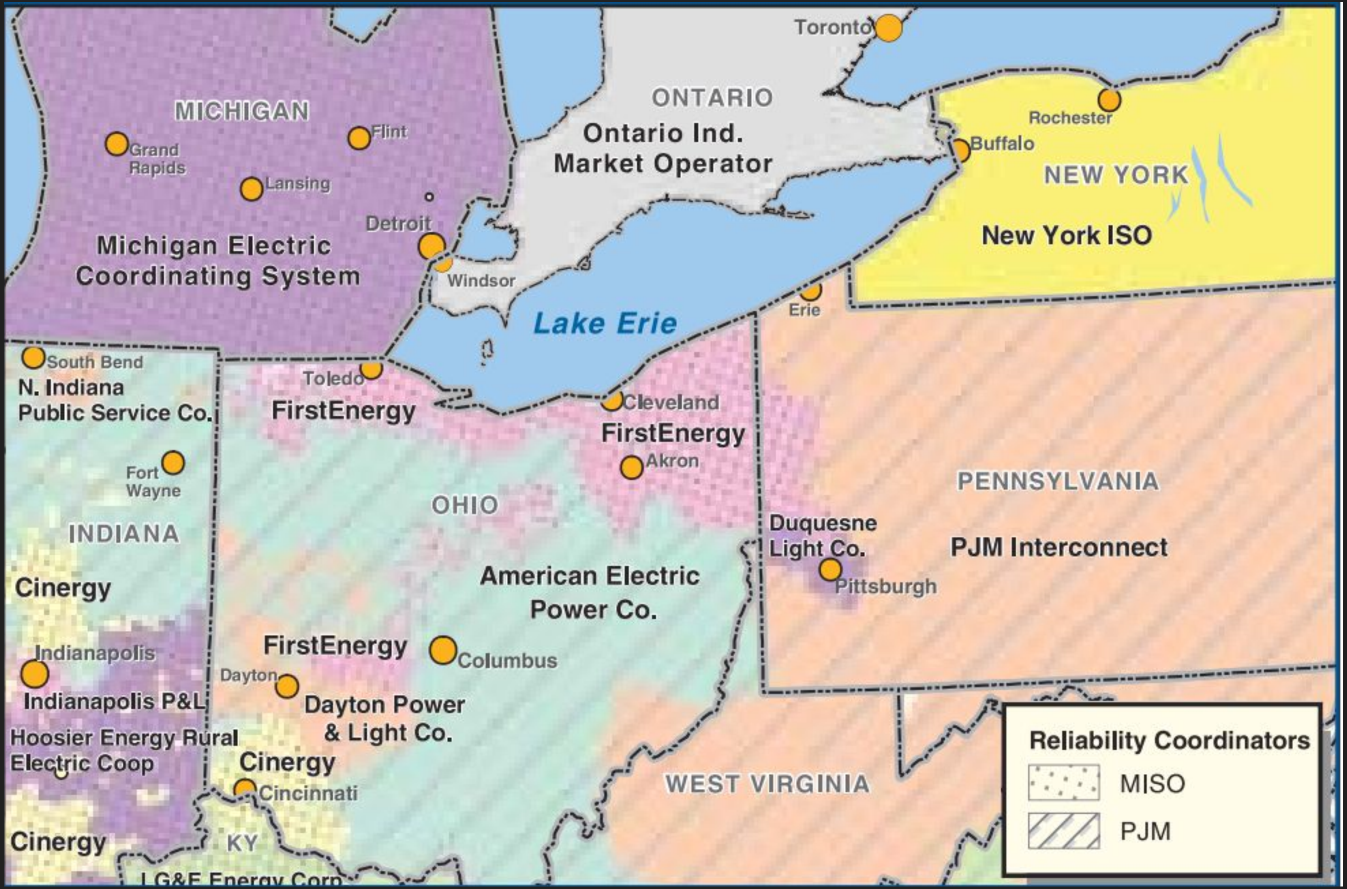
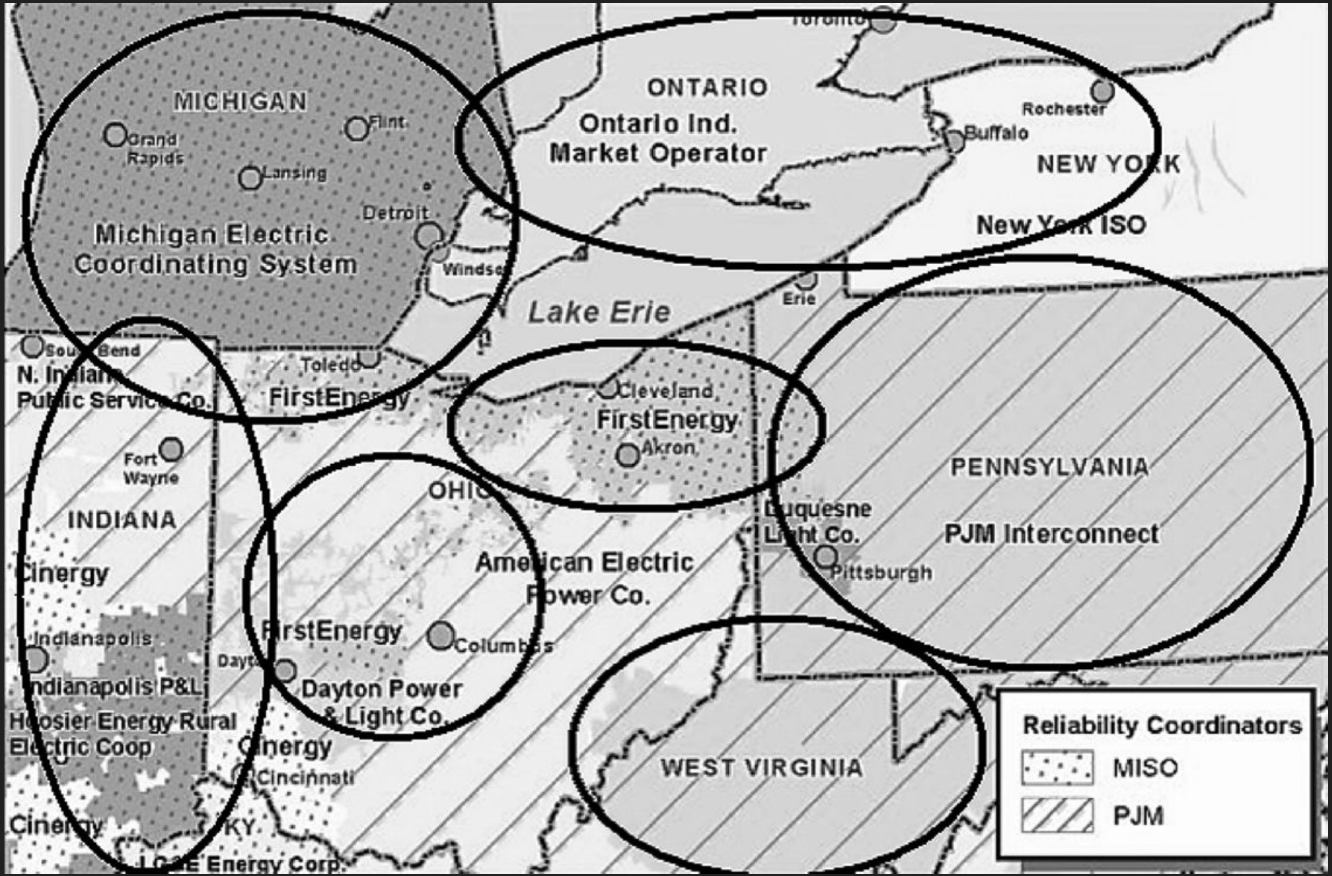
Power grid partitioning

"Data-Driven Partitioning of Power Networks Via Koopman Mode Analysis"
by Raak, Susuki and Hikihara

Presented by André and Pontus



http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/BlackoutFinal-Web.pdf



http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1717588

Agenda

Controlled islanding
- Why?
- How?

Previous methods
- Modelling
- Partitioning

Proposed method
- Koopman modes
- Math!

Results & Conclusions

Controlled islanding - why?

Stop faults from cascading!

Power outage in 2003 due to one tree (and contributing factors)!

Disturbances cause the grid to oscillate

Controlled islanding - how?

Separate the grid into smaller grids

- Isolate faults
- Quicker recovery

- Maintain power balance! **Generation ≈ Load**
- Create islands with balanced load and **high stability**

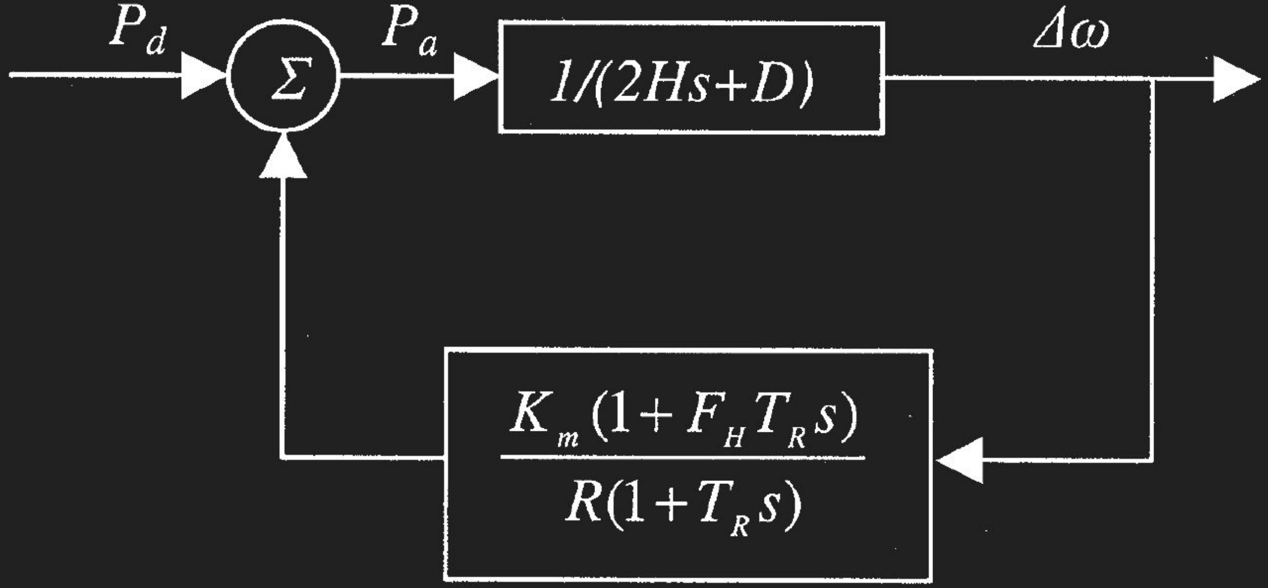
Solving this is the main problem!

Controlled islanding - how?

Many previous methods:

- Model the grid's dynamic properties down to individual components
- Group power buses by some (dynamic) property
- Create islands from suitable grouping

Previous methods



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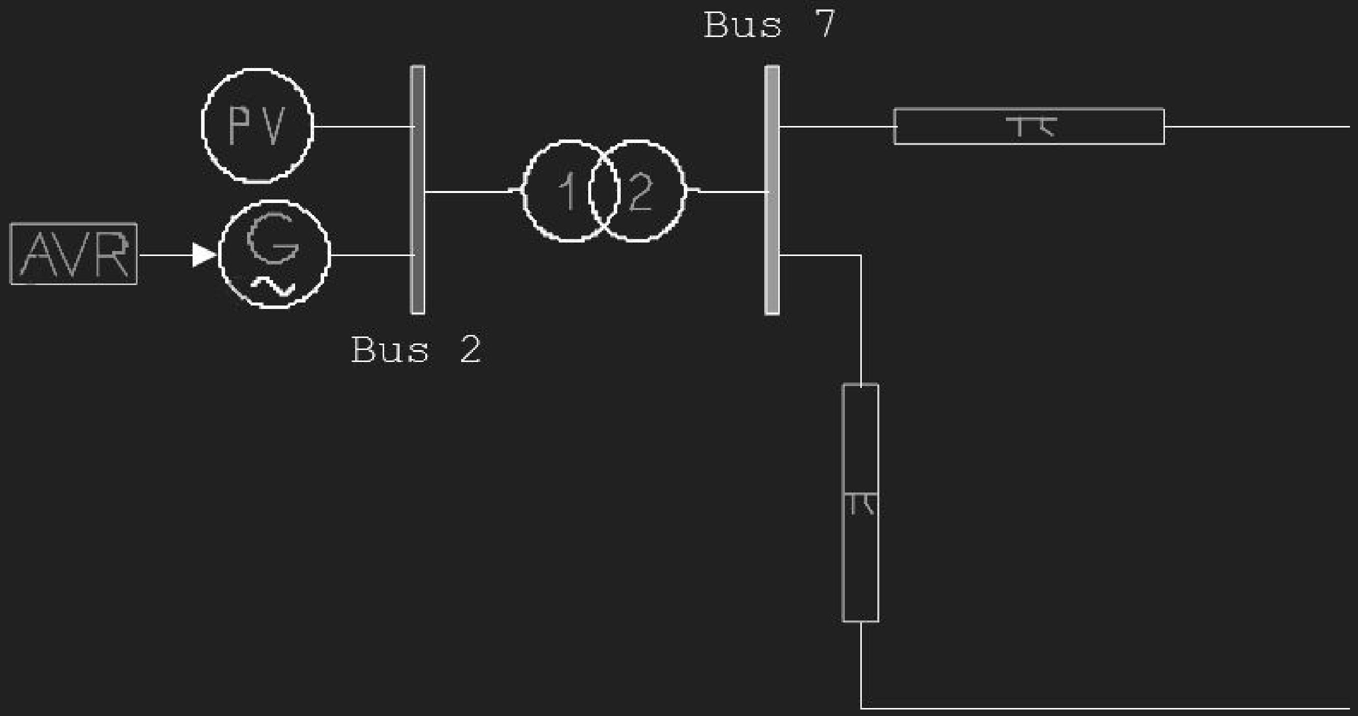
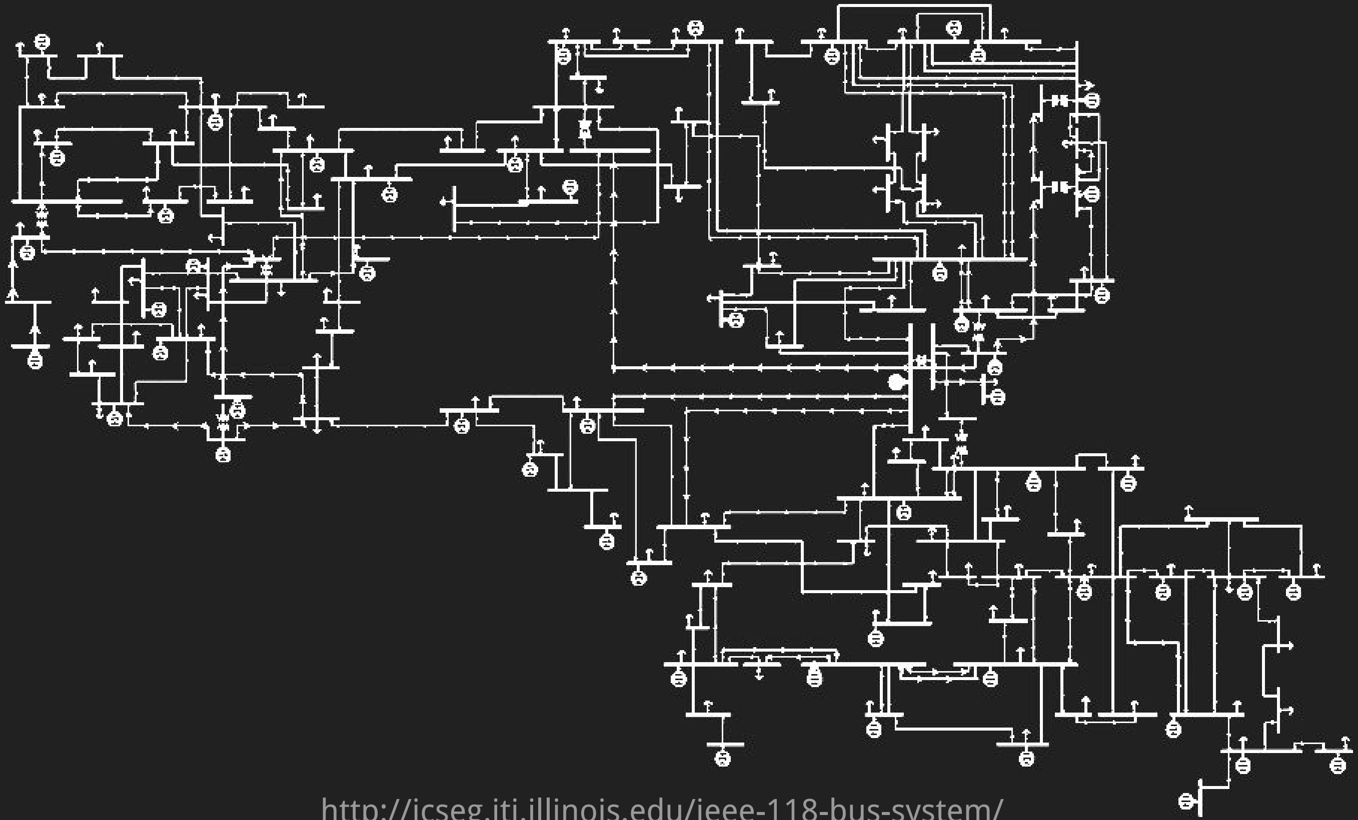
Previous methods



Previous methods



http://icseg.iti.illinois.edu/ieee-118-bus-system/

Previous methods

Based on linear models

Requires (hundreds or thousands of) accurate parameters for all parts of the grid

- Generators
- Transformers
- Power lines
- Loads
- …

Often calculated offline, as steady-state systems

Is there a better method?

Real disturbances are dynamic - far from steady-state!

However, slow coherency successful on simulations of the blackout in 2003!

Slow coherency groups buses by their calculated low-frequency modes

New method wishlist

Data-driven - no grid parameters!

Make decisions based on the real dynamics of the system

Not confined to linearized models

Koopman operator

"Hamiltonian systems and transformation in Hilbert space"

Bernard Koopman, 1931

Linear operator that captures nonlinear phenomena

Used in many dynamic systems, such as fluid dynamics

By sampling phase angles we can find the dynamic modes!

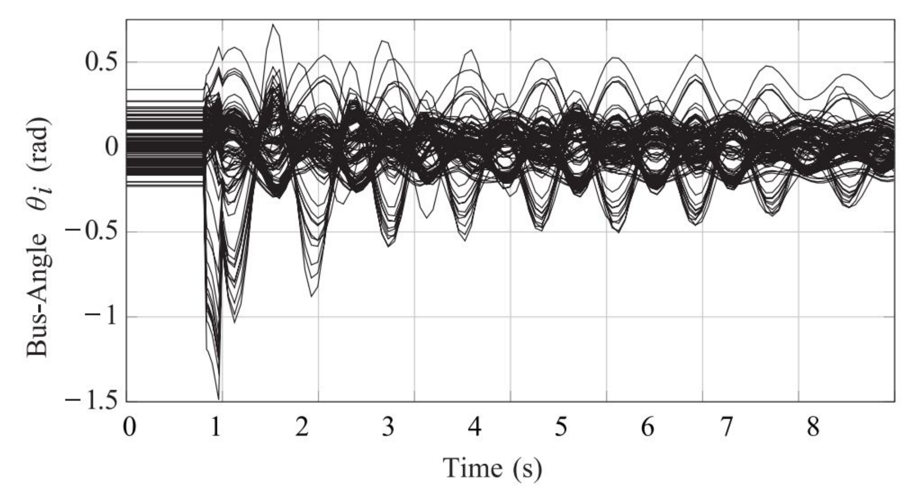
Find buses that oscillate in harmony

Math!

States $x \in \mathcal{M}$ represent the phase angles of all the buses

System evolves over time as phase angles oscillate (naturally, or due to disturbances)

We want to know the dynamics of the oscillations!



Math!

Function that generates the next state from the current state

$$\boldsymbol{x}_{k+1} = \boldsymbol{\Phi}^h(\boldsymbol{x}_k), \qquad h := t_{k+1} - t_k$$

$$g : M \rightarrow \mathbb{R}$$

Observable, i.e. measurement

All following slides: http://ieeexplore.ieee.org/document/7243366/

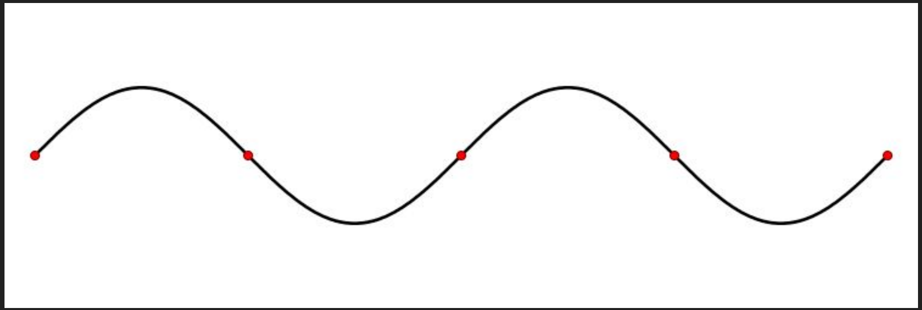
Math!

Koopman operator!

$$(\mathcal{U}g)(\boldsymbol{x}) = g(\boldsymbol{\Phi}^h(\boldsymbol{x}))$$

Eigenfunction

$$\mathcal{U}\varphi_i = \lambda_i \varphi_i, \quad i = 1, 2, \ldots$$



Math!

We are interested in the **dynamic properties** of the system

Koopman operator is linear

For our case:

i:th Koopman eigenvalue

$$\boldsymbol{g}(\boldsymbol{x}_k) = \sum_{i=1}^{\infty} \lambda_i^k \varphi_i(\boldsymbol{x}_0)\boldsymbol{v}_i$$

i:th Koopman mode

i:th eigenfunction

Now it gets a little complicated...

Complications

Calculating eigenvalues and modes from measurements is “challenging”

Approximate with an Arnoldi-type algorithm to get:

$$\left.\begin{aligned} \boldsymbol{g}_k &= \sum_{i=1}^{N} \tilde{\lambda}_i^k \tilde{\boldsymbol{v}}_i, \; k = 0, \ldots, N-1, \\ \boldsymbol{g}_N &= \sum_{i=1}^{N} \tilde{\lambda}_i^N \tilde{\boldsymbol{v}}_i + \boldsymbol{r}, \end{aligned}\right\}$$

Finding partitions

We want to group the buses in the grid by the “largest” dynamic properties

Sort the calculated modes and eigenvalues by growth rate $|\lambda_i|$ and norm $||v_i||$

Case #	No. j	GR $\lvert\tilde{\lambda}_j\rvert$	Freq. [Hz] $\mathrm{Im}[\ln\tilde{\lambda}_j]/(2\pi T_s)$	Norm $\lVert\tilde{\boldsymbol{v}}_j\rVert$	ClC ClC_j^{ℓ}	θ_{sep} (deg)
	1	1	0	3.29	0, 0	180
	2	0.9977	±1.04	0.28	0.009, 0.008	177
	3	0.9976	±1.24	0.25	0.036, 0.018, 0.028	77, 103, 180
(i)	¦	0.9975	±3.29	0.05	0.130, 0.074	173
	¦	0.9970	±0.21	0.02	0.091, 0.004	185

Finding partitions

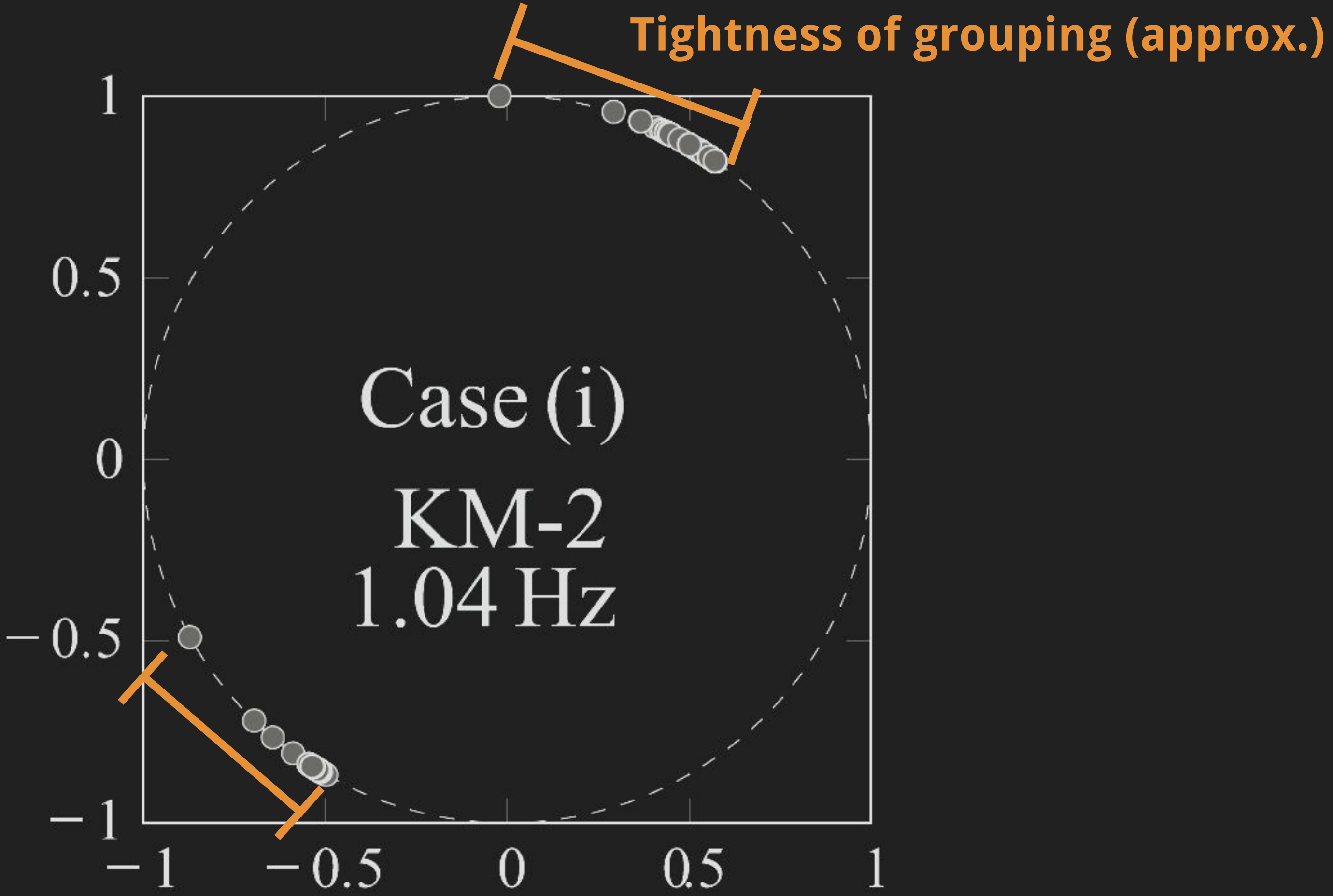
We want to group the buses in the grid by the “largest” dynamic properties

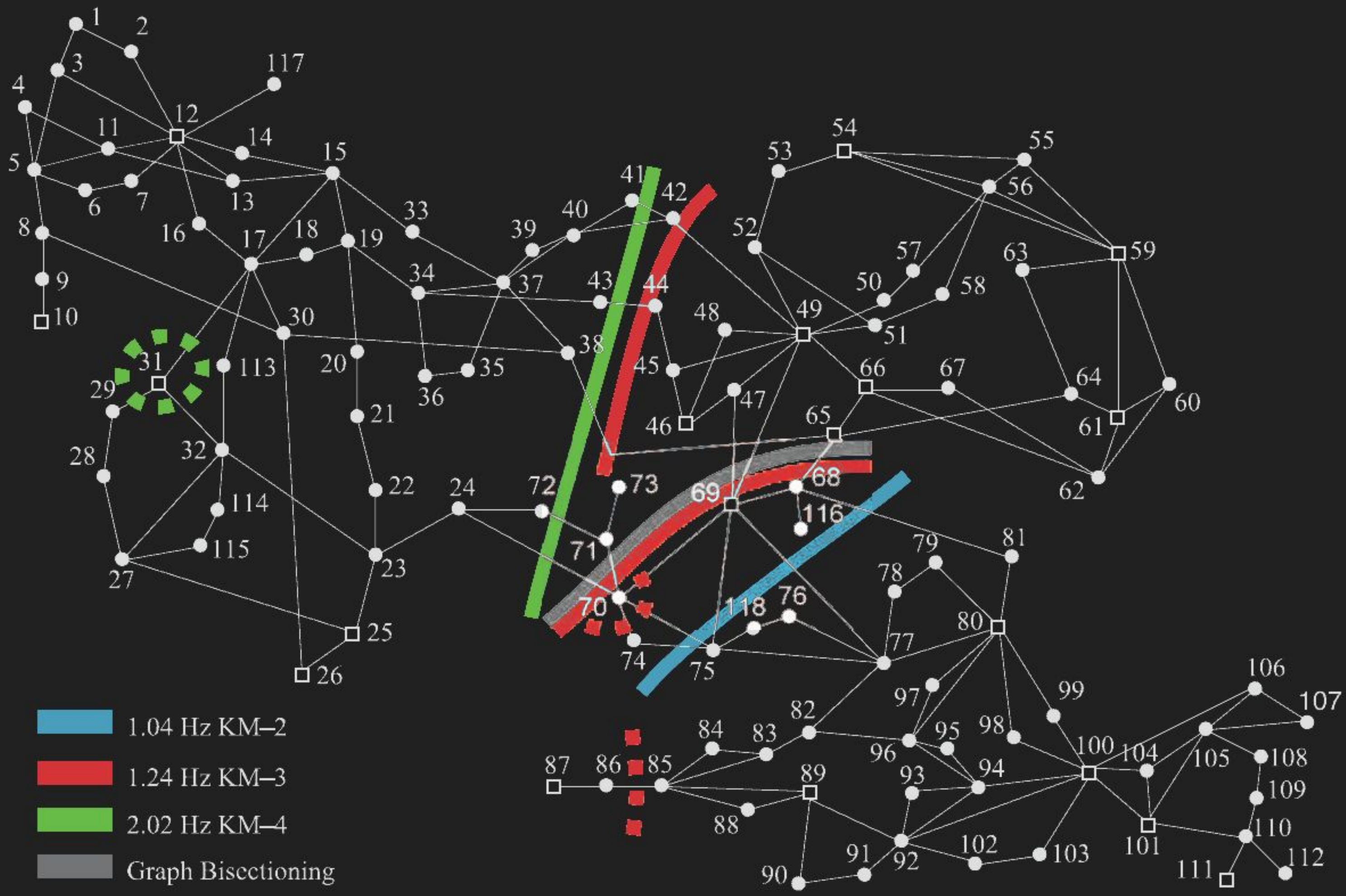
Sort the calculated modes and eigenvalues by growth rate $|\lambda_i|$ and norm $||v_i||$

Calculate how tightly buses conform to each dominant mode

Discard modes that do not have a tight grouping

Partition (using k-means) according to phase angle


Tightness of grouping (approx.)
1
0.5
0
−0.5
−1
−1
−0.5
0
0.5
1
Case (i)
KM-2
1.04 Hz


1.04 Hz KM–2
1.24 Hz KM–3
2.02 Hz KM–4
Graph Bisectioning

Result

Large correlation with other methods

- The method captures **essential dynamic properties**, without modelling!
- Finds all partitionings that slow coherency and graph bisectioning find

Not yet a deployable method

- Sensitive to noise (use filtering!)
- Phasor Measuring Units are not installed at all buses
- Effect of unsynchronized measurements is unknown

Conclusions

Cascading failures can be a problem in sensitive grids (ran at their limit)

Previous methods required detailed models

New method uses measurements to find dynamics of system

Captures essential properties of previous methods, without modelling

Still a research topic!

Read more!

Yang, B., Vittal, V., & Heydt, G. T. (2006). Slow-Coherency-Based Controlled Islanding - A Demonstration of the Approach on the August 14, 2003 Blackout Scenario. *IEEE Transactions on Power Systems*, 21(4), 1840-1847.

Susuki, Y., Mezic, I., Raak, F., & Hikihara, T. (2016). Applied Koopman operator theory for power systems technology. *Nonlinear Theory and Its Applications*, IEICE, 7(4), 430-459.

(Reading list)