Energy at Hopkins

JOHNS HOPKINS
RALPH O'CONNOR SUSTAINABLE ENERGY INSTITUTE

Options for Mitigation Measures

Avenues for new research

Enrique Mallada

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ESIG/G-PST Special Topic Workshop

March 28, 2024

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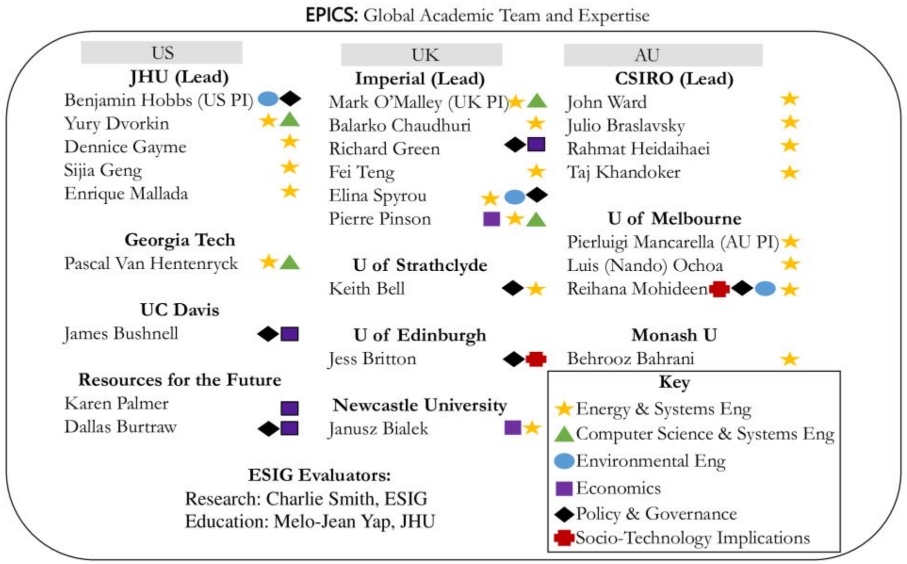


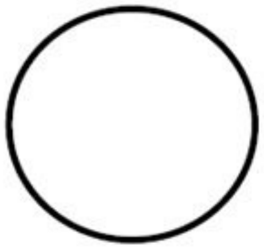
NSF Global Center: EPICS
Electric Power Innovation for a Carbon-free Society

Outline

- A Word of Caution: GFM IBRs Complex Dynamics
  - Faster controls **can speed up the transition to chaos**
- Decentralized Stability Analysis in Power Grids
  - Generalizing control tools for network systems
- Avenues for Future Research
  - Early detection via critical slow-down
  - Novel IBR control designs: Trading Freq. vs Volt. Support
  - The role of operations in SSO prevention

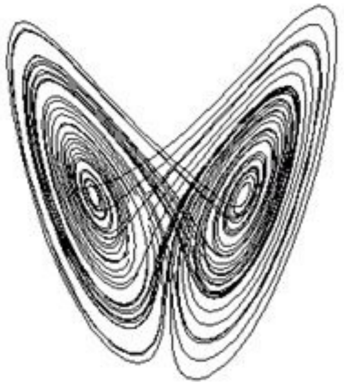
Nonlinear Phenomena in IBR-rich Grids

Sustained oscillatory behavior is intrinsically **nonlinear phenomena** induced by **bifurcations** which often can leads to **chaos**



limit cycle

limit torus



chaotic attractor

Prior art (1989[1] – 2004[2]) focus on nonlinear phenomena induced by synchronous machines.

Three well-known routes to chaos[3]:

- **Period-doubling** route: doubling of subsequent periodicities.
- Ruelle-Takens-Newhouse **quasi-periodicity route**: quasi-periodic torus attractors.
- Maneville-Pomeau **intermittency route**: sudden bursts to chaos.

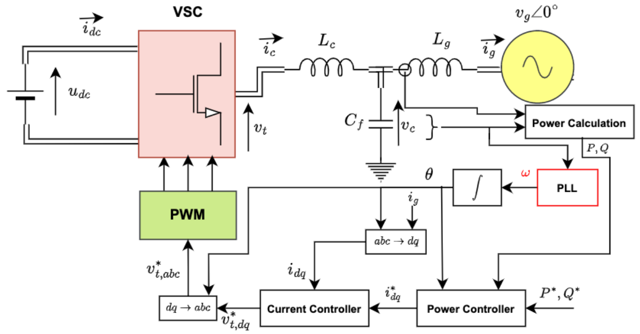
[1] I Dobson, H.-D. Chiang, *Towards a theory of voltage collapse in electric power systems*. Systems & Control Letters 1989
[2] J. Hongjie et al, *Three routes to chaos in power systems.* Canadian Conference on Electrical and Computer Engineering 2004
[3] Abraham, Arimondo, and Boyd, *Instabilities, dynamics and chaos in nonlinear optical systems.*

Nonlinear Phenomena in IBR-rich Grids

Q1: Can IBR-rich power grids induce chaotic behavior?

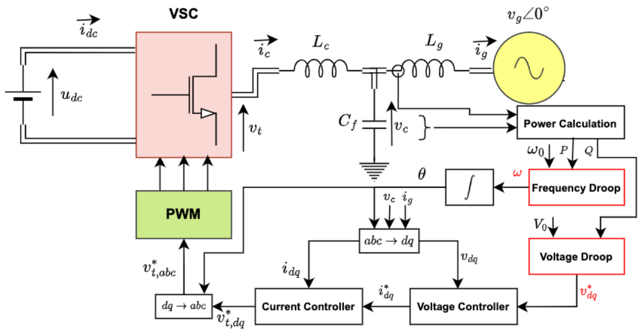
Q2: Is there a fundamental difference between GFL and GFL Inverters?

Grid Following Inverter

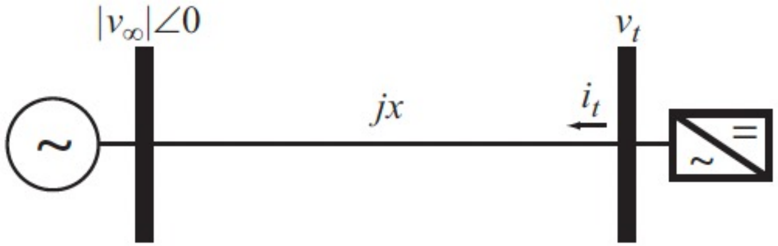


VS

Grid Forming Inverter

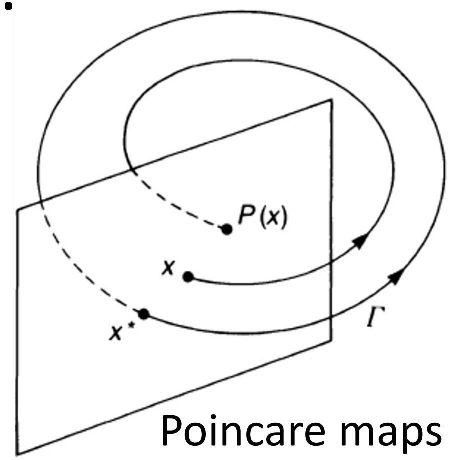


Problem Setup:



- IBR connected to infinite bus
- Use current controller gain K_p as bifurcation parameter

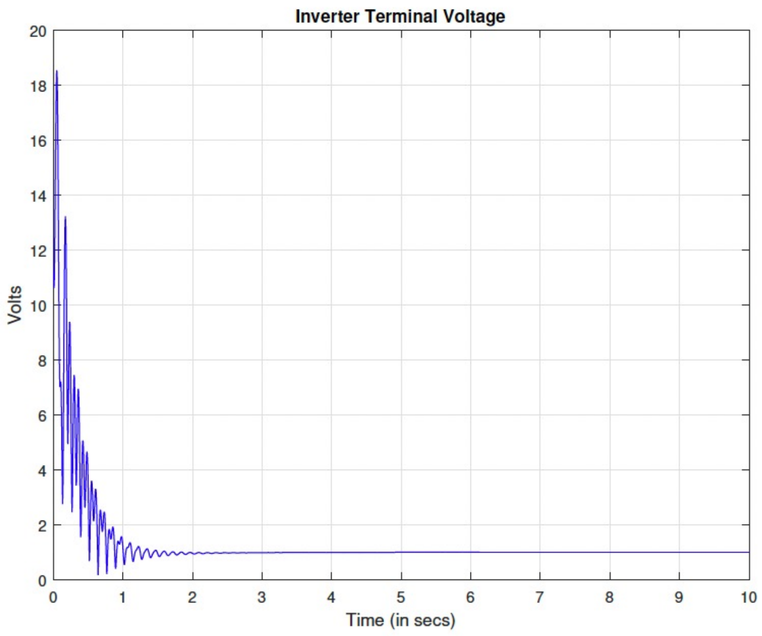
Analysis Tool:

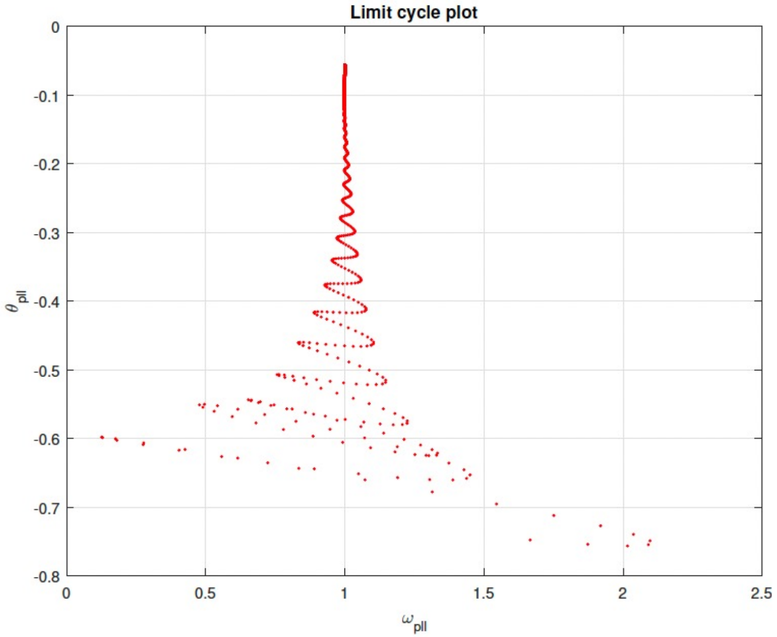


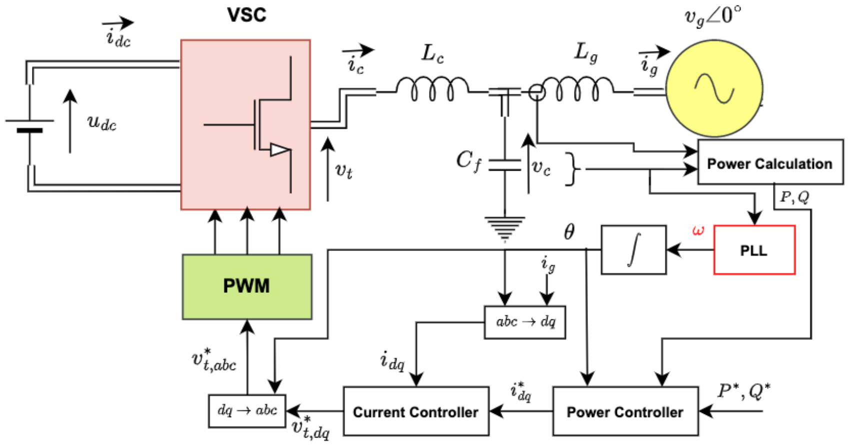
Poincare maps

GFL Inverter

Case 1: Normal Operation $(K_p = 1.5) \Rightarrow$ Fixed Point



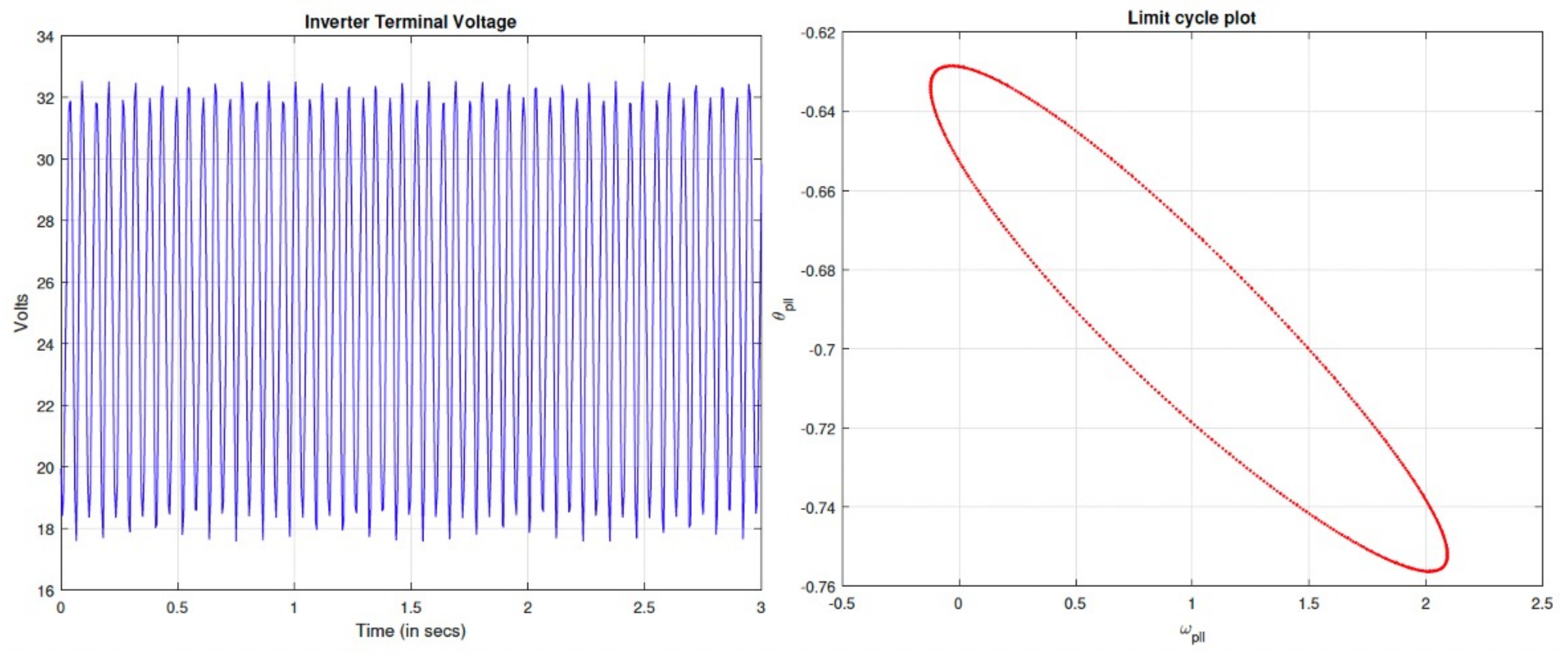


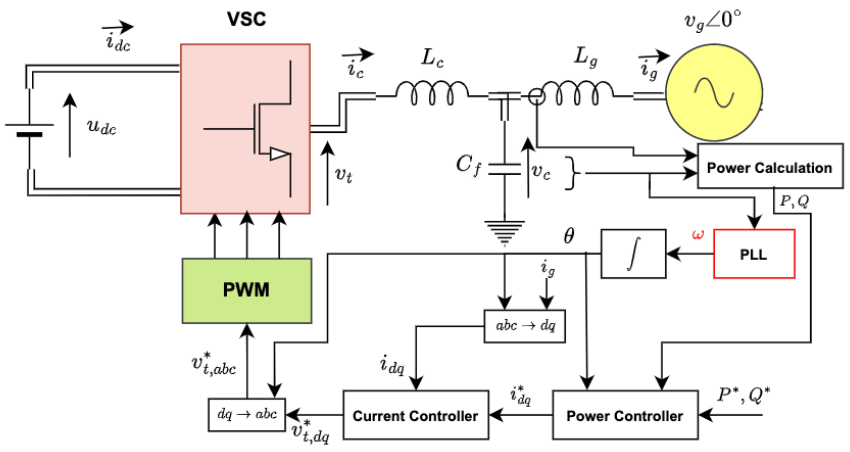


Bifurcation parameter is chosen as the proportional gain K_p of the current controller.

GFL Inverter

Case 2: $(K_p = 3.0) \Rightarrow$ Period-1 Orbit (T=0.115s)

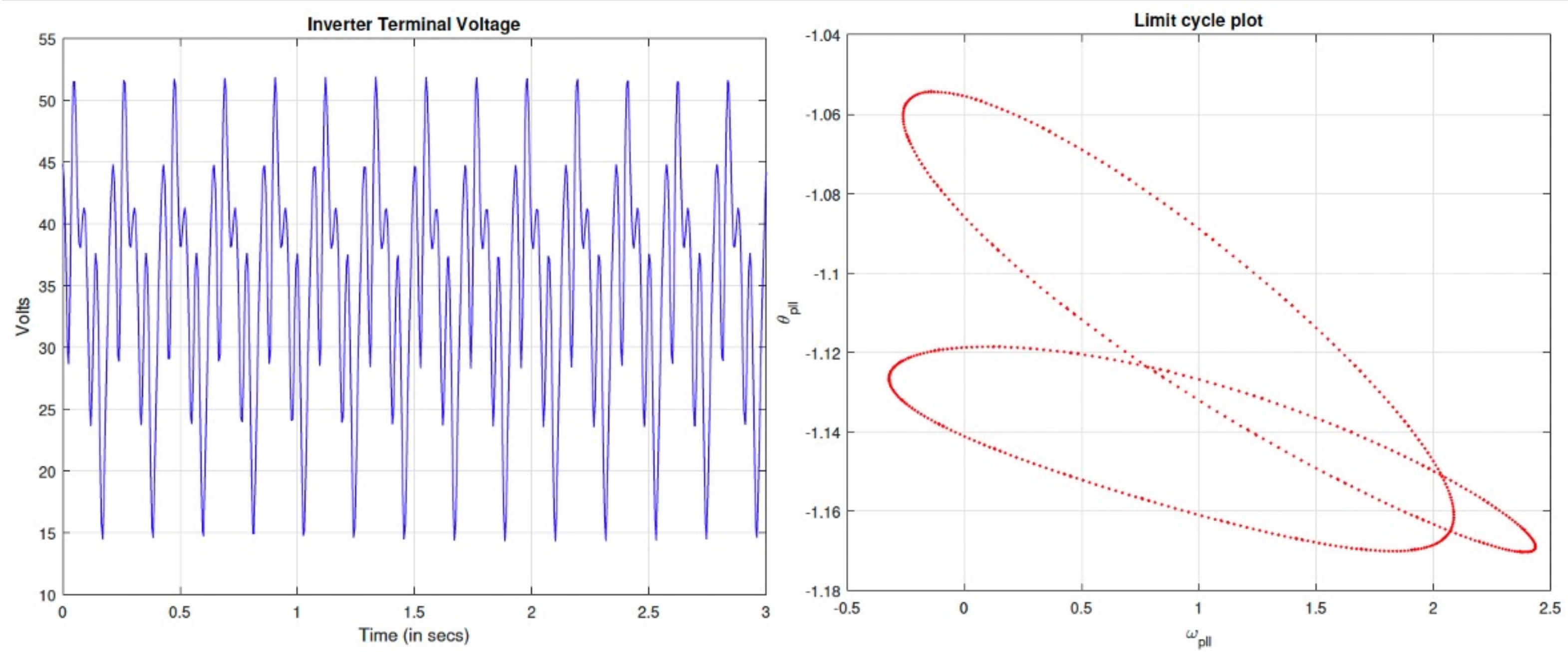


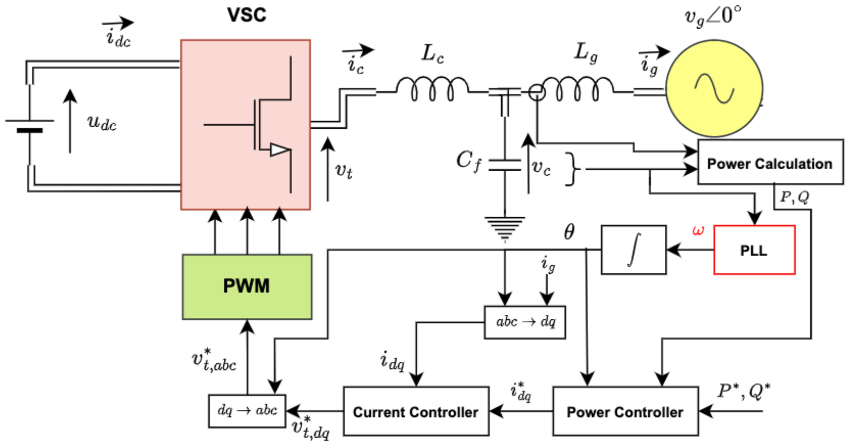


Bifurcation parameter is chosen as the proportional gain K_p of the current controller.

GFL Inverter

Case 3: $(K_p = 5) \Rightarrow$ Period-2 Orbit (T=0.215s)

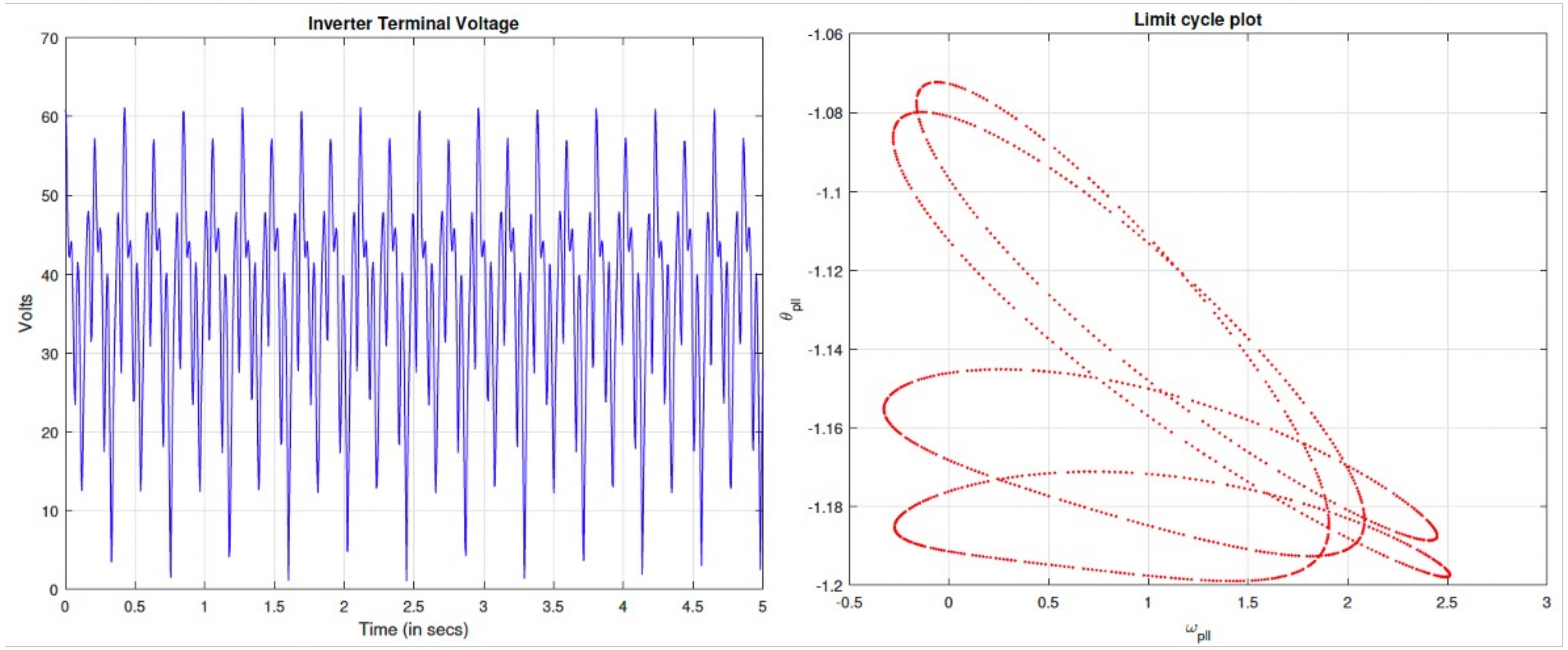


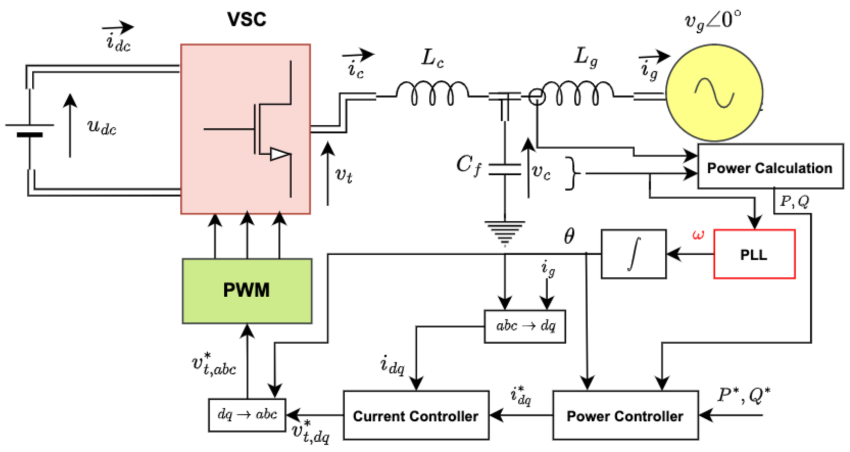


Bifurcation parameter is chosen as the proportional gain K_p of the current controller.

GFL Inverter

Case 4: $\left(K_p = 5.5\right) \Rightarrow$ Period-4 Orbit (T=0.425s)

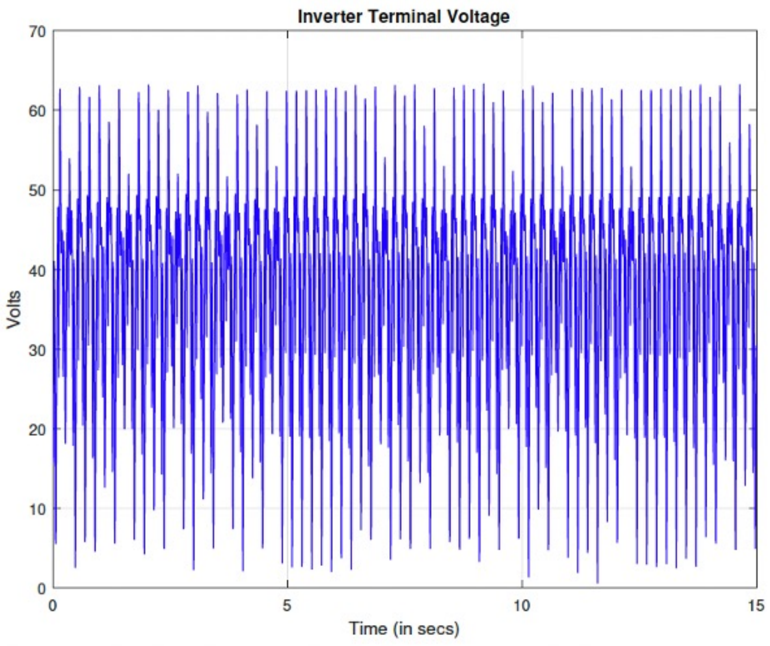


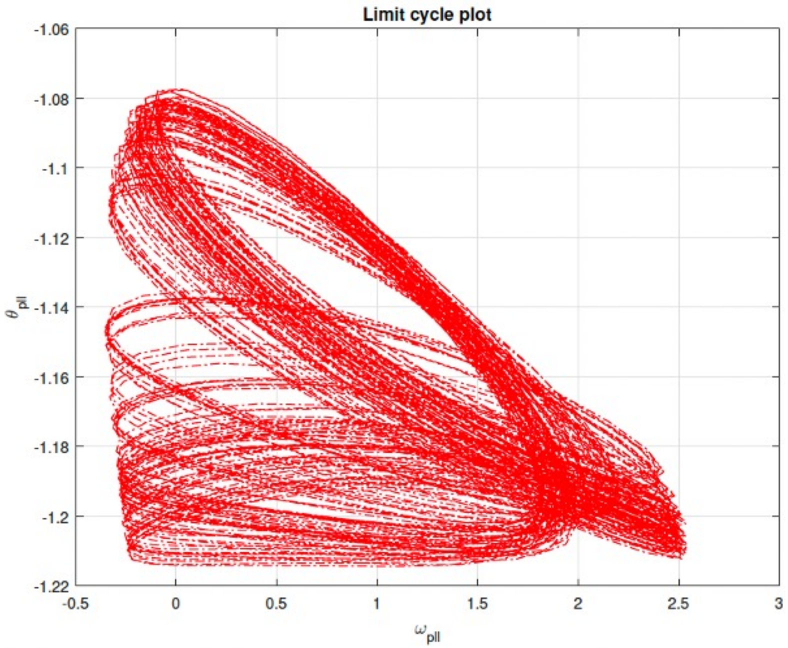


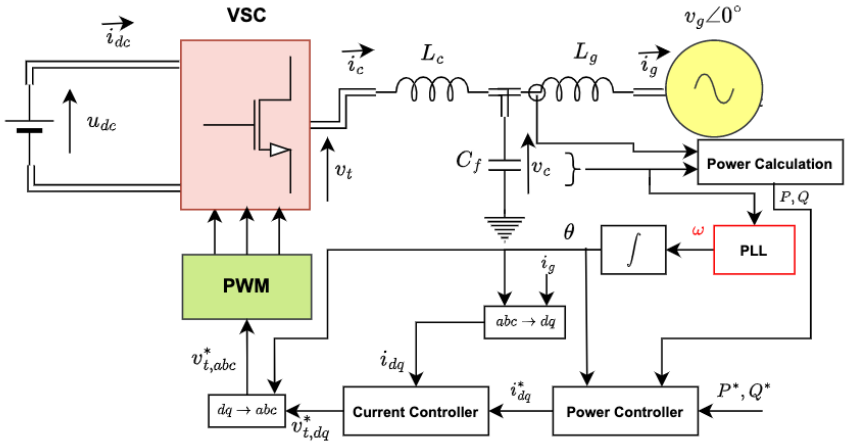
Bifurcation parameter is chosen as the proportional gain K_p of the current controller.

GFL Inverter

Case 5: $(K_p = 5.7) \Rightarrow$ Chaos







Bifurcation parameter is chosen as the proportional gain K_p of the current controller.

Nonlinear Phenomena in IBR-rich Grids

1. *Can IBR-rich power grids induce chaotic behavior?*
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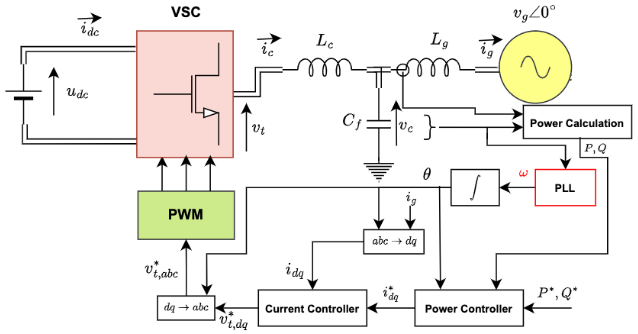
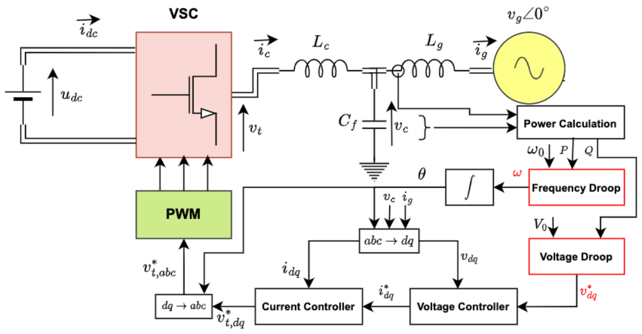
Grid Following Inverter



VS

Grid Forming Inverter

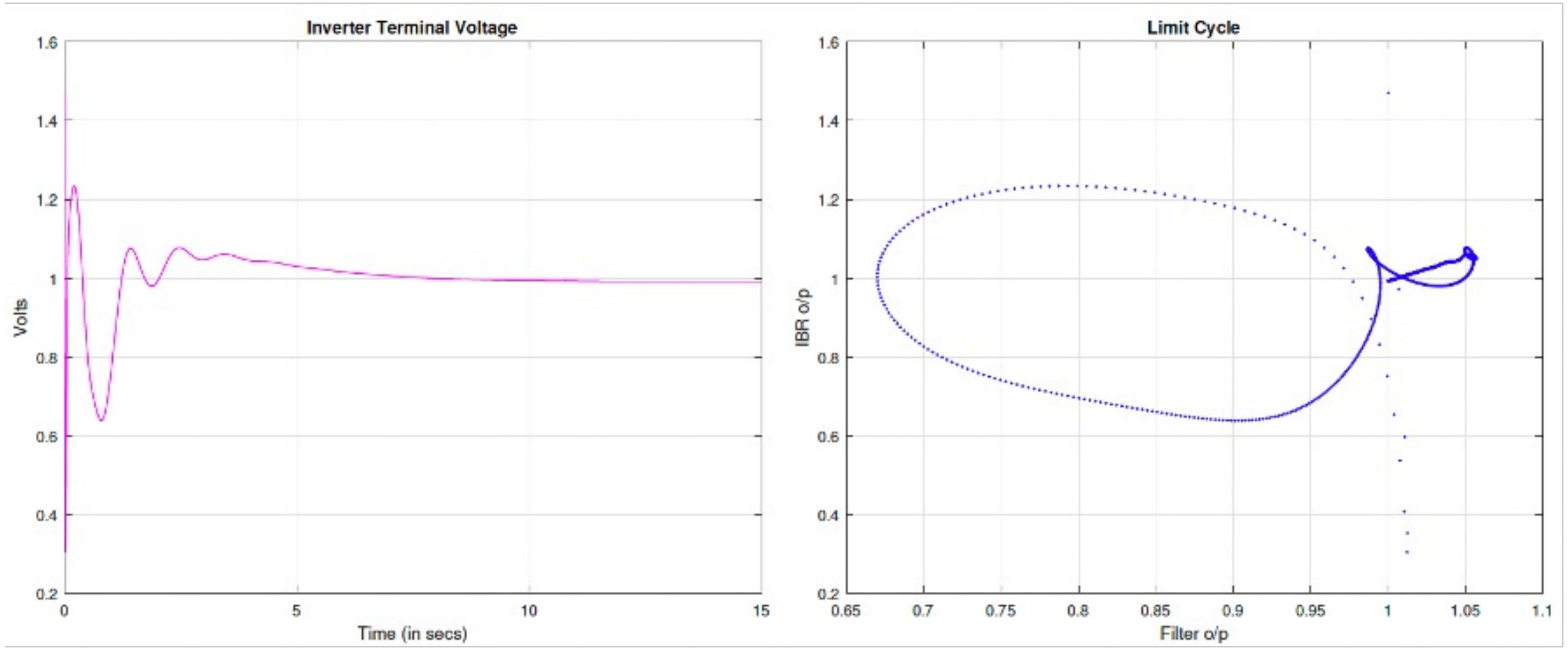


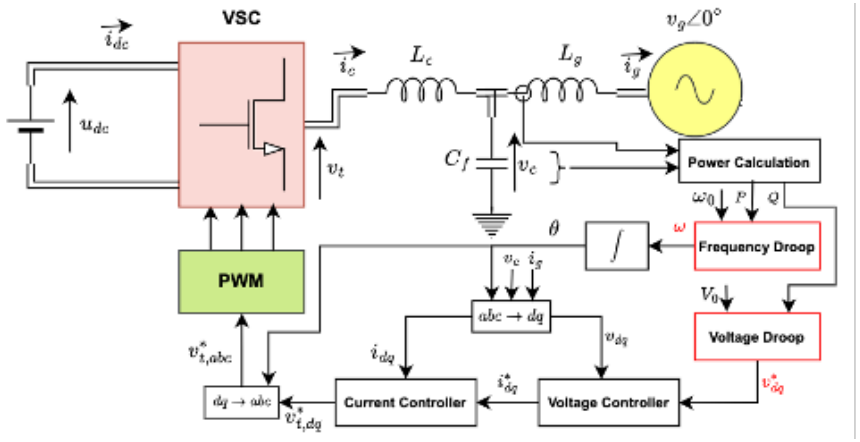
Observations:

- ➢ Grid-following (GFL) inverter ⇒ Period-doubling route

GFM Inverter

Case 1: Normal Operation $(K_p = 2.5) \Rightarrow$ Fixed Point

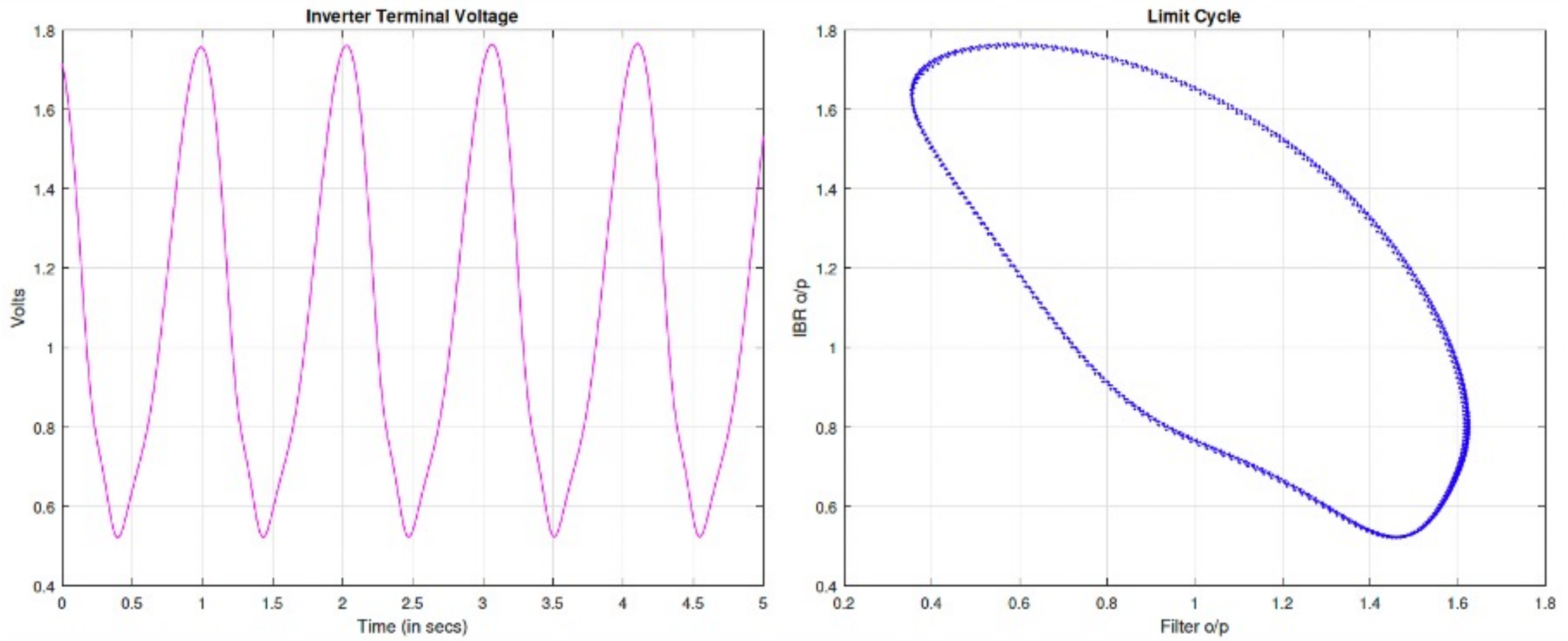


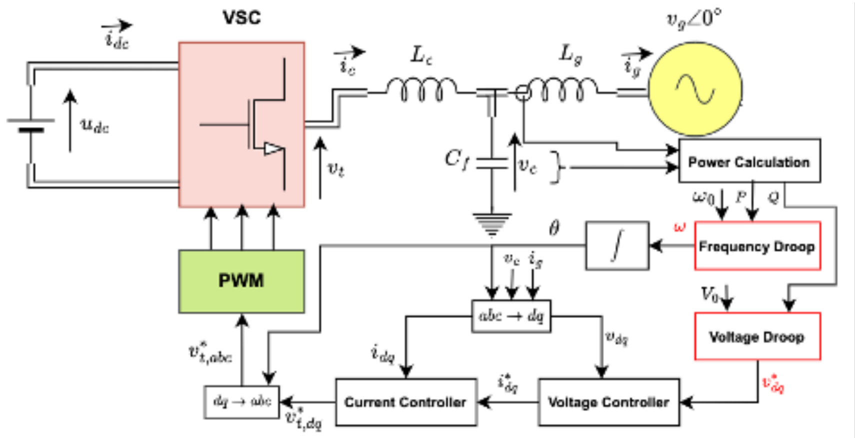


Bifurcation parameter is chosen as the proportional gain K_p of the current controller.

GFM Inverter

Case 2: $\left(K_p = 0.636998540037319\right) \Rightarrow$ Period-1 Orbit





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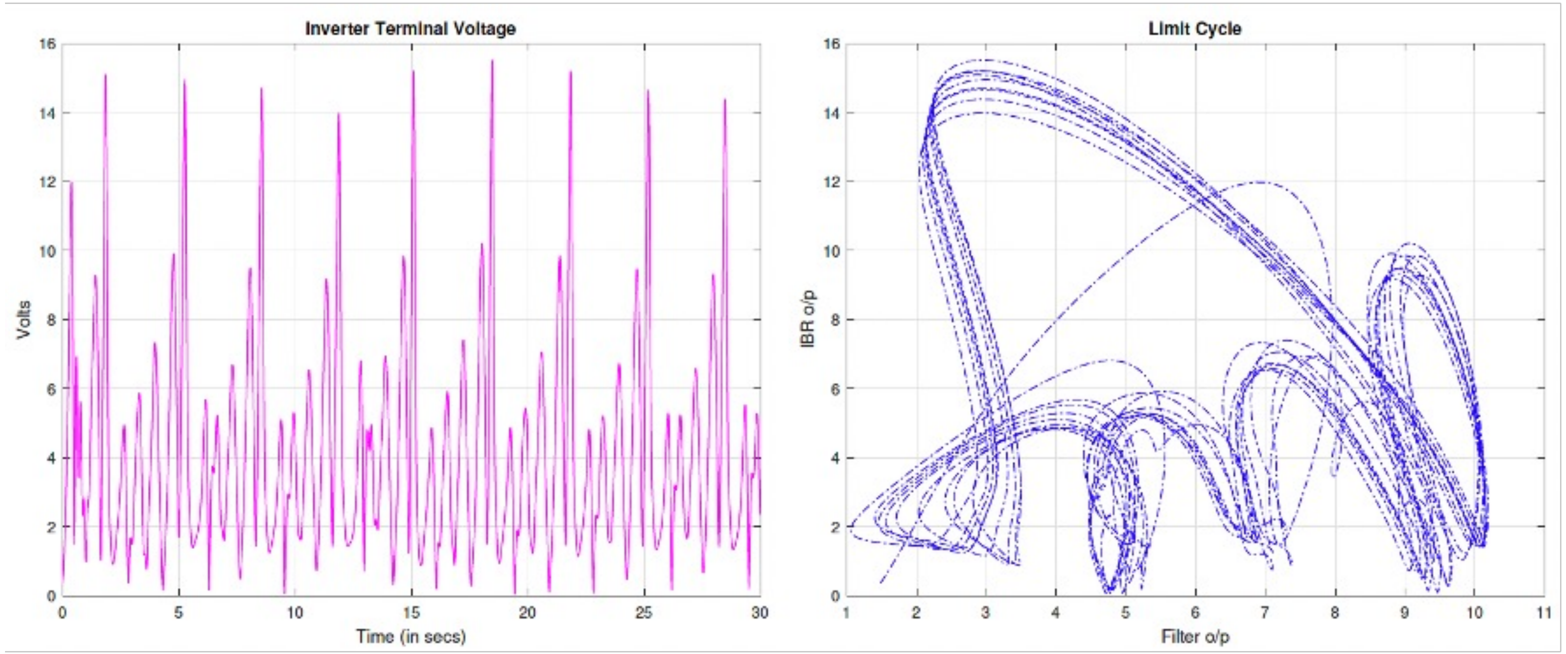
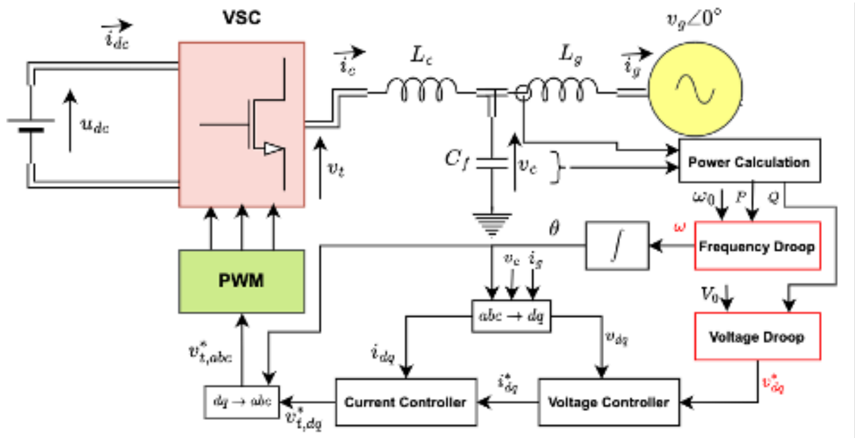
GFM Inverter

Case 3: $\left(K_p = 0.636998540037318\right) \Rightarrow$ Chaos





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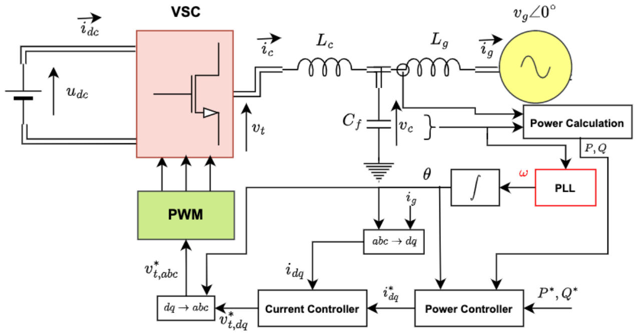
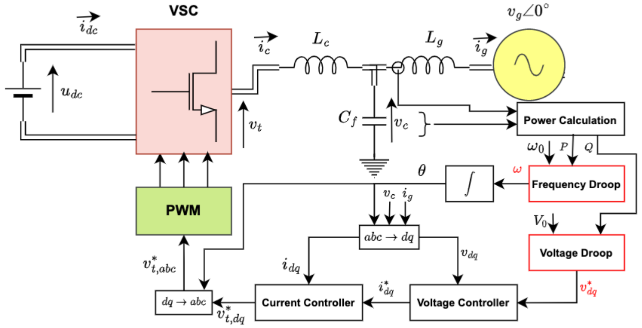


VS

Grid Forming Inverter



Observations:

- Grid-following (GFL) inverter ⇒ Period-doubling route
- Grid-forming (GFM) inverter ⇒ Intermittency route

Observations: GFM inverters can produce even more complex behavior

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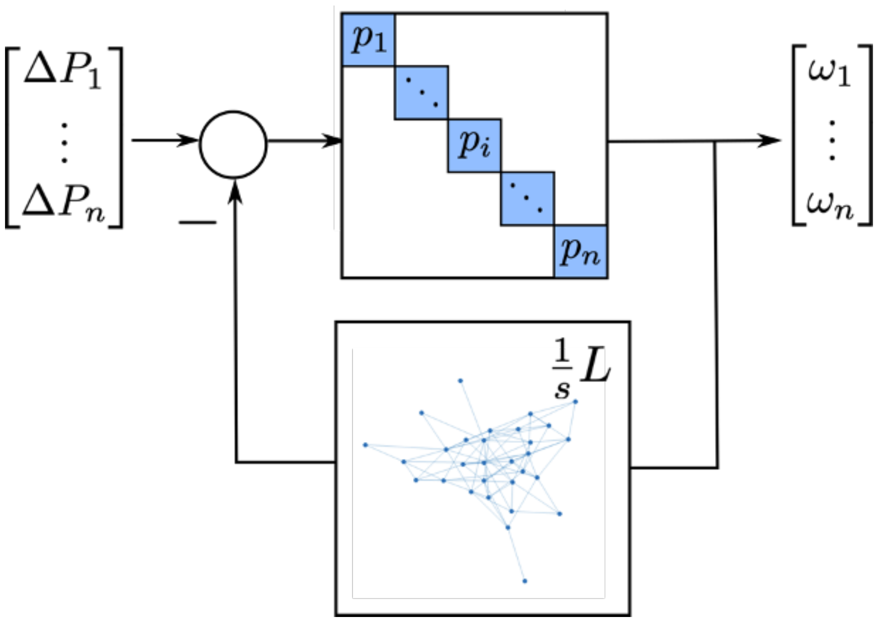
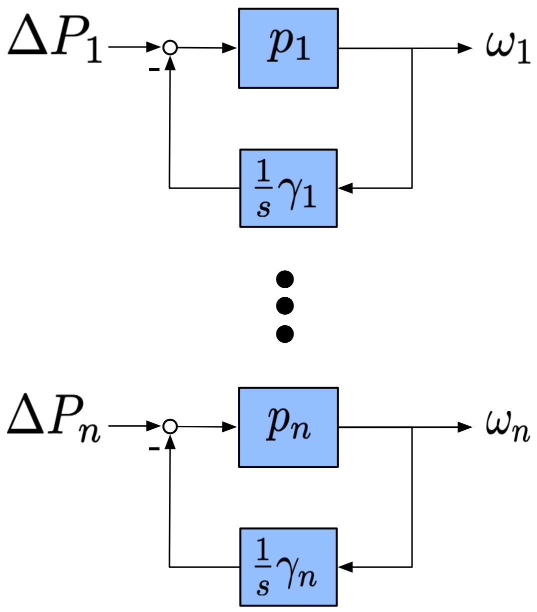
Decentralized Stability Analysis in Power Grids [TCNS 19]



1.When does this interconnection is stable?

2. Can we analysis and control design based on ***local rules****?*

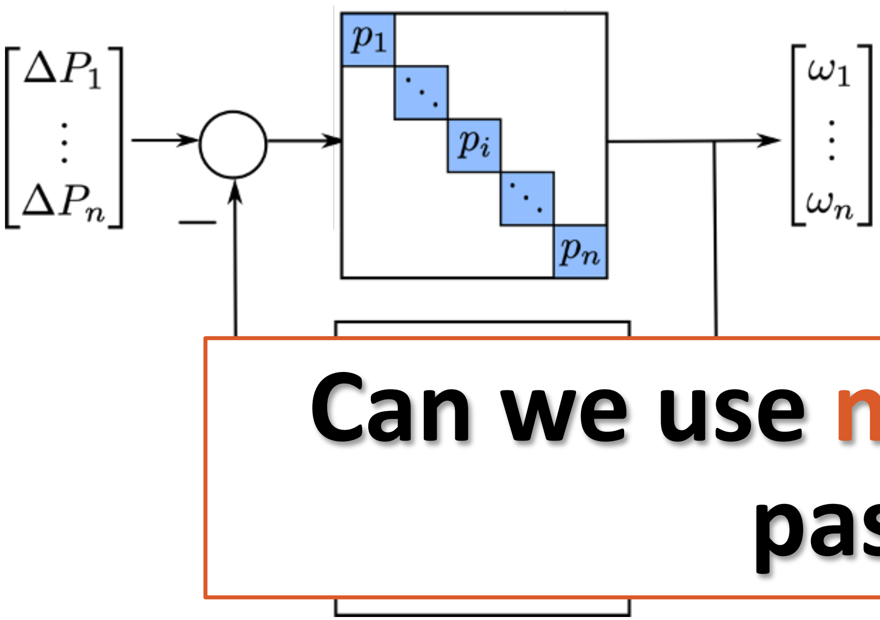


Problem Setup:

- *Linearized* power flows, *lossless*
  $$L_{ij} = b_{ij} v_i v_j \cos(\theta_i^* - \theta_j^*)$$
- Bus i: arbitrary *siso* transfer function:
  $$\omega_i = p_i(s)\,\Delta P_i \qquad \text{(SGs or IBRs)}$$

[TCNS 19] Pates, M. Robust Scale Free Synthesis for Frequency Regulation in Power Systems. **IEEE Transactions on Control of Network Systems, 2019**

Decentralized Stability Analysis in Power Grids [TCNS 19]



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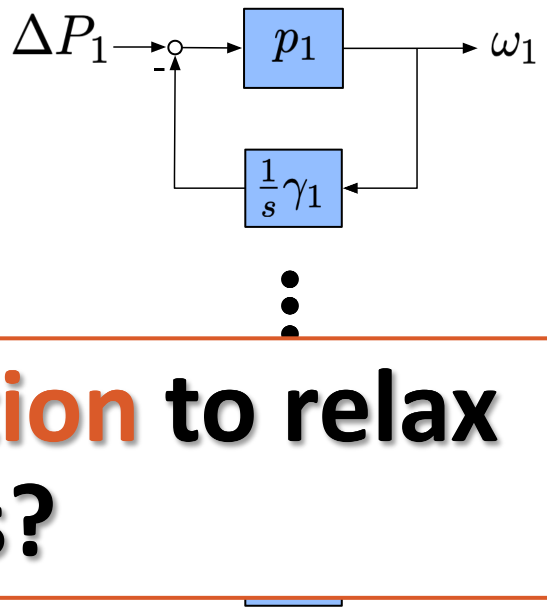


Richard Pates

Can we use network information to relax passivity conditions?

Standard Approach: Passivity

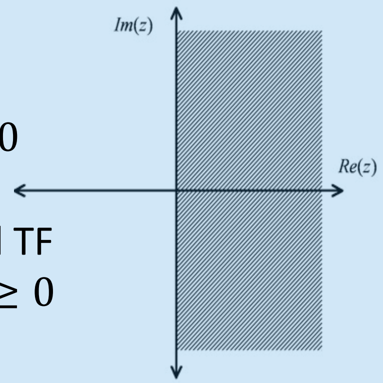
- If $p_i(s)$ is strictly positive real (SPR), then the interconnection is stable for **all networks L!**

Positive Real (PR) TF

$$\mathrm{Re}[p_i(s)] \geq 0$$

Strictly Positive Real TF

$$\mathrm{Re}[p_i(s-\varepsilon)] \geq 0$$



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Classical Result: Absolute Stability

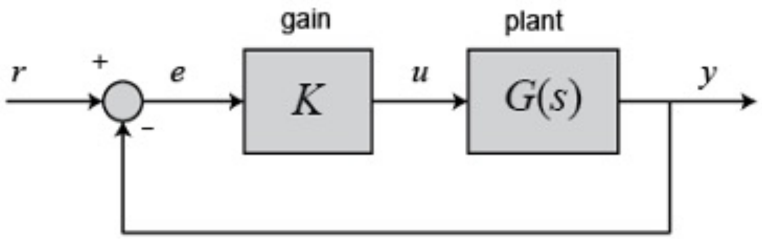
IEEE TRANSACTIONS ON AUTOMATIC CONTROL

Frequency Domain Stability Criteria—Part I

R. W. BROCKETT, MEMBER, IEEE AND J. L. WILLEMS

Abstract—The objective of this paper is to illustrate the limita-

II. THE GENERALIZED POPOV THEOREM

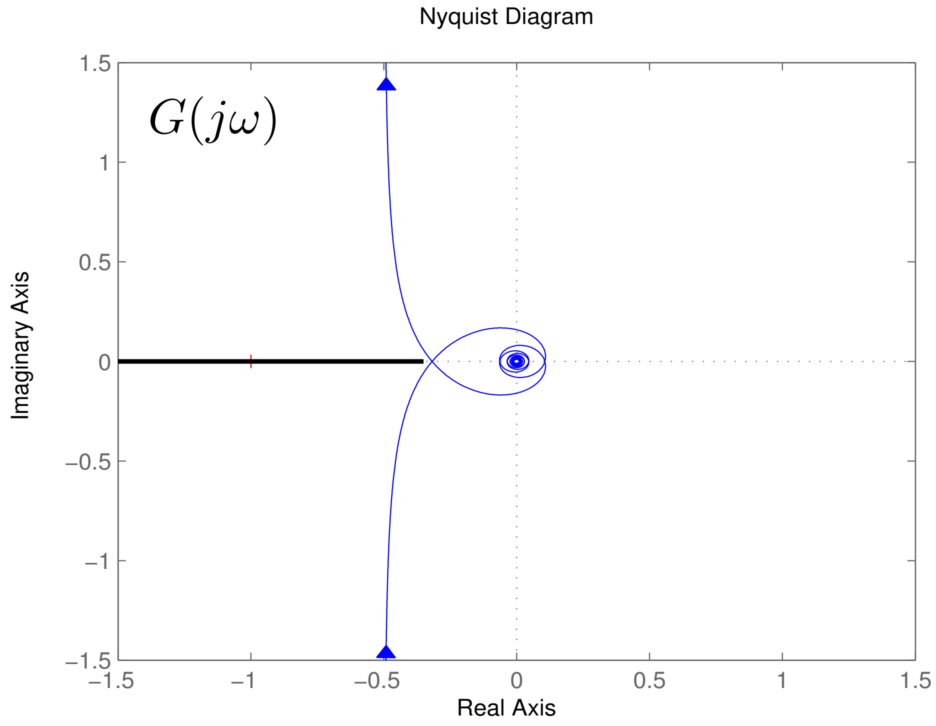


Stable for $0 \leq K \leq k^*$?

Assume: $G(s)$ is stable

Define: $h(s) \in PR$ (passive)

Test: If $h(s)\big(1 + k^* G(s)\big) \in SPR$ (strictly passive)
then, **yes!**



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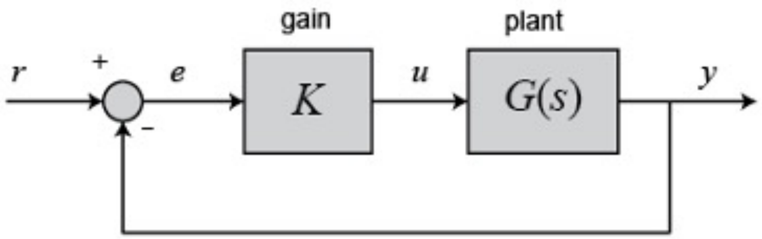

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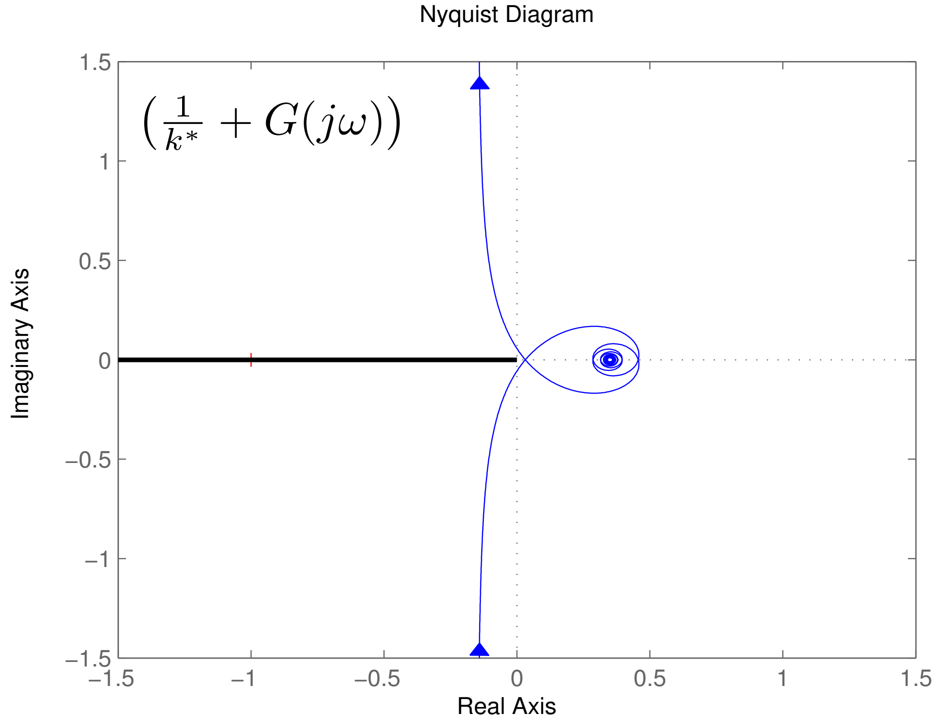

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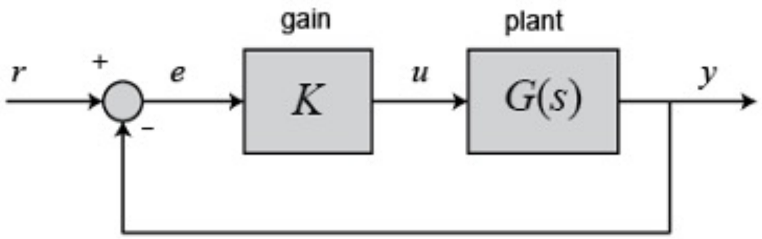

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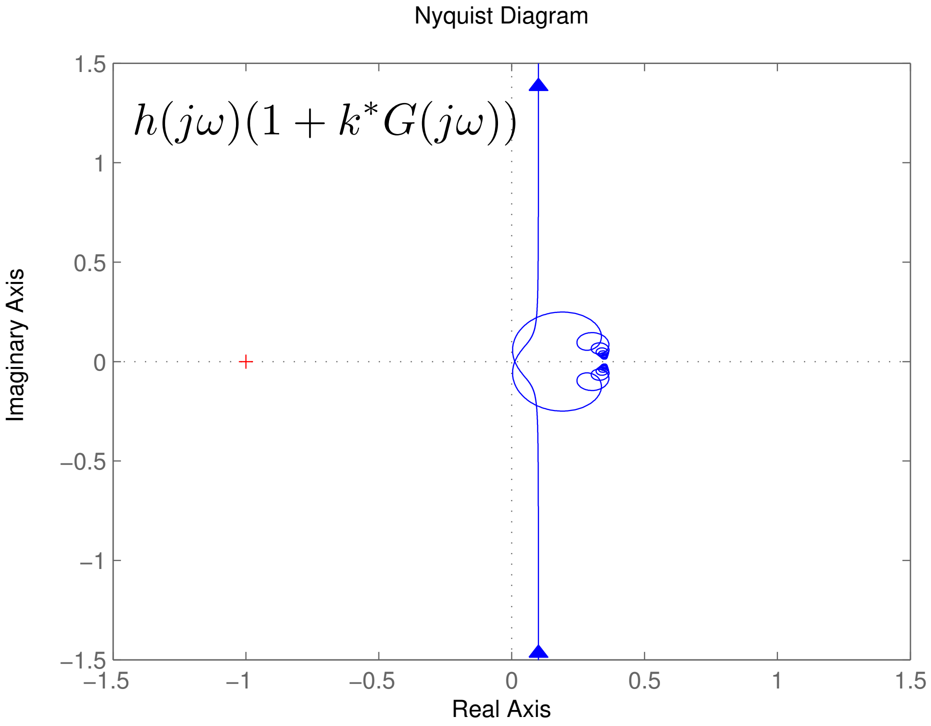

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Scale-free Stability Analysis

Key Idea: Exploit limited network information to relax passivity condition

- Let γ_i be a local connectivity bound: $[L]_{ii} = \sum_{j \in N_i} b_{ij} v_i v_j \cos(\theta_i^* - \theta_j^*) \leq \frac{\gamma_i}{2}$

Brockett & Willems '65

Assume: $G(s)$ is stable

Define: $h(s) \in PR$ (passive)

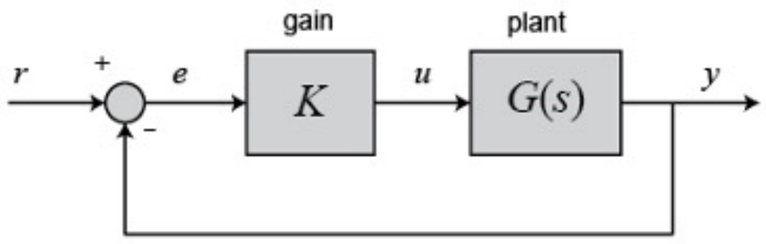
Test: If $\boldsymbol{h(s)\big(1 + k^* G(s)\big) \in SPR}$ (strictly) then system is stable for all $0 \leq K \leq k^*$

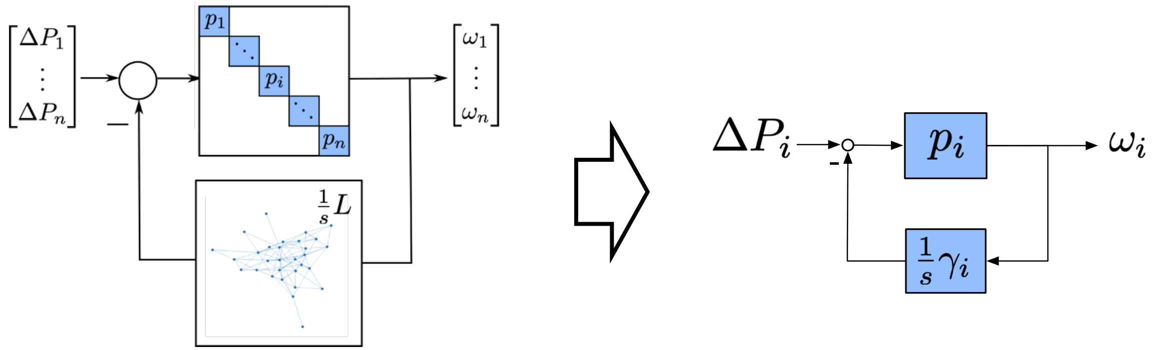
Pates & Mallada 2019

Assume: $p_i(s)$ is stable

Define: $h(s) \in PR$ (passive)

Test: If $\boldsymbol{h(s)\left(1 + \gamma_i \frac{1}{s} p_i(s)\right) \in SPR, \forall i}$, then system stable for networks $[L']_{ii} \leq \frac{\gamma_i}{2}, \forall i$





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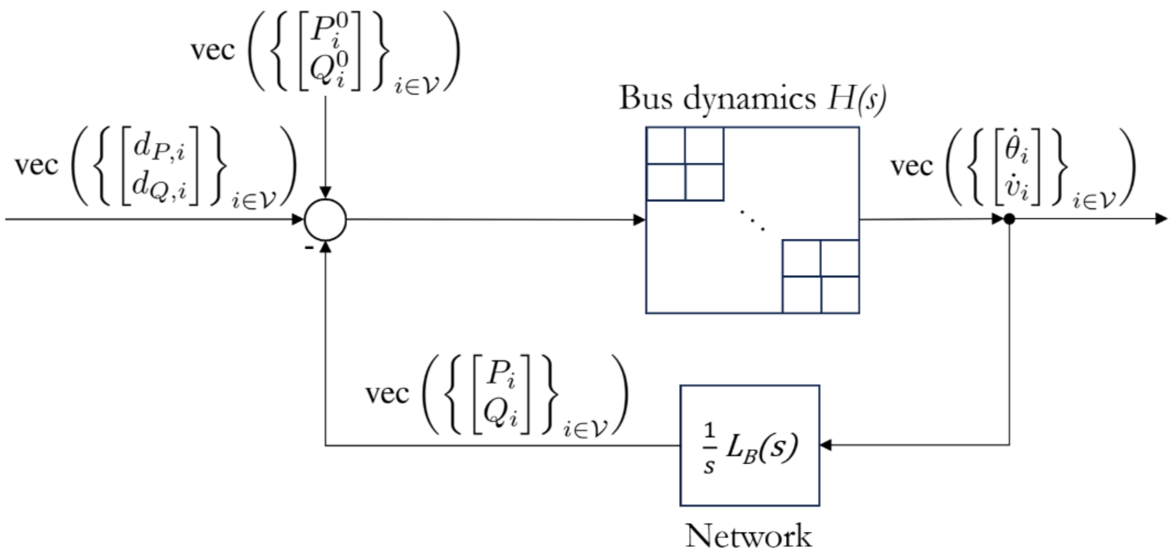
Decentralized Stability Analysis for IBR Power Systems



Bus dynamics: Droop-based grid-forming IBR (MIMO)

$$\begin{cases}\dot\theta_i &= \omega_i\\ \omega_i &= \omega_i^0 + m_i^p f_i^p(s)(P_i^0 - P_i), \qquad \forall i \in \mathcal{V}_{inv}.\\ v_i &= V_i^0 + m_i^q f_i^q(s)(Q_i^0 - Q_i).\end{cases}$$

Bus dynamics: Synchronous machine (SISO)

$$\dot\theta_i = \frac{1}{M_i s + D_i} P_i, \quad \forall i \in \mathcal{V}_{sm}.$$

Theorem:

If for all $i \in \mathcal{V}_{inv}$ the loop gain m_i^q satisfy

$$0 \le m_i^q \le \frac{1}{2\left(V_{\max,j} - V_{\min,i}\right)|b_{ii}|}$$

for all $j \in \mathcal{N}_i$, then the system is stable

Remarks:

- Fully decentralized (plug-and-play)
- Robust to network operating points
- Based on input-output models
- Several assumptions…

[PESGM 24] Siahaan, M, Geng, Decentralized Stability Criteria for Grid-Forming Control in Inverter-Based Power Systems. **PES General Meeting 2024**

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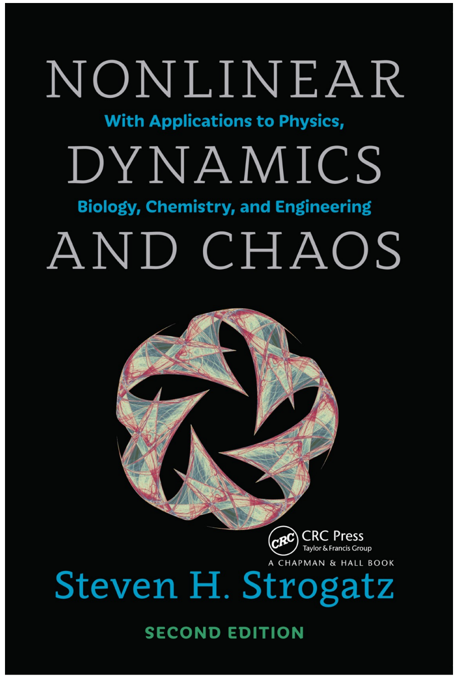
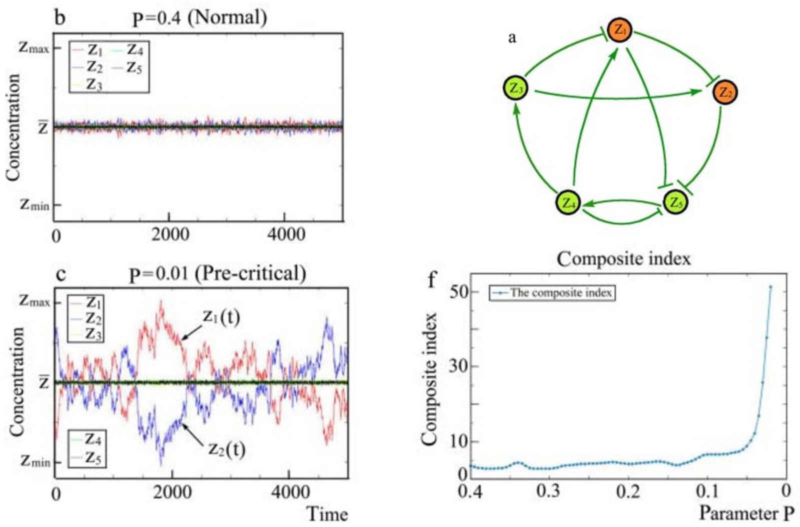
Early Detection via Critical Slowdown

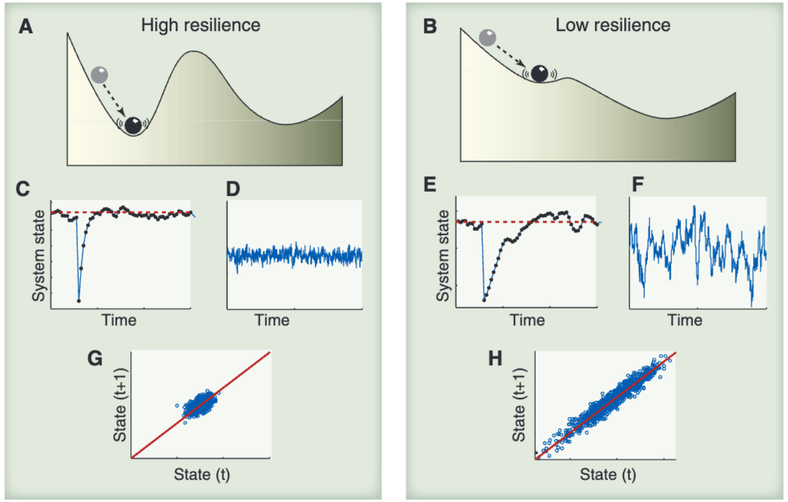


Transition to instability via bifurcations has the specific signature of *critical slowing down*

Early disease detection[1]



Loss of resilience[2]



Research Questions:

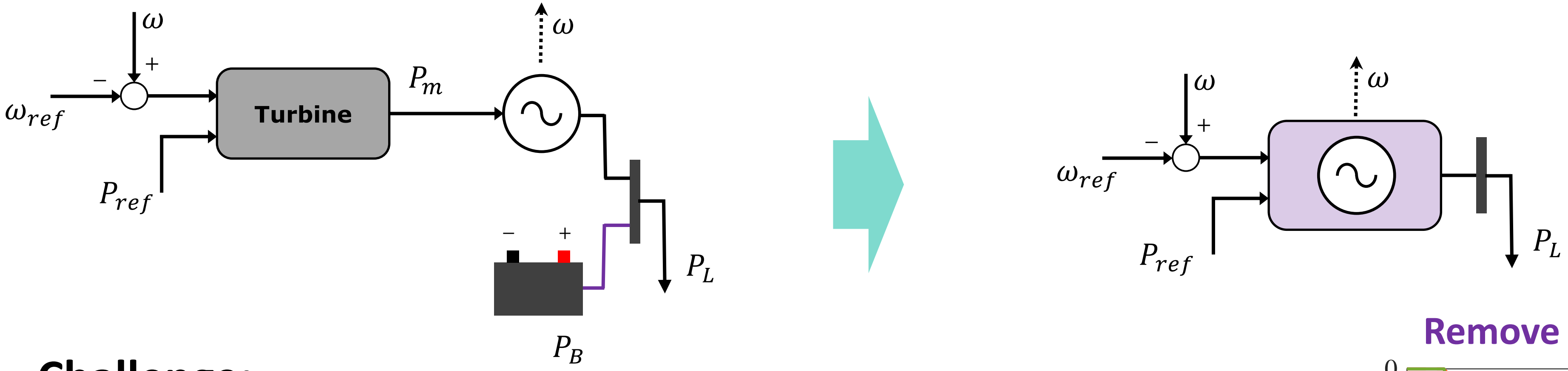
- Is critical slow-down a measurable feature in SSO transition to instability?
- Can we use critical slow down signatures to develop early alarm notifications?
  - What is the role of ML/AI in identifying these signatures?

[1] L. Chen et al. Detecting early-warning signals for sudden deterioration of complex diseases by dynamical network biomarkers, **Scientific reports 2012**

[2] M. Scheffer et al. Anticipating critical transitions, **Science 2012**

Novel control designs for exploring trade-offs

IBR control flexibility enable control behavior not possible before: ***Grid Shaping***

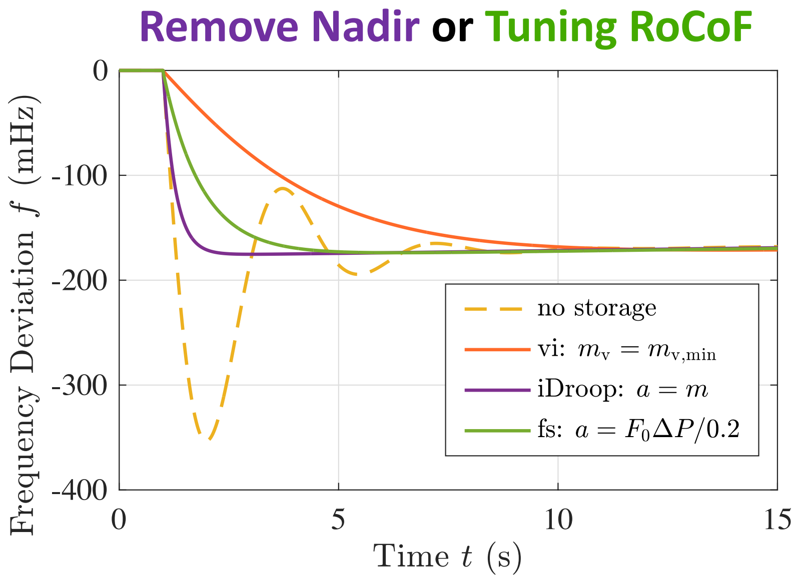


Challenge:

- SSO limits inverter ability to shape frequency response

Research Questions:

- Can we design controllers that trade-off between stability and performance?
- Can we dynamically tune controllers based on grid conditions?

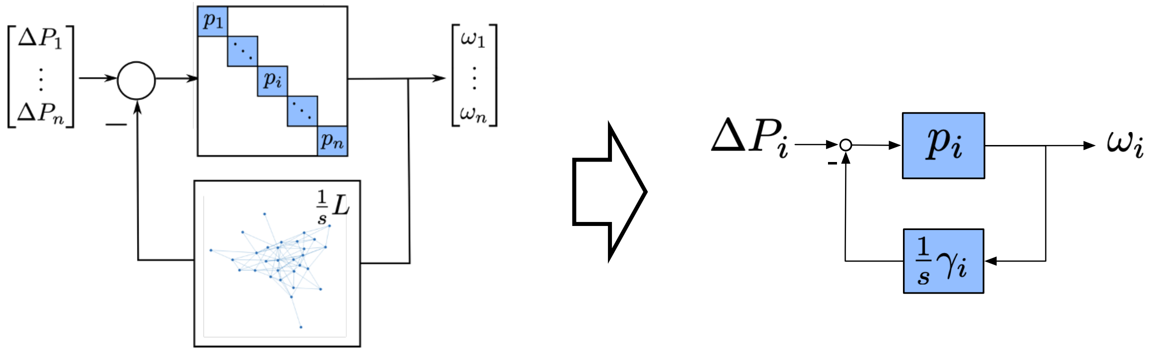


[LCSS 20] Jiang, Bernstein, Vorobev, M. Grid-forming frequency shaping control for low-inertia power systems **IEEE Control Systems Letters 2020**

[LCSS 23] Poolla, Lin, Bernstein, M, Groß. Frequency shaping control for weakly-coupled grid-forming IBRs **IEEE Control Systems Letters 2023**

The role of Operations in SSO prevention

Emergence of oscillations depends on *grid conditions* and *control tunning*



Power Flow Constraint

$$\sum_{j \in N_i} b_{ij} v_i v_j \cos(\theta_i^* - \theta_j^*) \leq \frac{\gamma_i}{2}$$

IBR Dynamics Constraint

$$\boldsymbol{h(s)\left(1 + \gamma_i \frac{1}{s} p_i(s)\right) \in SPR}$$

Research Questions:

- Can we design dispatch mechanisms that can prevent SSO?
- Can dispatch mechanisms also inform about control tuning?
- How should we implement such mechanisms with inaccurate models?

Summary

- A Word of Caution: GFM IBRs Complex Dynamics
  - Faster controls **can speed up the transition to chaos**
- Scale-free Small-signal Stability Analysis
  - Generalizing control tools for network systems
- Avenues for Future Research
  - Early detection via critical slow-down
  - Novel IBR control designs: Trading Freq. vs Volt. Support
  - The role of operations in SSO prevention

Thanks!

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