From Coupled-oscillators to Synchronous Generators

-- Searching for the Regions of Attraction of Networked-Nonlinear Systems

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My Research Interests

- Renewable energy system planning, design and operation
  - Grid-connected battery system
  - Distributed energy management
- Networked nonlinear system stability dynamics
  - Off-line analysis
  - On-line control

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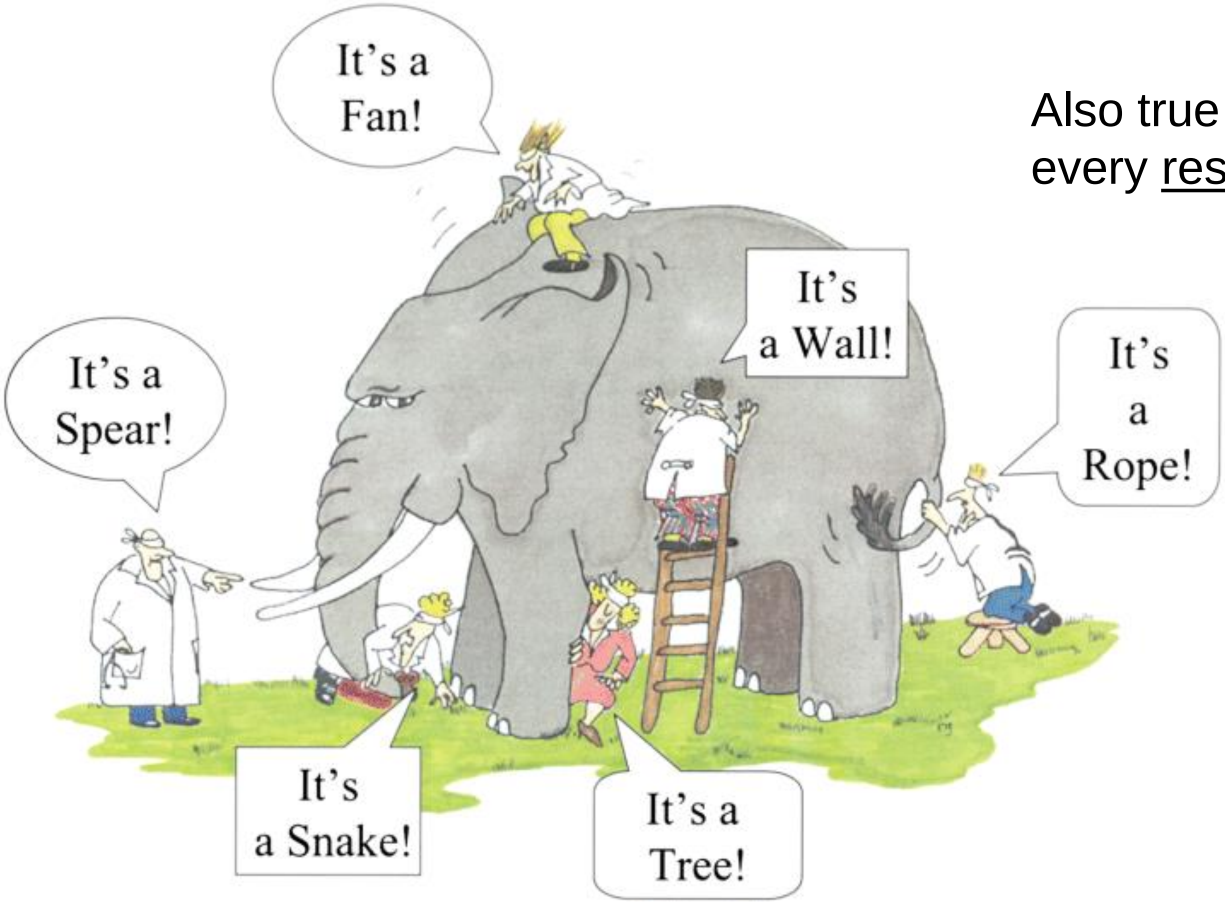
A summary picture of today's topic



Also true for almost every research project!

Blind men and an elephant: https://en.wikipedia.org/wiki/Blind_men_and_an_elephant

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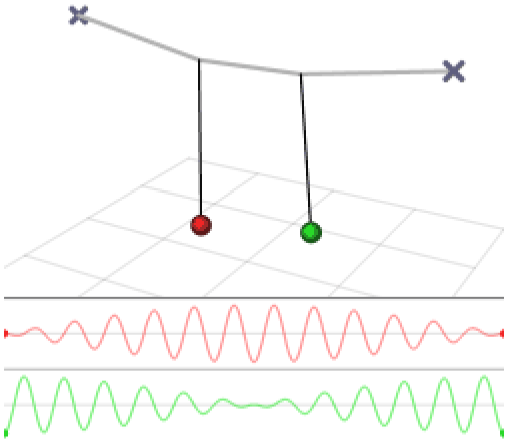
Outline

- Introduction
  - Coupled Oscillators
  - Synchronous Generators
- Region of attractions of nonlinear systems
  - Basin Stability
  - Results on Power System Transient Stability
- Next Steps

Coupled Oscillators

- Oscillators
  - Pendulum
  - Metronome
  - Single firefly flashes
  - …
- Coupled Oscillators
  - Couple Pendulums by springs
  - Couple Metronomes by a platform
  - Synchronous Fireflies



https://en.wikipedia.org/wiki/Oscillation#Coupled_oscillations

J. Peña Ramirez, L. A. Olvera, H. Nijmeijer, and J. Alvarez, “The sympathy of two pendulum clocks: beyond Huygens’ observations,” *Sci. Rep.*, vol. 6, no. March, p. 23580, Mar. 2016.

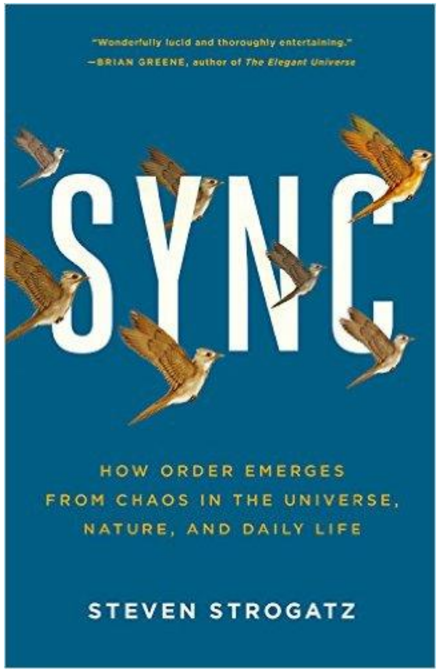
- Couple metronomes by a platform

https://youtu.be/Aaxw4zbULMs

Additional Reading on Coupled Oscillators

Steve Strogatz

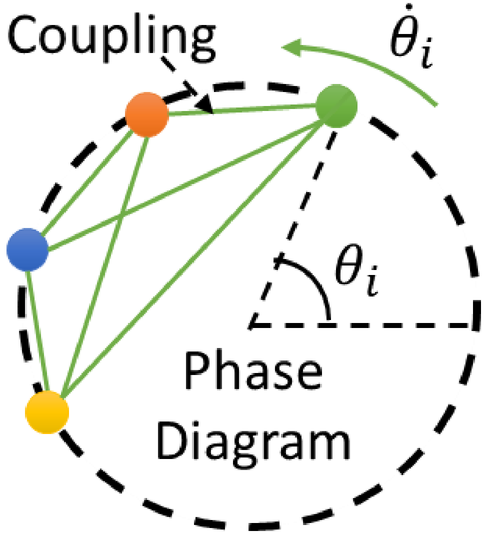
- TED talk: How things in nature tend to sync up
  - https://www.youtube.com/watch?v=aSNrKS-sCE0
- Book: "Sync: How Order Emerges From Chaos In the Universe, Nature, and Daily Life"



"Can Smarter Solar Inverters Save the Grid?"
http://spectrum.ieee.org/energy/renewables/can-smarter-solar-inverters-save-the-grid

The Kuramoto Model

$$\dot{\theta}_i = \omega_{0,i} + \frac{K}{N}\sum_{j=1}^{N} a_{ij}\sin\left(\theta_j - \theta_i\right), \forall i, j = 1, \dots, N.$$



- $\theta_i(t)$, phase angle of the ith oscillator
- $\dot{\theta}_i(t)$, angular velocity
- $\omega_{0,i}$, natural frequency
- K, is the coupling strength
- N, is the number of oscillators
- a_{ij} is the corresponding element in the adjacency matrix

Acebrón, Juan A., et al. "The Kuramoto model: A simple paradigm for synchronization phenomena." *Reviews of modern physics* 77.1 (2005): 137.

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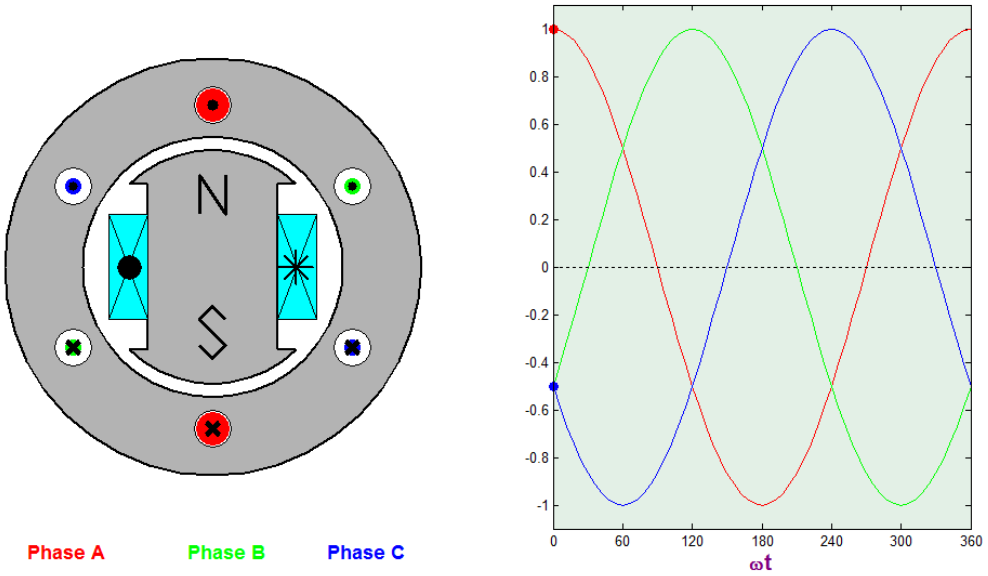
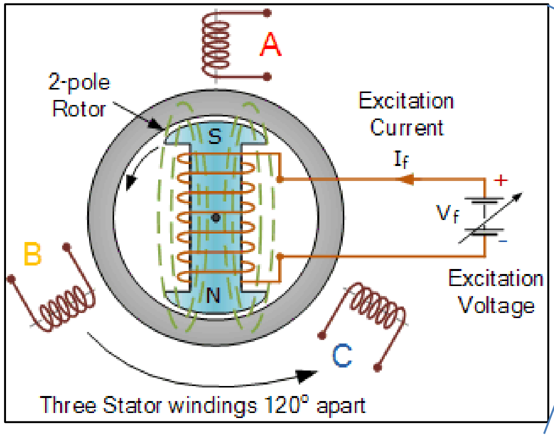
Synchronous Generators

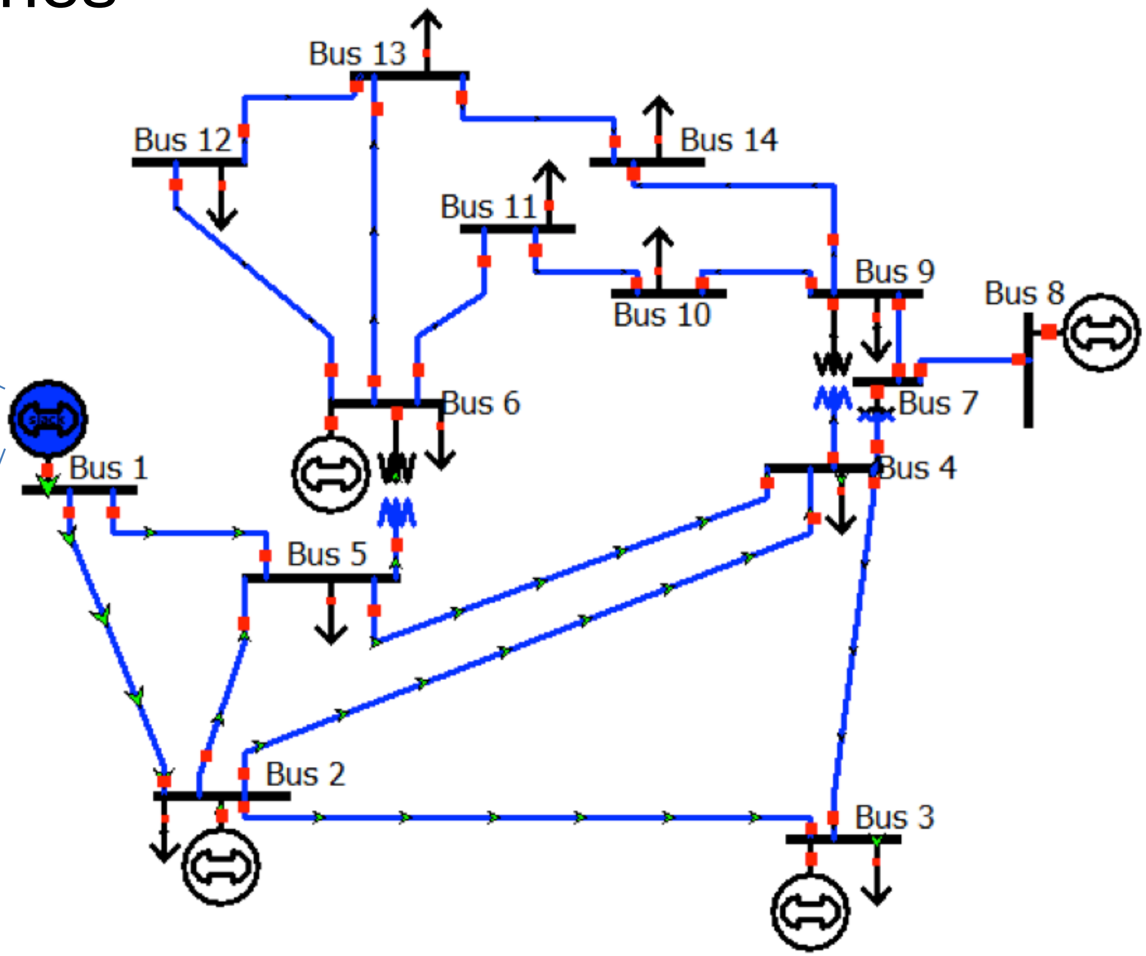
- Three-phase synchronous generator and its output voltages
  - "Synchronous": rotor speed directly related to out put voltage frequencies



http://people.ece.umn.edu/users/riaz/animations/alternator.html

- Power Systems Dynamics
  - Oscillators(generators) coupled by transmission lines





Video: putting generators online

- Power system stability
  - In few milliseconds to seconds
  - The ability of an electric power system, for a given initial condition to regain a state of equilibrium after disturbance (small and large).
    - Load change
    - Network topology change
    - Equipment failure
    - Renewable energy variation
    - …
  - Power system instability – generators loss of synchronism

The Challenge

- The dynamic response of our power system are changing:
  - The legacy grid can be considered as a low-pass filter
  - The future grid will behave differently under normal and abnormal conditions
    - High penetration of renewable energy – not dispatchable
    - More power electronic devices – fast response
- It's time to looking for new approaches to model and control such system

Suggested Connections to Power Systems Stability

$$\dot{\theta}_i = \omega_{0,i} + \frac{K}{N}\sum_{j=1}^{N} a_{ij}\sin(\theta_j - \theta_i)$$

$$M_i\ddot{\theta}_i + D_i\dot{\theta}_i = \omega_i + \boldsymbol{P_i(t)} + E_iE_jY_{ij}\sum_{j=1}^{N} a_{ij}\sin(\theta_j - \theta_i)$$

Kuramoto Model	**Modeling efforts on power system modeling by coupled oscillators**
Node dynamics: $\dot{\theta}_i$	Generators as non-uniform Kuramoto model $\dot{\theta}_i \rightarrow M_i\ddot{\theta}_i + D_i\dot{\theta}_i$
Natural frequency: ω_i	Consider power injection as the natural frequency: $\omega_i \rightarrow \omega_i + P_i(t)$
Coupling between nodes: K	Consider non-uniform coupling strengths (thermal limit of transmission line) in effective network model $K \rightarrow K_i$
Network: a_{ij}	Kron reduction and linearization steady-state model, generator nodes only
Interaction with other networks	Multiplex network

Why Kuramoto Model might not be sufficient for our problem?

- The generator model used by power system engineers for transient stability study:
  - 6th order generator model

$$T'_{do}\frac{dE'_q}{dt} = -E'_q - (X_d - X'_d)\left[I_d + \frac{X'_d - X''_d}{(X'_d - X_{ls})^2}(-\psi_{1d} - (X'_d - X_{ls})I_d + E'_q)\right] + E_{fd}$$

$$T''_{do}\frac{d\psi_{1d}}{dt} = -\psi_{1d} + E'_q - (X'_d - X_{ls})I_d$$

$$T'_{qo}\frac{dE'_d}{dt} = -E'_d - (X_q - X'_q)\left[I_q + \frac{X'_q - X''_q}{(X'_q - X_{ls})^2}(-\psi_{2q} - (X'_q - X_{ls})I_q + E'_d)\right]$$

$$T''_{qo}\frac{d\psi_{2q}}{dt} = -\psi_{2q} + E'_d - (X'_q - X_{ls})I_q$$

$$\frac{d\delta}{dt} = \omega - \omega_s$$

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} = T_M - \frac{X''_d - X_{ls}}{(X'_d - X_{ls})}E'_q I_q - \frac{X'_d - X''_d}{(X'_d - X_{ls})}\psi_{1d}I_q + \frac{X''_q - X_{ls}}{(X'_q - X_{ls})}E'_d I_d + \frac{X'_q - X''_q}{(X'_q - X_{ls})}\psi_{2q}I_d - (X''_q - X''_d)I_d I_q - D\frac{d\delta}{dt}$$

  - 2nd order exciter model

$$T_R\frac{dV_{TR}}{dt} = \sqrt{{E_d}^2 + {E_q}^2} - V_{TR}$$

$$T_A\frac{dE_{fd}}{dt} = -E_{fd} + K_A(V_{ref} - V_{TR} + PSS_{out})$$

  - 3rd order controller (PSS) model

$$T_w\frac{dpss1}{dt} = \omega - pss1$$

$$T_{d1}\frac{dpss2}{dt} = G_{pss}\left(\omega_s - \frac{T_{n1}}{T_{d1}}\right)(\omega - pss1) - pss2$$

$$T_{d2}\frac{dpss3}{dt} = \left(\omega_s - \frac{T_{n2}}{T_{d2}}\right)\left(\frac{T_{n1}}{T_{d1}}G_{pss}(\omega - pss1) + pss2\right) - pss3$$

$$PSS_{out} = \frac{T_{n2}}{T_{d2}}\left(\frac{T_{n1}}{T_{d1}}G_{pss}(\omega - pss1) + pss2\right) + pss3$$

This is the model for one node.

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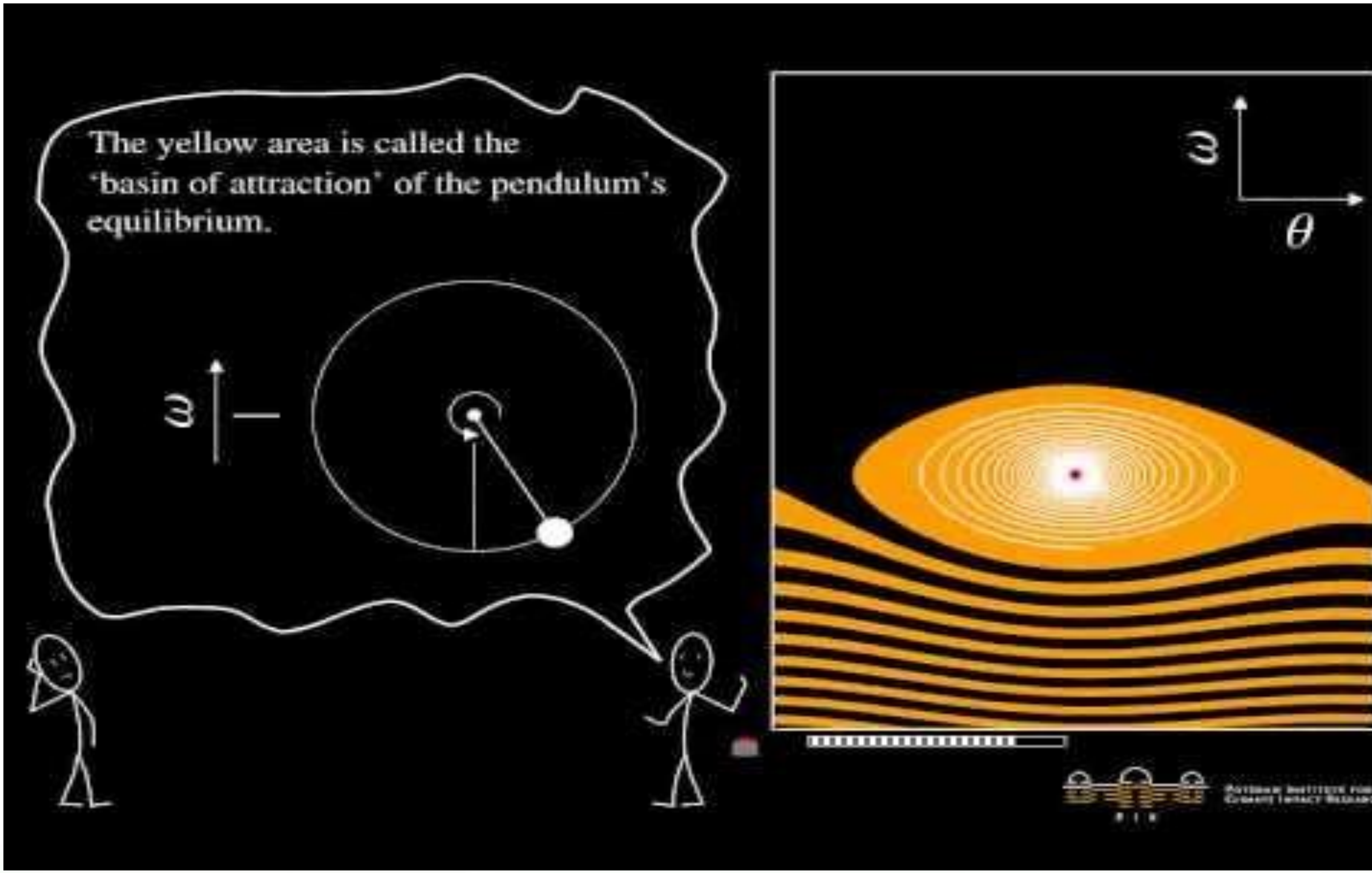
Basin Stability



https://www.youtube.com/watch?v=dFjf_d69HtY

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Basin Stability

- Basin Stability is sample-based, non-linear, nonlocal sample-based approach:

$$\dot{\phi} = \omega$$
$$\dot{\omega} = -\alpha\omega + T - K\sin\phi,$$

1. Draw a number of initial states from post perturbation system state's probability density function $\rho(X)$.

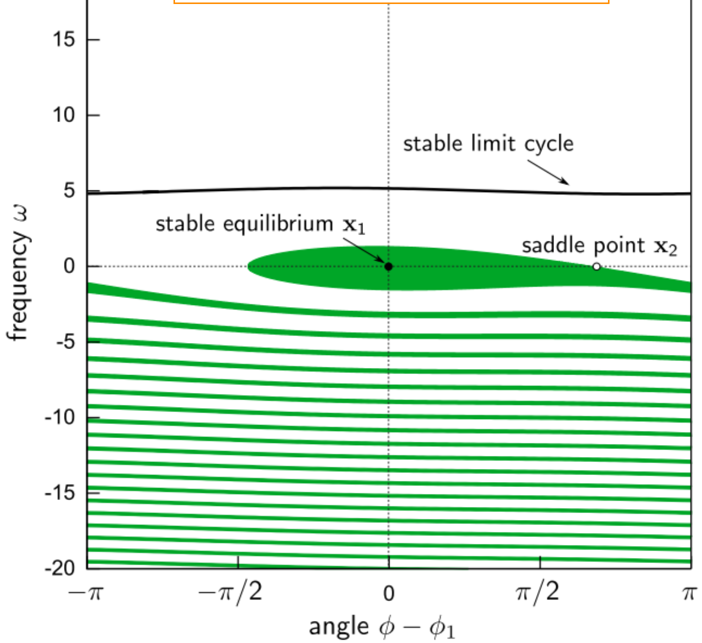
2. For every initial state in T, substitute it into the detailed system model and simulate the system with time-domain simulation.

3. Count the number of initial states U that the corresponding trajectories converge to equilibrium point in set A.

4. Calculate the approximated Basin Stability as $S(\mathcal{B}) \approx U/T$.

$$S(\mathcal{B}) = \int \mathcal{X}_{\mathcal{B}}(X)\,\rho(X)dX$$

$$\mathcal{X}_{\mathcal{B}}(X) = \begin{cases} 1 & if\ f\ (X) \in \mathcal{B} \\ 0 & otherwise \end{cases}$$



Phase Space of the Damped Driven Pendulum

Menck, Peter J., Jobst Heitzig, Norbert Marwan, and Jürgen Kurths. "How basin stability complements the linear-stability paradigm." *Nature physics* 9, no. 2 (2013): 89.

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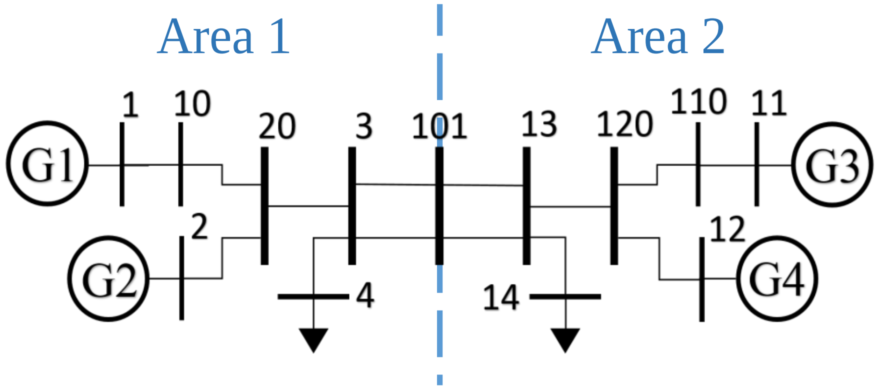
A power system experiment

- Assume:
  - A stable power system (pre fault)
  - Then fault happen: the state has been pushed to a new location
- Questions: can we go back to the equilibrium?



Single line diagram of the two-area four-machine system.

Generator phase angle

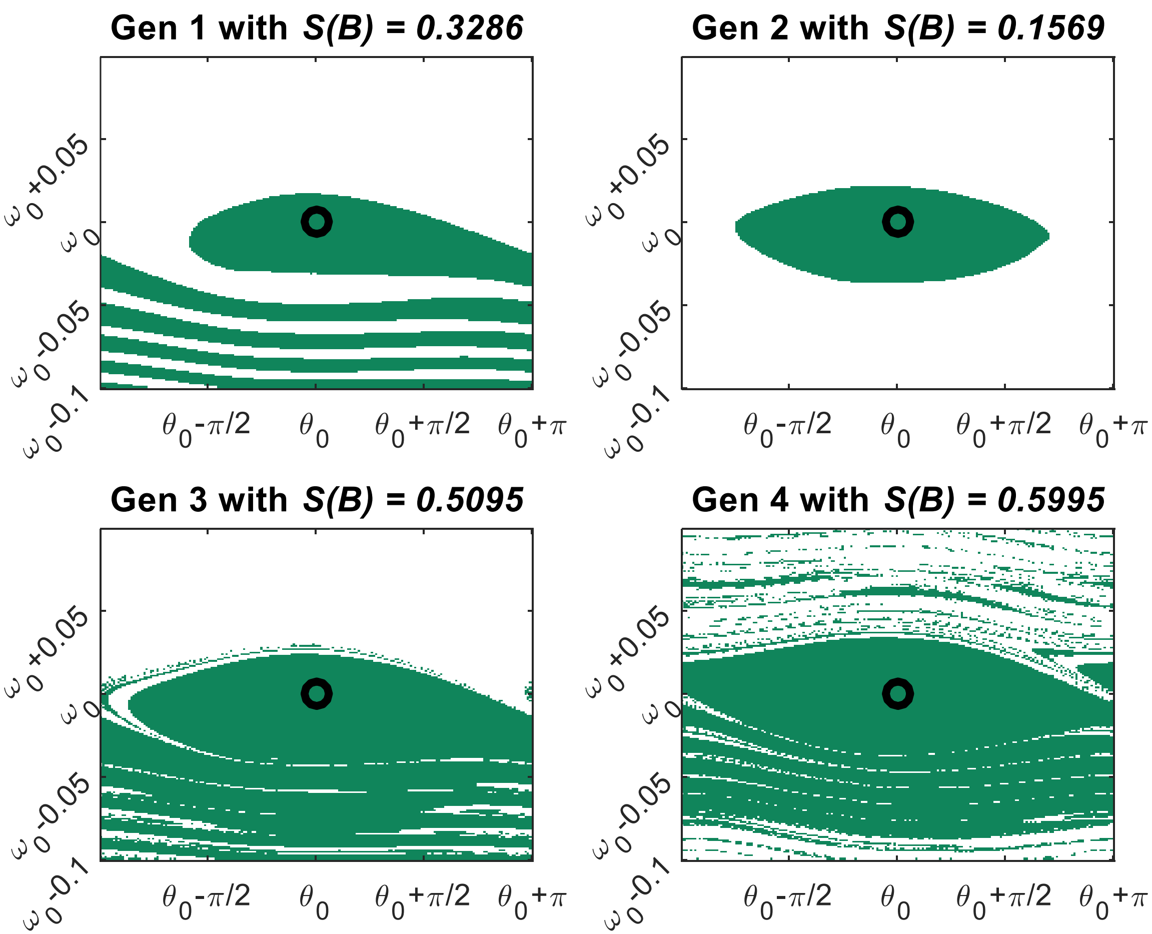
Phase angle difference is coupled with power flow.

$$\dot{\theta}_i = \omega_{0,i} + \frac{K}{N}\sum_{j=1}^{N} a_{ij}\sin(\theta_j - \theta_i)$$

Generator rotor frequency

Coupling strength *K* is:
- Not the line impedance (static) as literature suggested!
- Real-time power flow (dynamic)

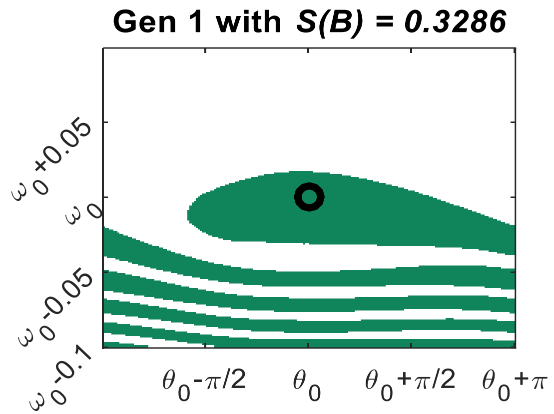
Single-node basin stability of two area 4-machine system

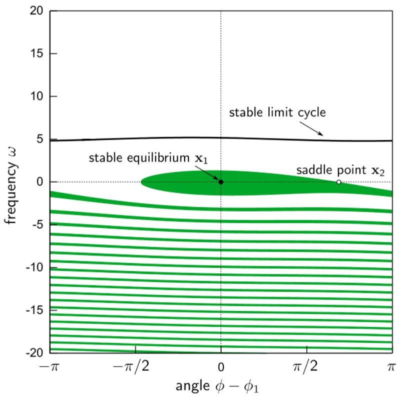


- Initial States (the states were disturbed) are generators' rotor angle and frequency
- Only one generator are disturbed at a time
- Green area indicates the stable region
- The whole system has a total number of dimension of 56. 14 dimensions on each node (sixth-order generator model, 2nd-order exciter and 3rd-order PSS)

Observations

- Not to far away from the pendulum result





- Regions of attraction for 4 generators are different, due to differences in
  – Generator parameters?
  – Transmission lines’ impendences?
  – Loads?

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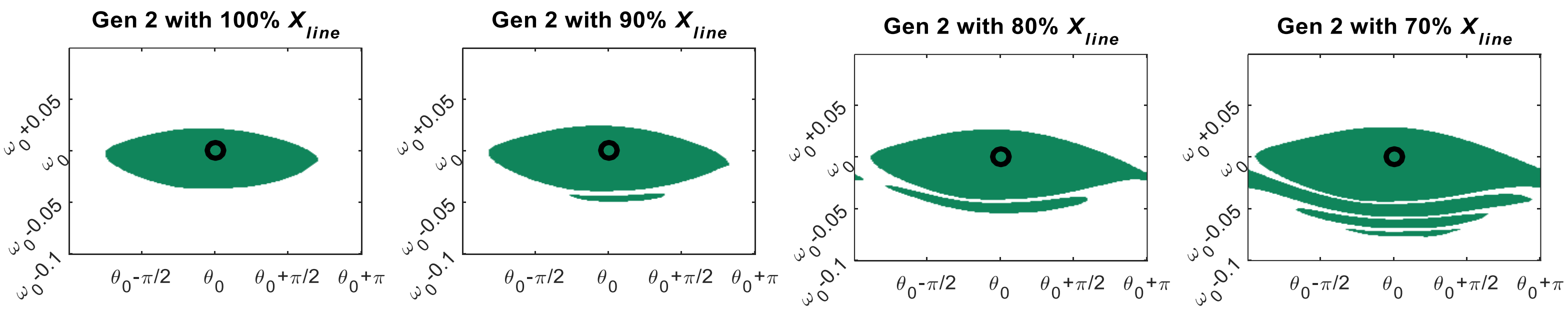
Can we change the shape?

(Make the regions of attraction larger?)

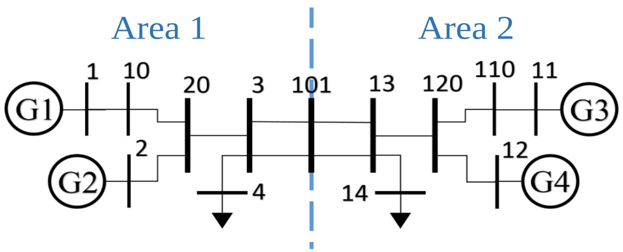
- Yes we can
  - By varying line impedance



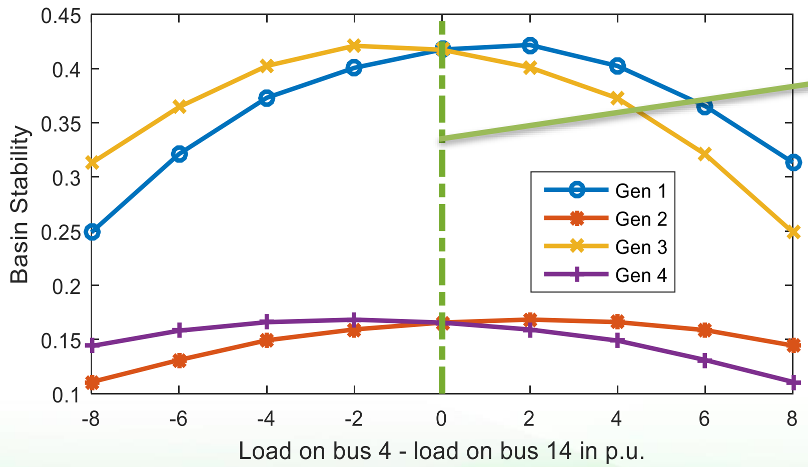
  - There are existing device can change transmission line impendence
    - Flexible AC transmission system (FACTS)

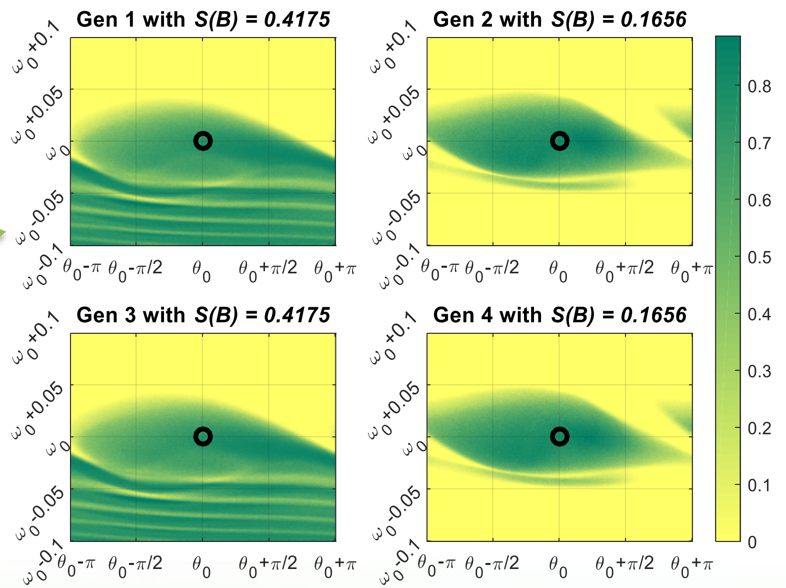
Z. Liu and Z. Zhang, "Quantifying transient stability of generators by basin stability and Kuramoto-like models," *in the 2017 North American Power Symposium (NAPS), Morgantown*, WV, 2017, pp. 1-6.

Can we change the shape?



- Yes
  - By changing the load
  - And also make the transmission lines have symmetric parameters





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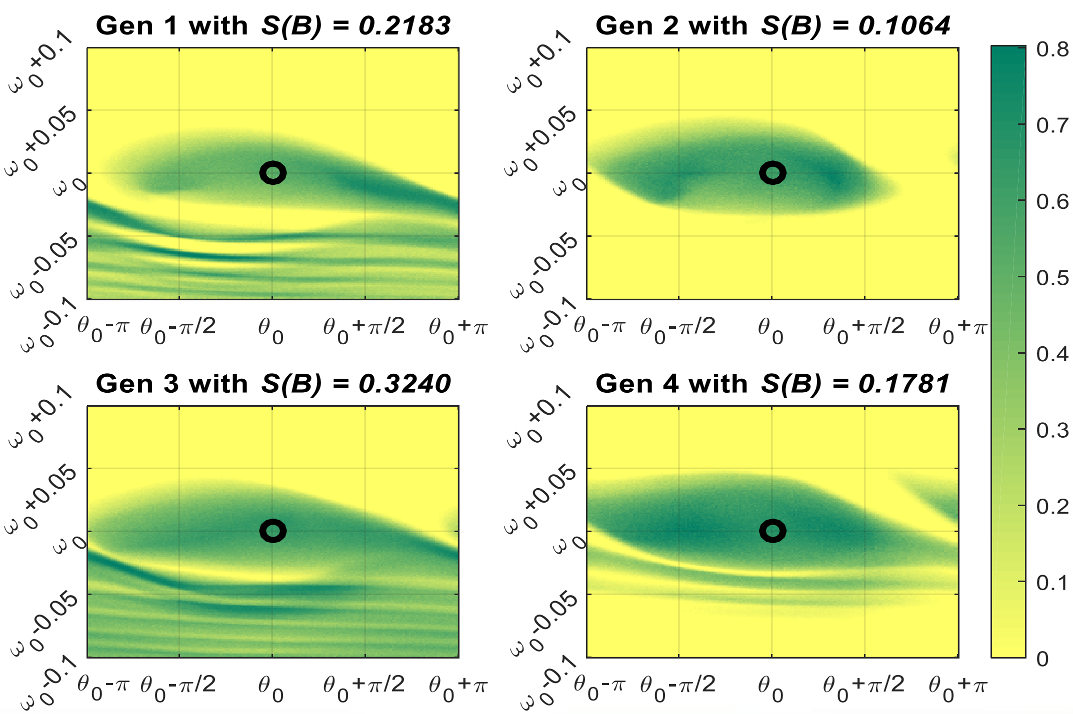
Is this the full picture?

- No…
- Recall that we have 11 states in the generator model:

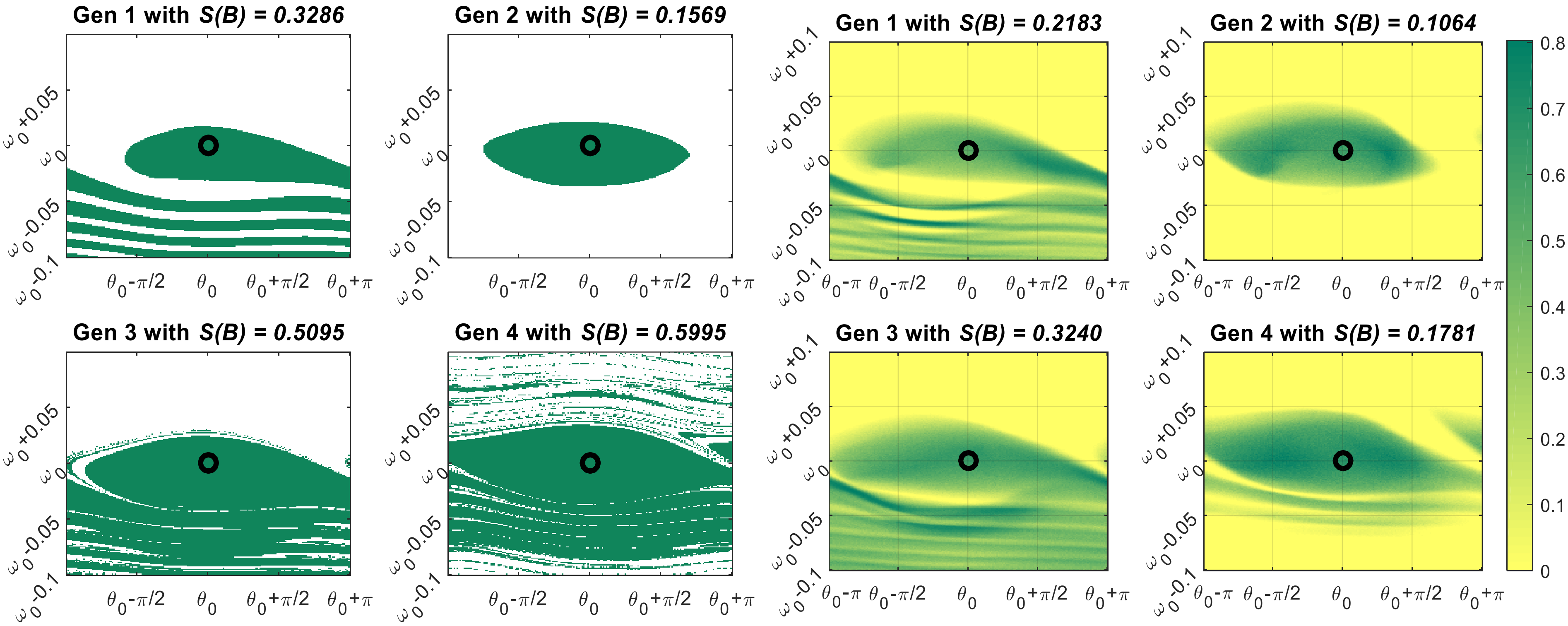


Use a heat map to present the other 9 dimensions.

Green means more stable results from the other 9 dimensions

Z. Liu, X. He, Z. Ding and Z. Zhang, "A Basin Stability-Based Metric for Ranking the Transient Stability of Generators," in *IEEE Transactions on Industrial Informatics*, 2018. Early access.

- Comparison with the 2-dimension plots



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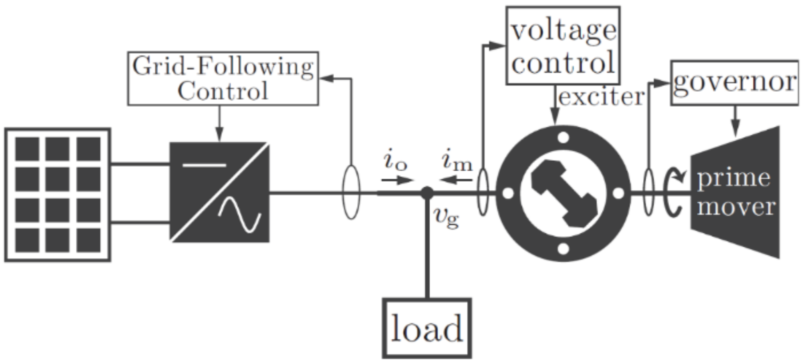
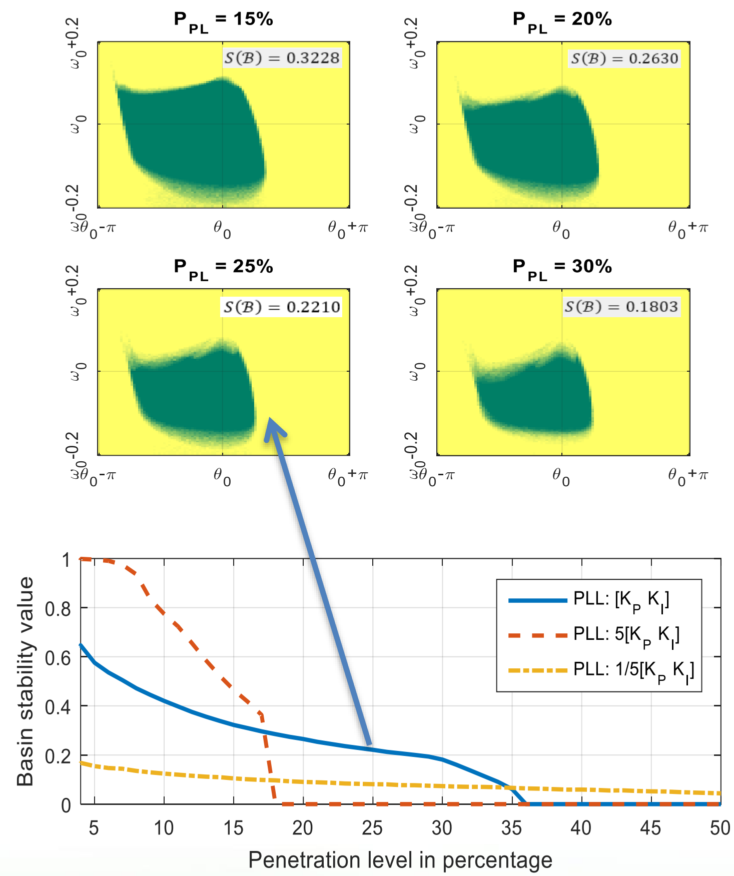
Is renewable energy helping the power system stability?

- Not always!



Simple system with one inverter and one generator

  – But better controllers can help



Zhao Liu, and Ziang Zhang, and Yanshen Lin, "Impact of Inverter-Interfaced Renewable Generation on Transient Stability at Varying Levels of Penetration" in *the 44th Annual Conference of the IEEE Industrial Electronics Society (IECON)*. Washington DC, USA, Oct. 2018.

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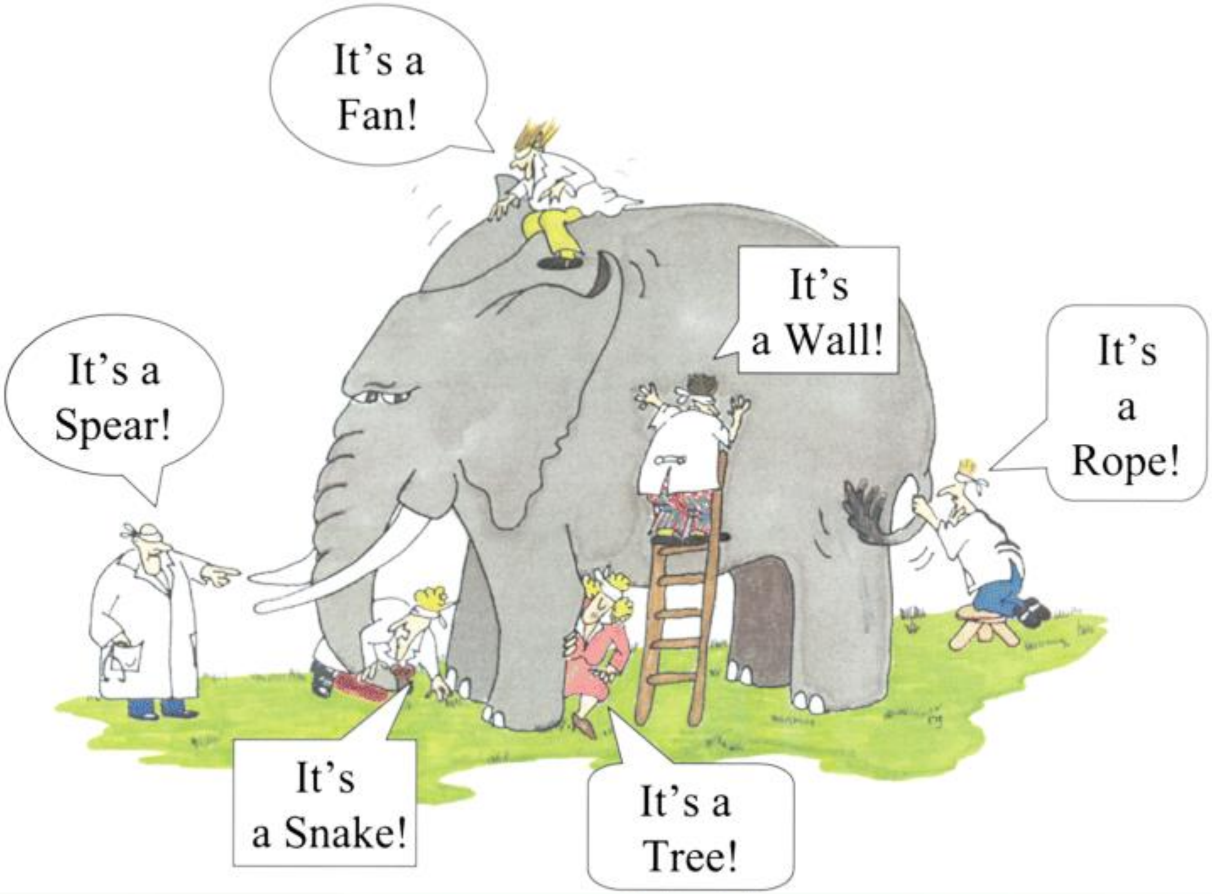
Next Steps

- Need new approaches to speedup the computation
  - For larger system
    - Multi-node basin stability
  - For real-time post fault control
- Need new control framework for inverter-interfaced renewable energy generation
  - Also an on-going effort in power electronics community
- Need better understanding on the fundamental physics of such system

Takeaways

- There is still a gap between:
  - The theoretical research on networked nonlinear system dynamics
  - The engineering application on power system transient stability analysis
- Sample based approach + parallel computing may shed some light on this area
- But there is still much work to do

Thank You!



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