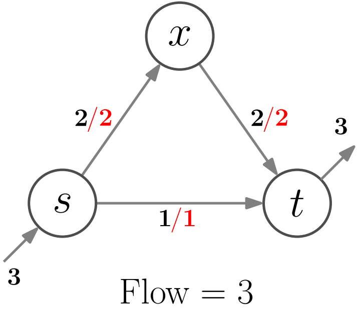
Overview

- Shift towards renewables $\Rightarrow$ decentrality & volatility
- **Switching**: Remove transmission lines to improve the power flow
- Can a static algorithm guarantee safe dynamic operation?
- Static and dynamic model for high voltage grid

Static Model [GRW+18]



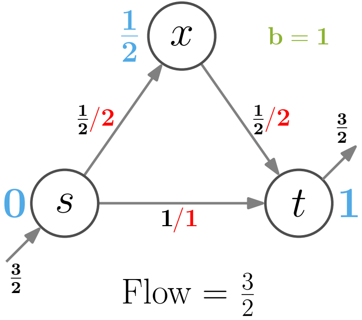
Static Model [GRW+18]



Edge flow: $f(e)$

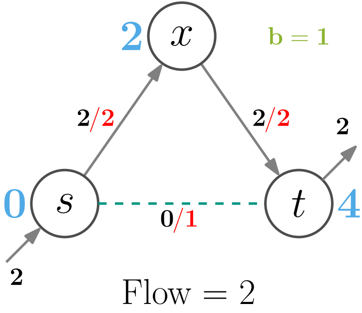
Capacity: $cap : E \to \mathbb{R}_{\geq 0}$

Static Model [GRW+18]



Edge flow:	$f(e) = b(e) \cdot (\Theta(j) - \Theta(i))$
Capacity:	$cap : E \to \mathbb{R}_{\geq 0}$
Potential angle:	$\Theta : V \to \mathbb{R}_{\geq 0}$
Susceptance:	$b : E \to \mathbb{R}_{\geq 0}$

Static Model [GRW+18]



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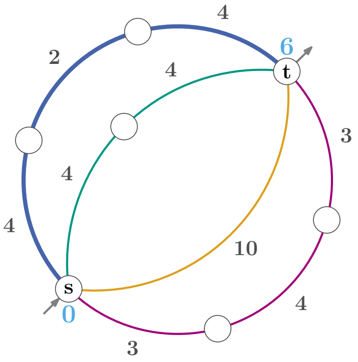
Switching Heuristic [GRW+18]

Let $\pi(s,t)$ a path from s to t:

$$\|\pi\| = \sum_{e\in\pi} b(e)^{-1} (= \text{length of } \pi)$$



$\|\pi_1\| = 3$

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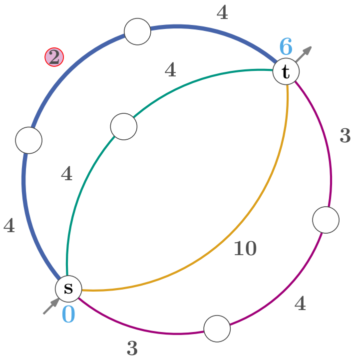

$$\|\pi_1\| = 3$$

$$\underline{\text{cap}}(\pi_1) = 2$$

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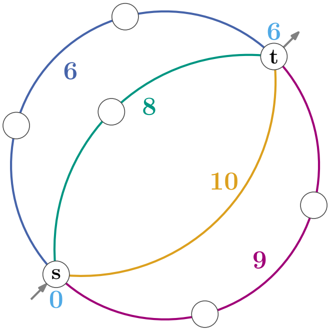
$$\Delta\theta(\pi) = \|\pi\| \cdot \underline{\text{cap}}(\pi)$$



$$\|\pi_1\| = 3$$

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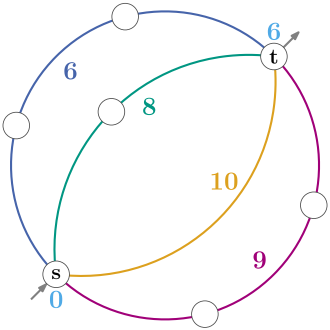
$$\pi_{\text{lim}}(s,t) = \min\{\Delta\theta(\pi) \mid \pi \text{ is } s\text{-}t\text{-path}\}$$



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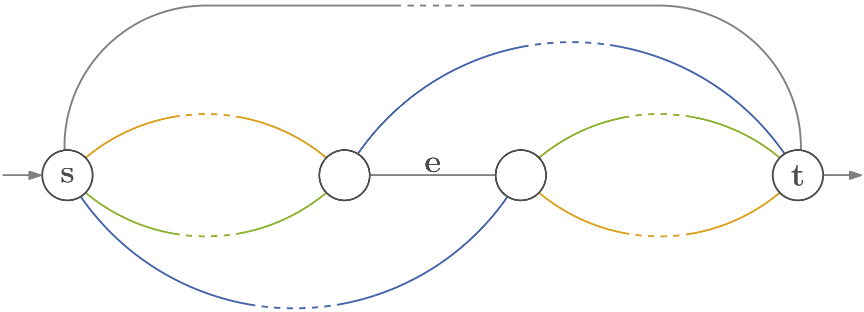
Switching Heuristic [GRW+18]

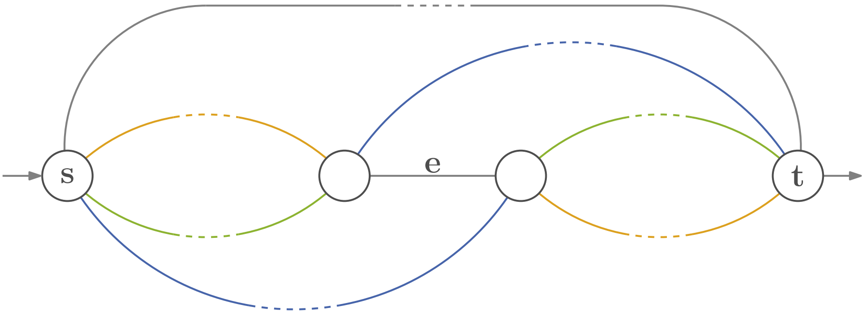
Switching Centrality: Which edge limits the power flow in most cases?



Switching Heuristic [GRW+18]

Switching Centrality: Which edge limits the power flow in most cases?

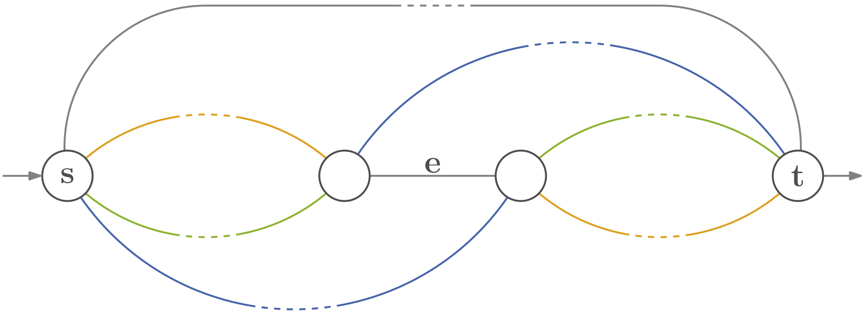
$$c_{\text{sw}}(e) := \frac{\#\pi_{\text{lim}}(s,t,e)}{\#\pi_{\text{lim}}(s,t)}$$



Switching Heuristic [GRW+18]

Switching Centrality: Which edge limits the power flow in most cases?

$$c_{\mathrm{sw}}(e) := \frac{1}{m} \sum_{s \in V} \sum_{t \in V \setminus \{s\}} \frac{\#\pi_{\mathrm{lim}}(s, t, e)}{\#\pi_{\mathrm{lim}}(s, t)}$$



Dynamic Model

What are the effects of switching over time?

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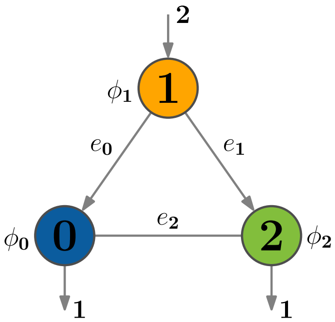
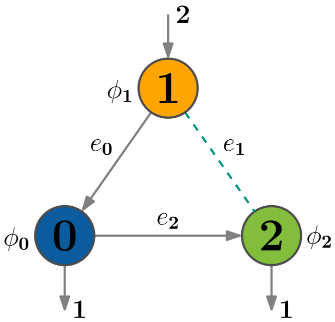


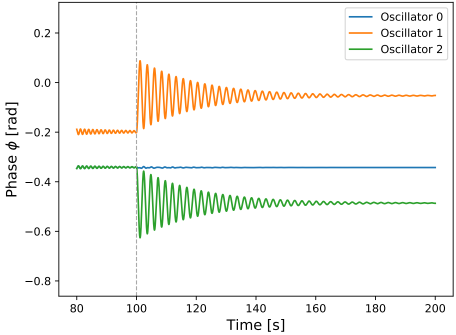
Switching of e_1 at $t_0 = 100$

Dynamic Model

What are the effects of switching over time?

$\Rightarrow$ Phase angles ϕ_i adopt





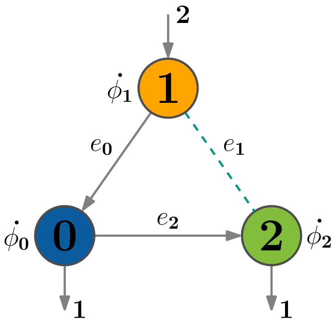
Switching of e_1 at $t_0 = 100$

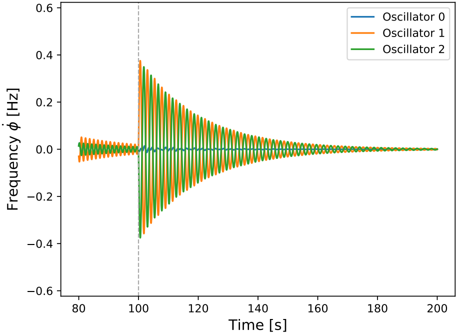
Dynamic Model

What are the effects of switching over time?

$\Rightarrow$ Phase angles ϕ_i adopt

$\Rightarrow$ Frequencies $\dot{\phi}_i$ are perturbed

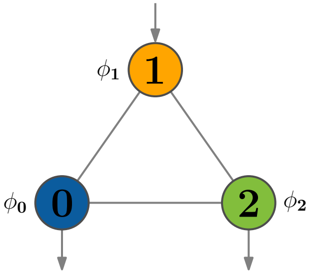




Switching of e_1 at $t_0 = 100$

Coupled Oscillators [FNP08]

- How do phase and frequency develop over time?
- Characterize generators and loads by their rotations



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- How do phase and frequency develop over time?
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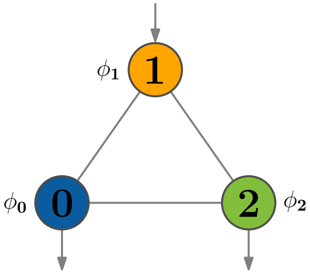
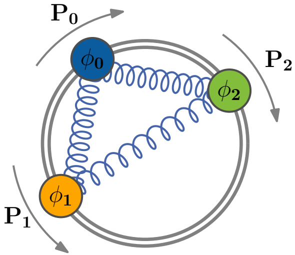
$$\ddot{\phi}_i = \underbrace{P_i}_{\text{generated power}} - \underbrace{\alpha\dot{\phi}_i}_{\text{damping}} + \sum_{j=1}^{n} \underbrace{K_{ij}\sin(\phi_j - \phi_i)}_{\text{transmitted power}}$$





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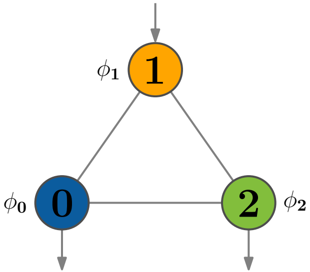

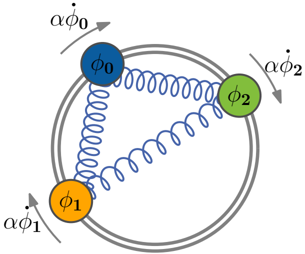

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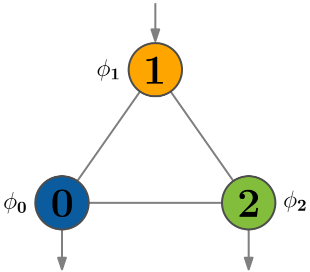

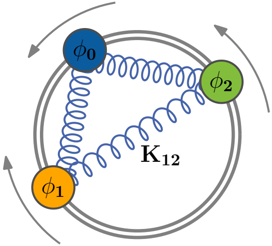

Evaluation

- NESTA Dataset [CGS14]
- Compute switching centrality
- Solve dynamic equations
- Compare properties

Stability

Does the switching centrality correlate to system stability?

- Small-signal analysis
- Mean-field theory

Stability

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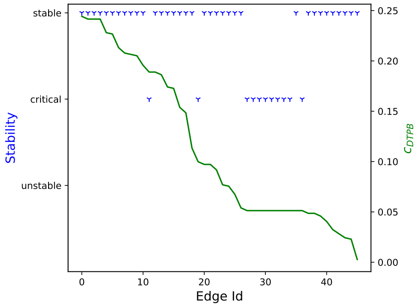

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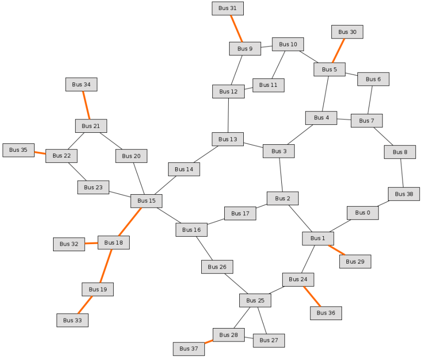
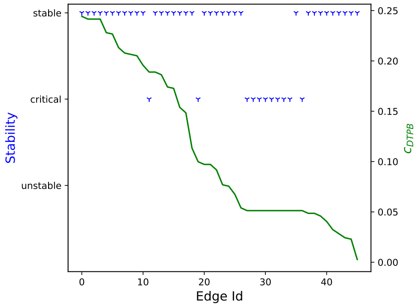
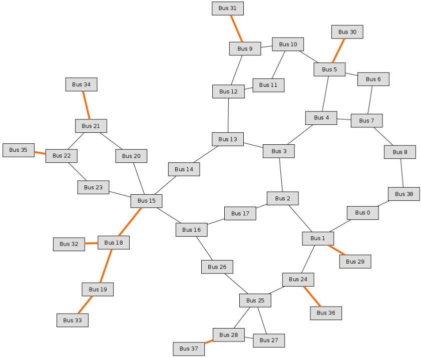


Stability

Does the switching centrality correlate to system stability?





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⇒ Switchings with highest centrality yield a stable network.

Load Redistribution

Is more load redistributed after switching with lower centrality?

- Edge load: Capacity saturation with load flow

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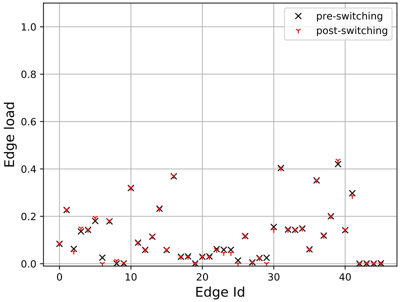
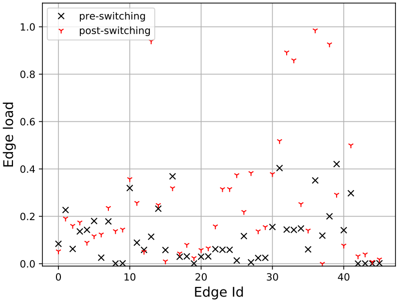
- Edge load: Capacity saturation with load flow



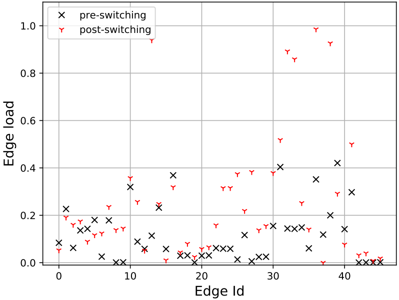
Highest centrality

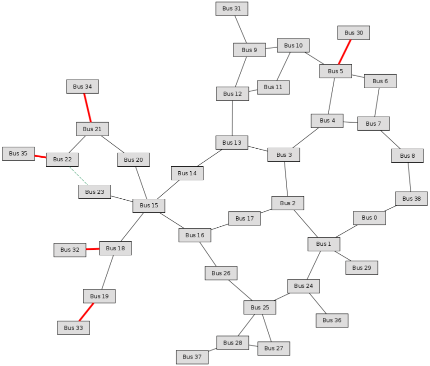


Lowest centrality

Load Redistribution

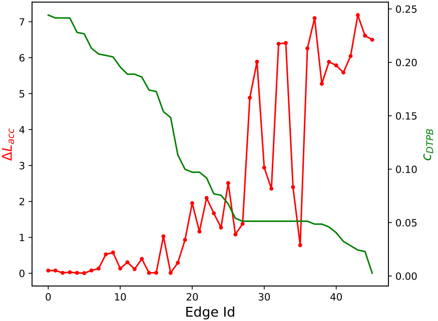
- Switching of edge $(22, 23)$





Accumulated Load Redistribution

- Load redistributed over all edges: $\Delta_{L_{acc}}$



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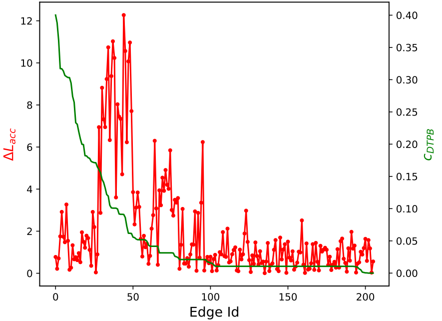

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Accumulated Load Redistribution

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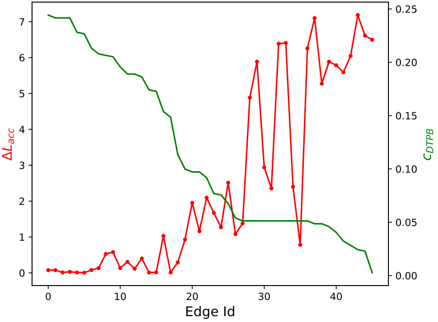

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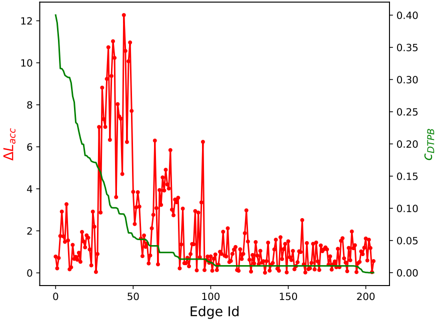

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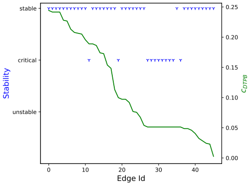
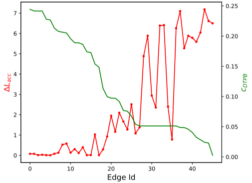
$\Rightarrow$ Lower centrality leads to more redistribution in many cases.

Conclusion

- Connect static and dynamic model
- Centrality measure provides useful switchings
- Stable net for high centrality
- More load redistribution for low centrality
- Exceptions due to topological properties





Future Work

- Limit heuristic to certain topologies (2-connected, ...)
- Refine dynamic model
- Time-expanded networks
  - Invalid states
  - Continuous Time-expanded

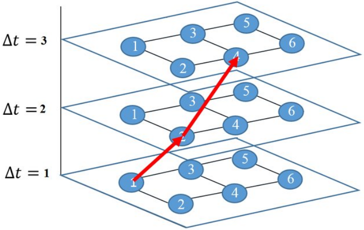


Image Source: A Decomposition Algorithm to Solve the Multi-Hop Peer-to-Peer Ride-Matching Problem - N. Masoud et al.

Sources

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G. Filatrella, A. H. Nielsen, and N. F. Pedersen.
Analysis of a power grid using a Kuramoto-like model.
The European Physical Journal B, 61(4):485–491, feb 2008.

Alban Grastien, Ignaz Rutter, Dorothea Wagner, Franziska Wegner, and Matthias Wolf.
The Maximum Transmission Switching Flow Problem.
pages 340–360, 2018.

Small-Signal Analysis

1) Reduce to first order

$$\dot{\phi}_i = \omega_i$$

$$\dot{\omega}_i = \underbrace{P_i - \alpha\omega_i + \sum_{j=1, j\neq i}^{n} K_{ij} \sin(\phi_j - \phi_i)}_{=f_i(\phi,\omega)}$$

System:

$$\begin{pmatrix} \dot{\phi} \\ \dot{\omega} \end{pmatrix} = \begin{pmatrix} \omega \\ f(\phi, \omega) \end{pmatrix}$$

2) Find equilibrium point $\boldsymbol{a} = (\phi_1', \dots, \phi_N', \omega_1', \dots, \omega_N')$

$$0 = \omega_i'$$

$$0 = P_i + \sum_{j=1, j\neq i}^{n} K_{ij} \sin(\phi_j' - \phi_i')$$

$$\begin{pmatrix} 0 \\ 0 \end{pmatrix} = \begin{pmatrix} \omega' \\ f(\boldsymbol{a}) \end{pmatrix}$$

Small-Signal Analysis

3) Linearization:

$$\begin{pmatrix} \dot{\phi} \\ \dot{\omega} \end{pmatrix} = \begin{pmatrix} \omega \\ f(\boldsymbol{a}) \end{pmatrix} \qquad \Longrightarrow \qquad \begin{pmatrix} \dot{\phi} \\ \dot{\omega} \end{pmatrix} = \begin{pmatrix} \omega' \\ f(\boldsymbol{a}) \end{pmatrix} + \boldsymbol{J}(\boldsymbol{a}) \cdot (\begin{pmatrix} \phi \\ \omega \end{pmatrix} - \boldsymbol{a})$$

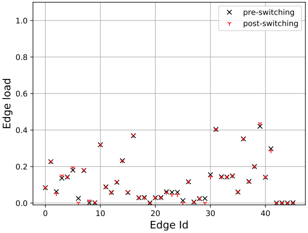
4) Calculate eigenvalues λ_i for $\boldsymbol{J}(\boldsymbol{a})$:

Stable:	$\mathrm{Re}(\lambda_i) < 0 \; \forall i$
Unstable:	$\exists i : \mathrm{Re}(\lambda_i) > 0$
Unknown (“critical”):	$\mathrm{Re}(\lambda_i) \leq 0 \; \forall i \wedge \exists i : \mathrm{Re}(\lambda_i) = 0$

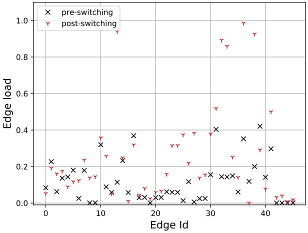
Edge Load

$$\ddot{\phi}_i = P_i - \alpha\dot{\phi}_i + \sum_{j=1}^{n} \underbrace{K_{ij}\sin(\phi_j - \phi_i)}_{=F_{ji}}$$

$$\text{Edge load: } L_{ij} = \frac{F_{ij}}{K_{ij}} = \sin(\phi_j - \phi_i)$$



Highest centrality

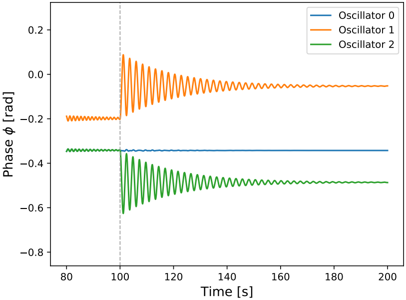


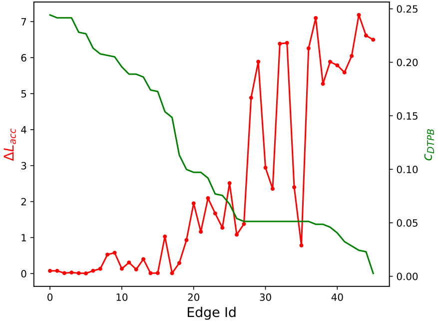
Lowest centrality

Accumulated Load Redistribution

- $L^1_{ij} = L_{ij}(t_0 - \delta), \qquad L^2_{ij} = L_{ij}(T)$

$$\Delta L_{ij_{acc}} := \sum_{\{i,j\} \in E} \left| L^1_{ij} - L^2_{ij} \right|$$

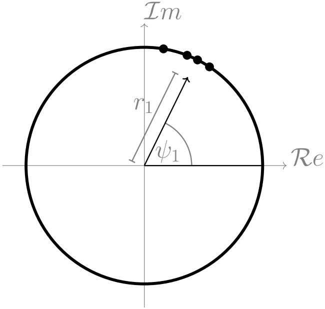




Mean-Fields

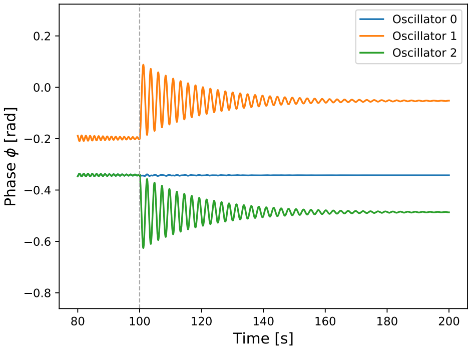
- Centroid on complex plane
- r: phase coherence
- ψ: average phase angle

$$re^{i\psi} = \frac{1}{N}\sum_{j=1}^{n} e^{i\phi_j}$$



Mean-Fields

$$r_{mean} := Re\left(\frac{1}{N}\langle|\sum_{i=1}^{n} e^{i\phi_j(t)}|\rangle_t\right)$$



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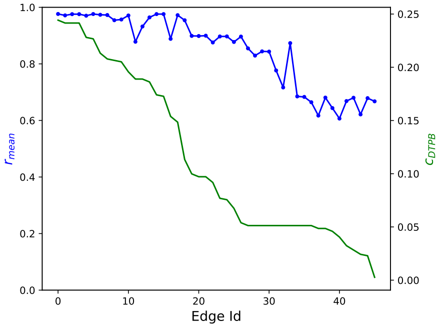

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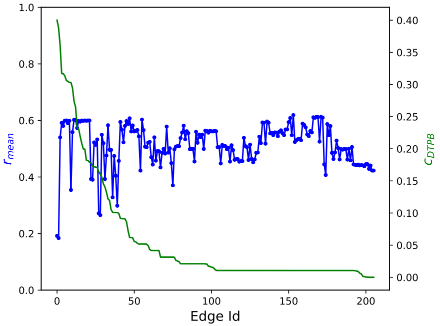

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