

Options for Mitigation Measures

Avenues for new research

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ESIG/G-PST Special Topic Workshop

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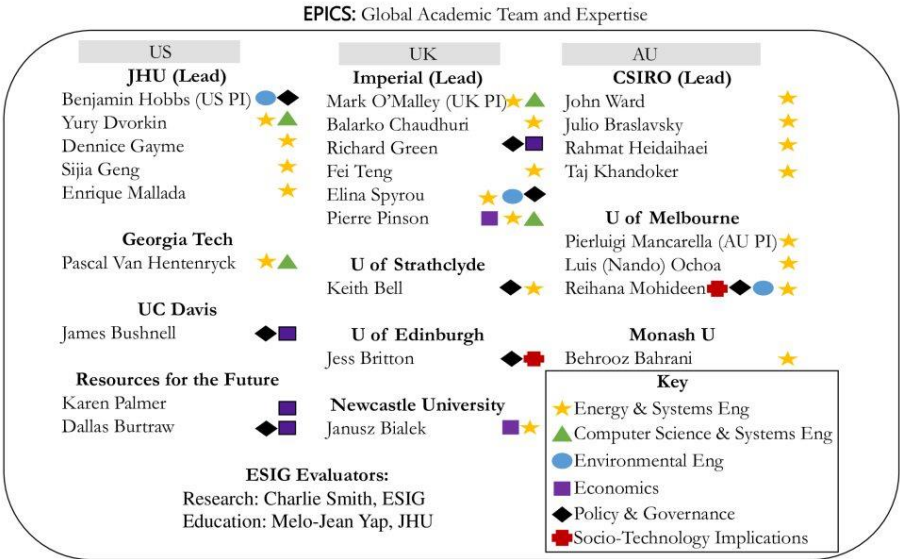
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NSF Global Center: EPICS
Electric Power Innovation for a Carbon-free Society

Outline

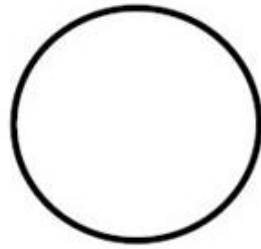
- A Word of Caution: GFM IBRs Complex Dynamics
 - Faster controls **can speed up the transition to chaos**
- Decentralized Stability Analysis in Power Grids
 - Generalizing control tools for network systems
- Avenues for Future Research
 - Early detection via critical slow-down
 - Novel IBR control designs: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



Nonlinear Phenomena in IBR-rich Grids



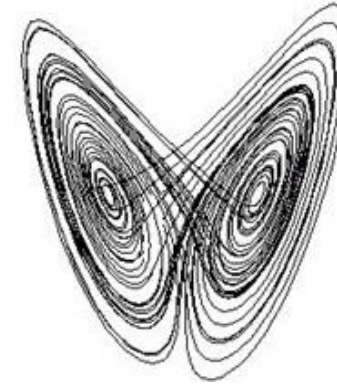
Sustained oscillatory behavior is intrinsically **nonlinear phenomena** induced by **bifurcations** which often can leads to **chaos**



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

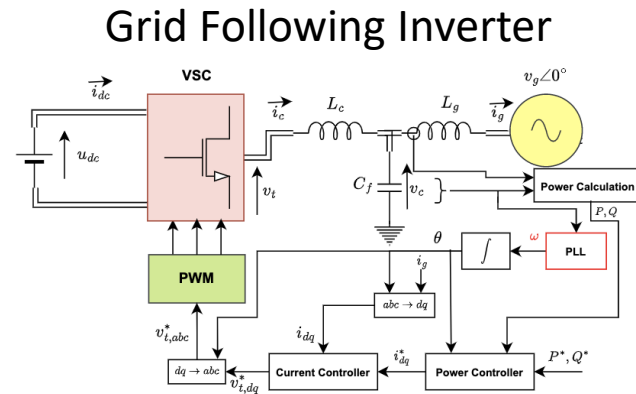
[3] Abraham, Arimondo, and Boyd, *Instabilities, dynamics and chaos in nonlinear optical systems*.



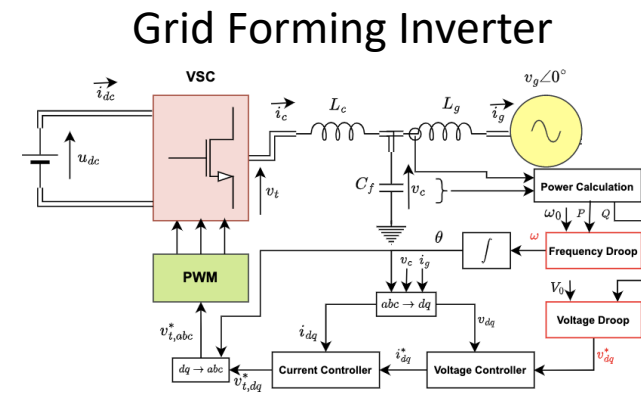
Nonlinear Phenomena in IBR-rich Grids

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

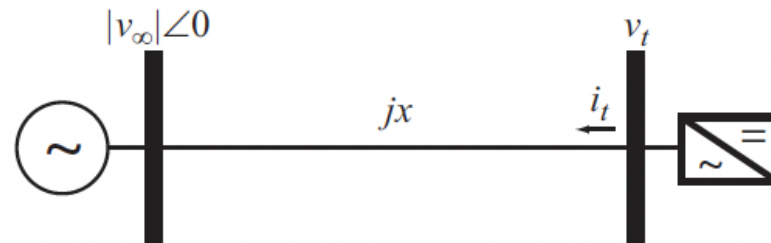
Q2: Is there a fundamental difference between GFL and GFL Inverters?



VS

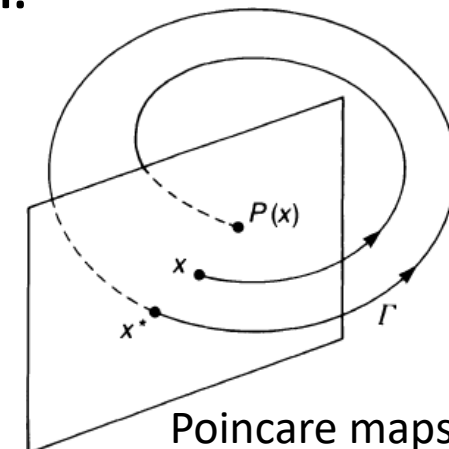


Problem Setup:



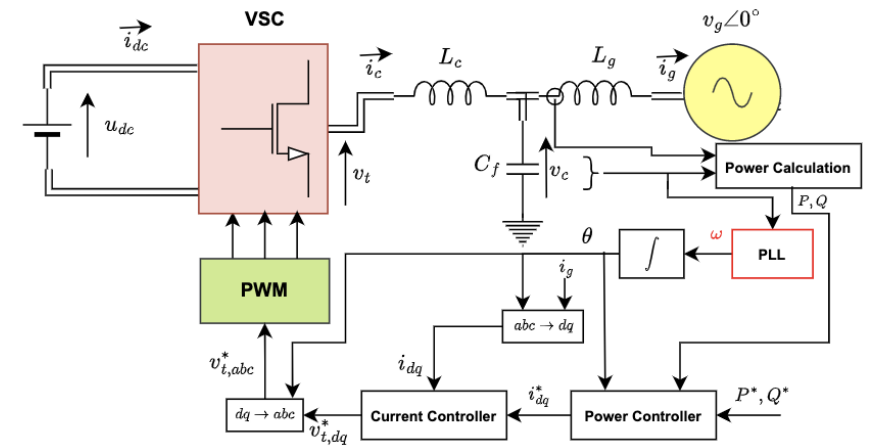
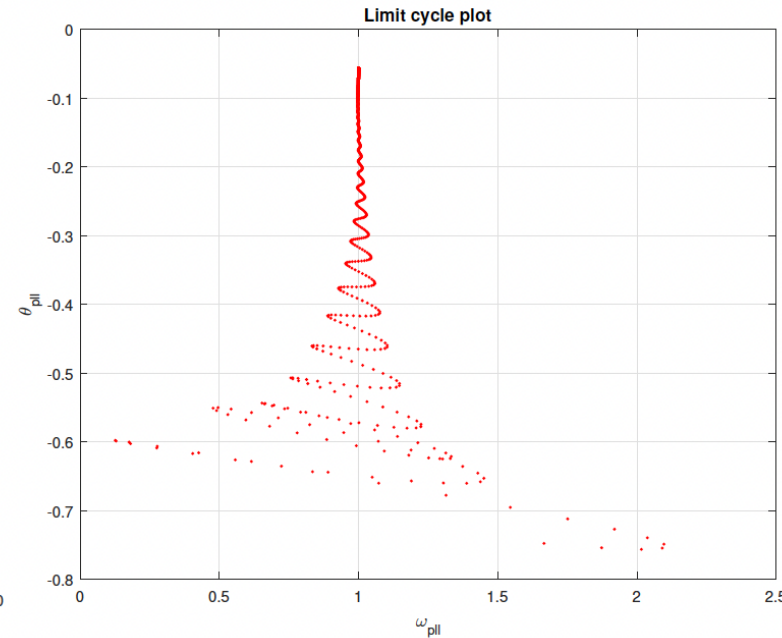
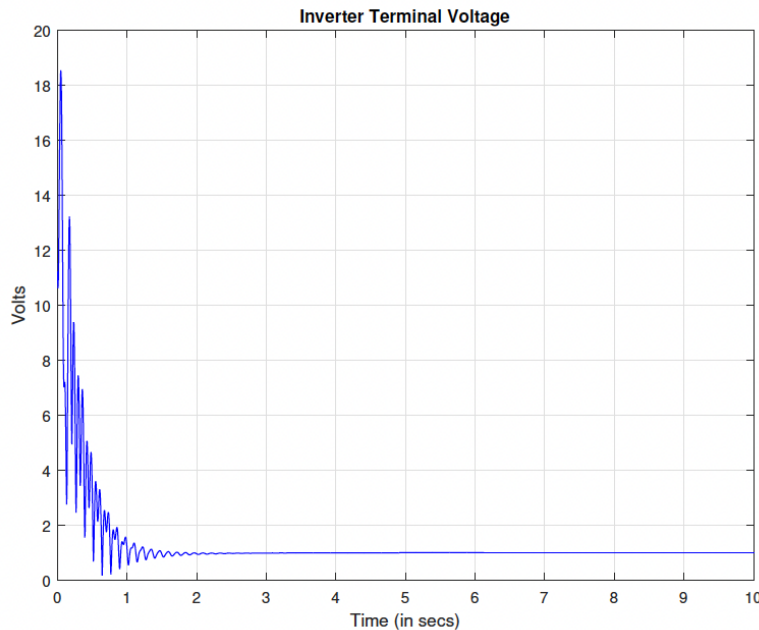
- IBR connected to infinite bus
- Use current controller gain K_p as bifurcation parameter

Analysis Tool:



GFL Inverter

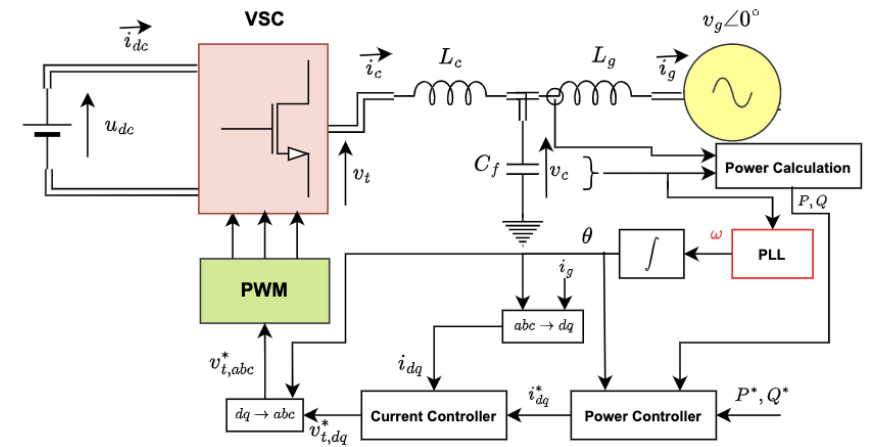
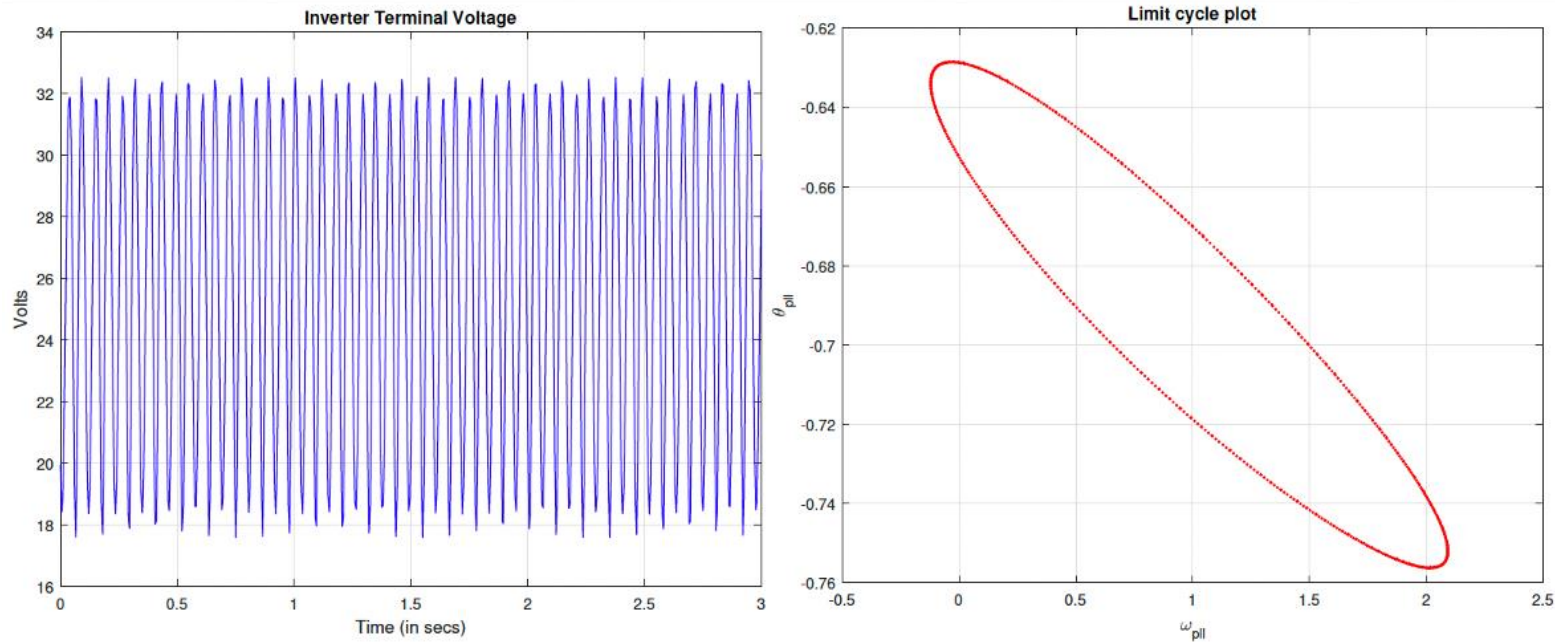
Case 1: Normal Operation ($K_p = 1.5$) $\Rightarrow$ Fixed Point



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

GFL Inverter

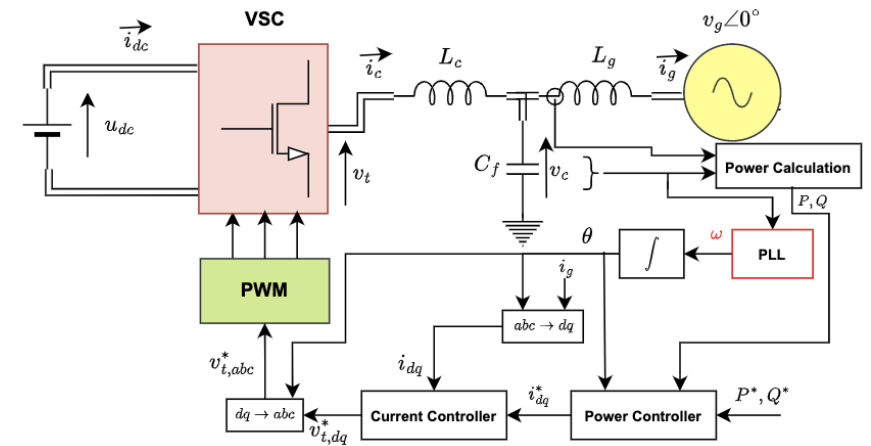
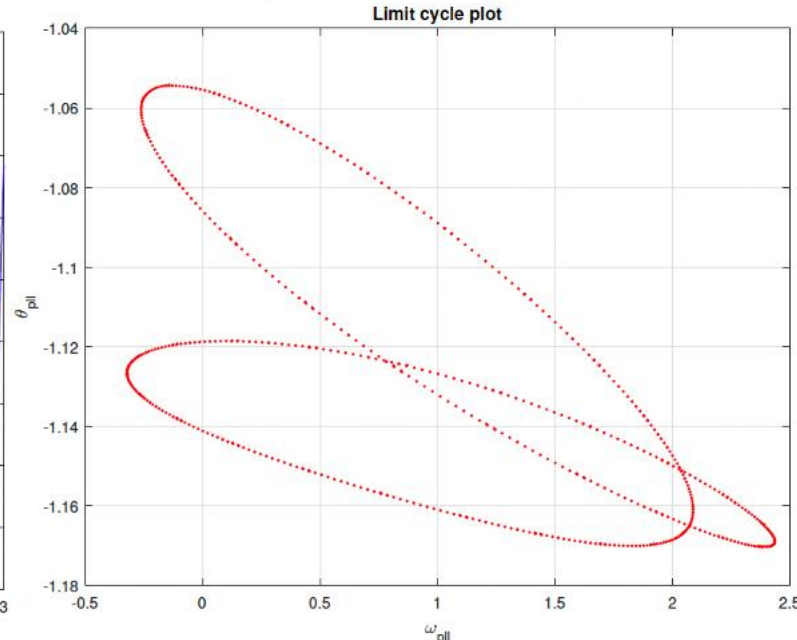
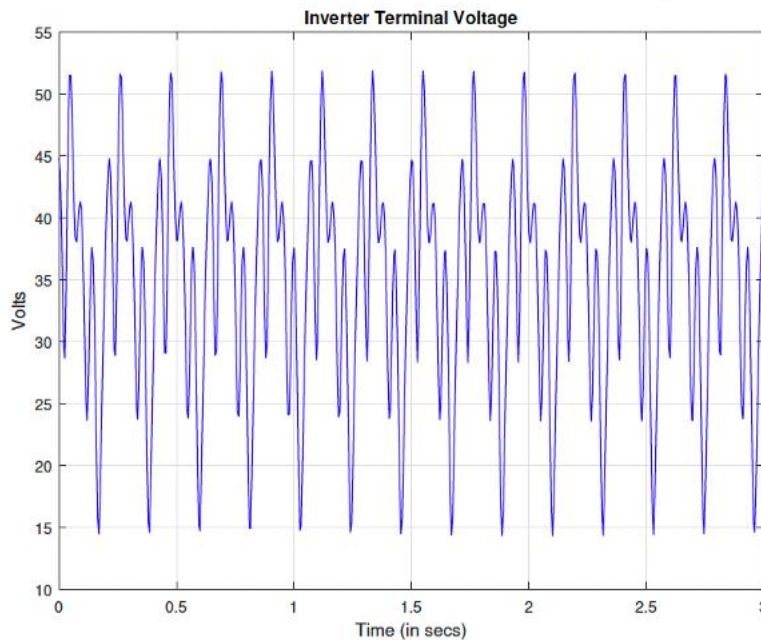
Case 2: ($K_p = 3.0$) $\Rightarrow$ Period-1 Orbit ($T=0.115s$)



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

GFL Inverter

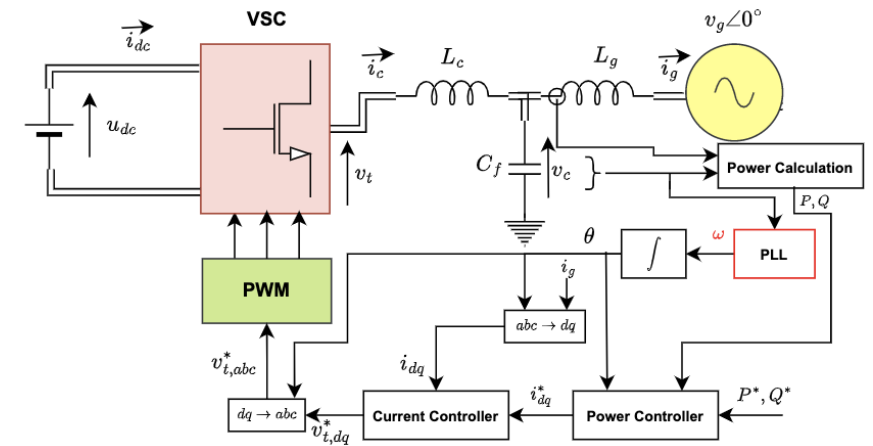
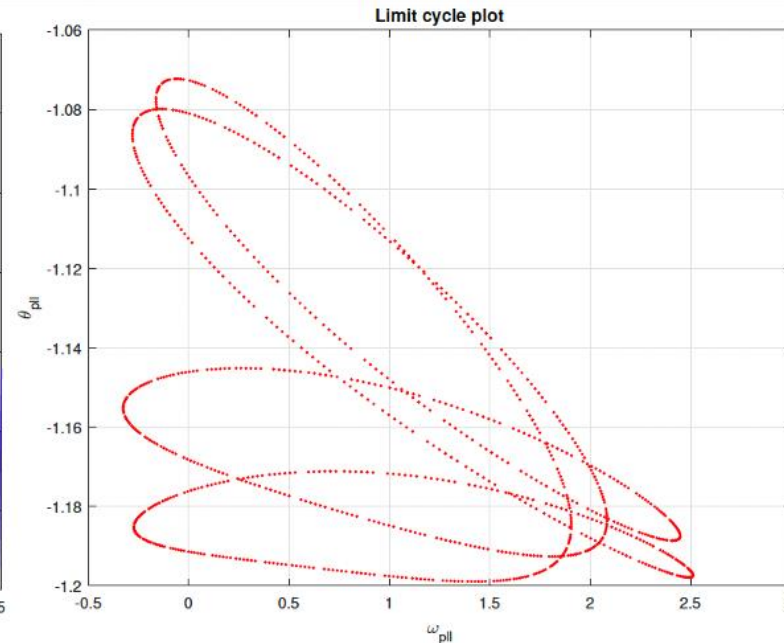
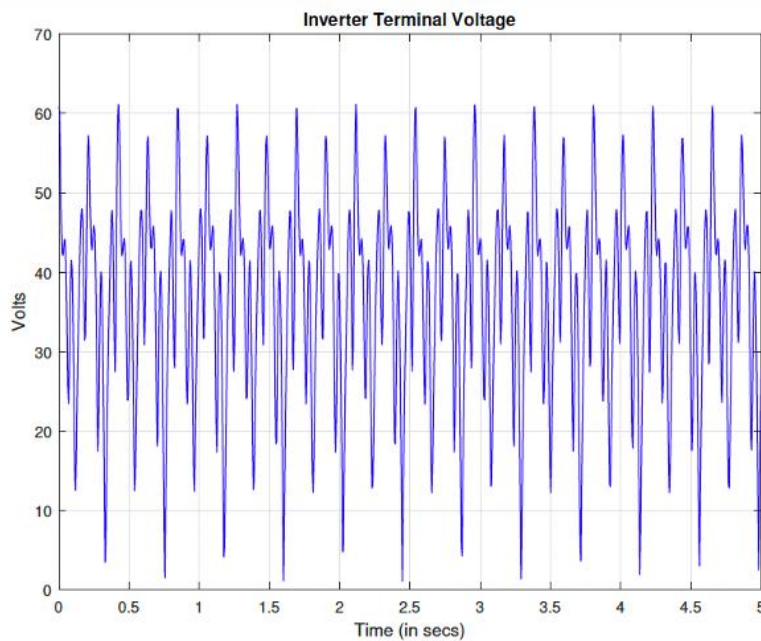
Case 3: ($K_p = 5$) $\Rightarrow$ Period-2 Orbit ($T=0.215s$)



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

GFL Inverter

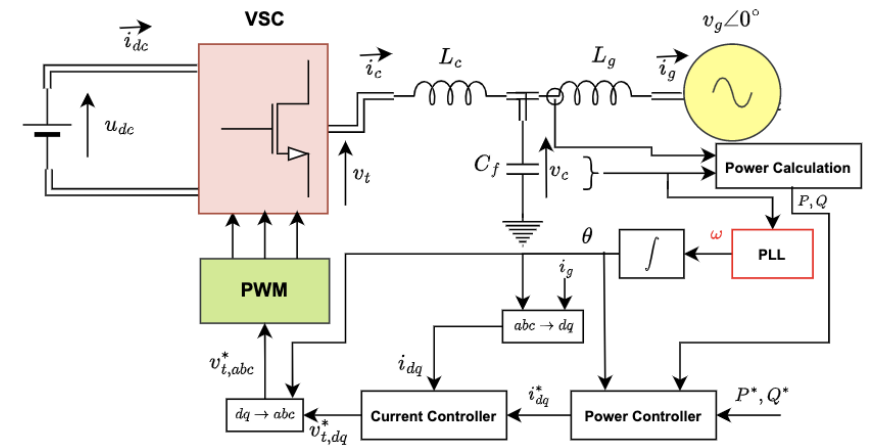
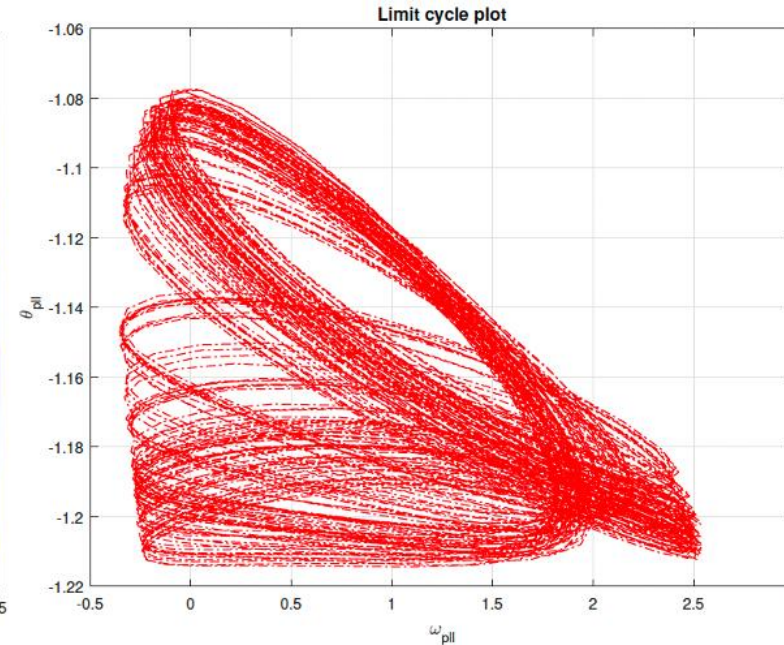
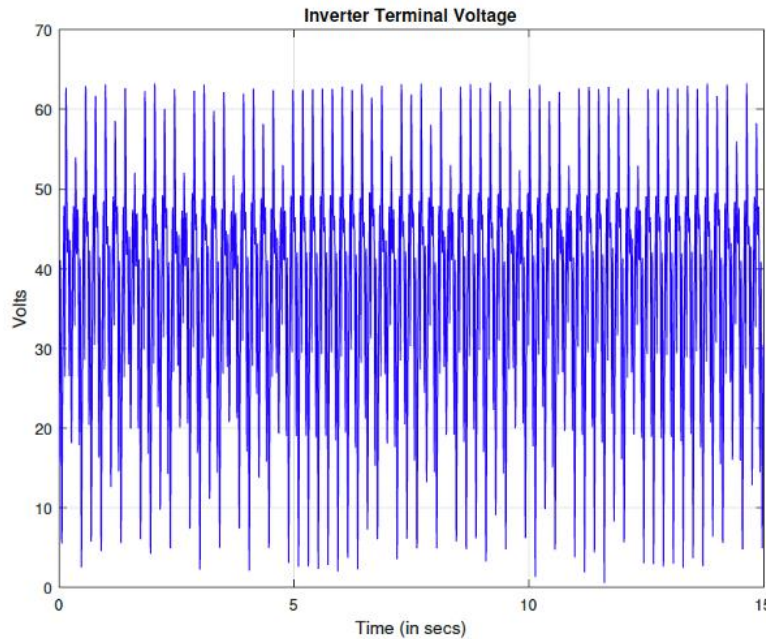
Case 4: ($K_p = 5.5$) $\Rightarrow$ Period-4 Orbit ($T=0.425s$)



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?*
2. *Is there a fundamental difference between GFL and GFL Inverters?*

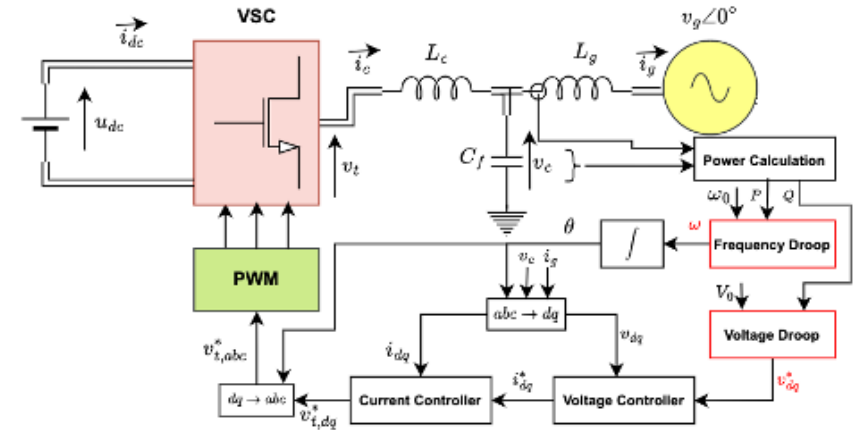
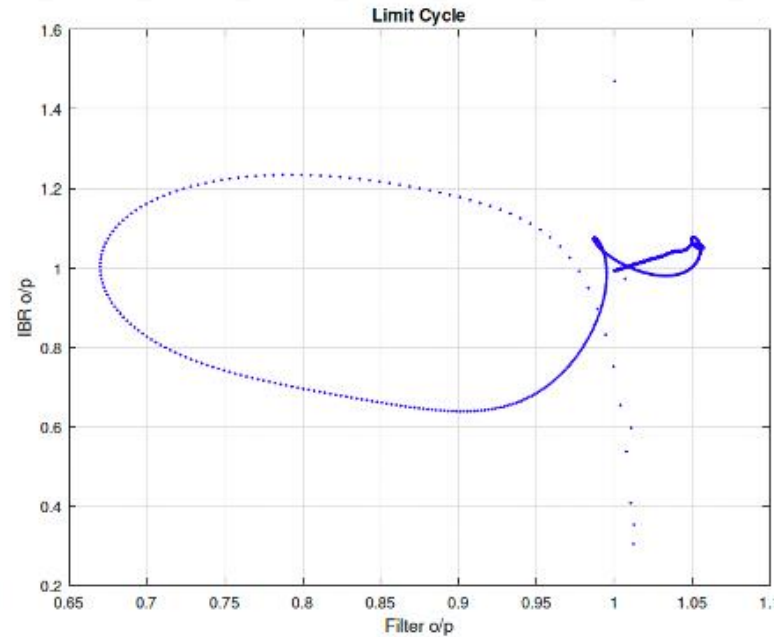
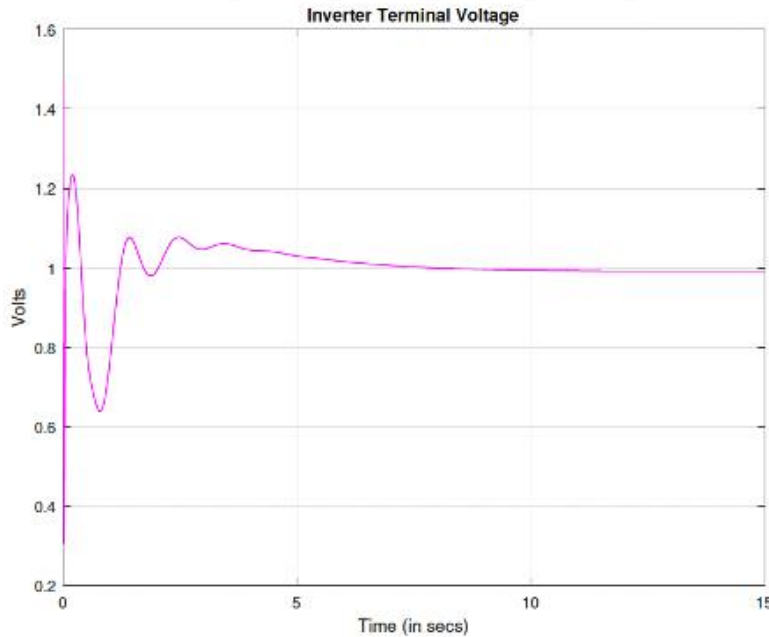


Observations:

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

GFM Inverter

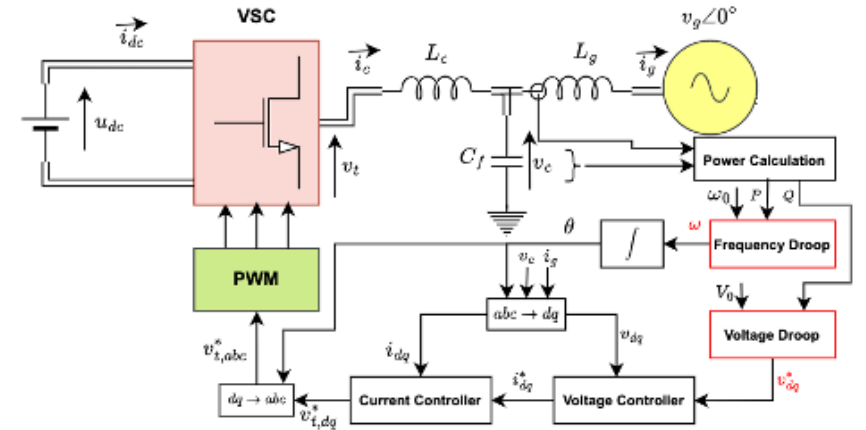
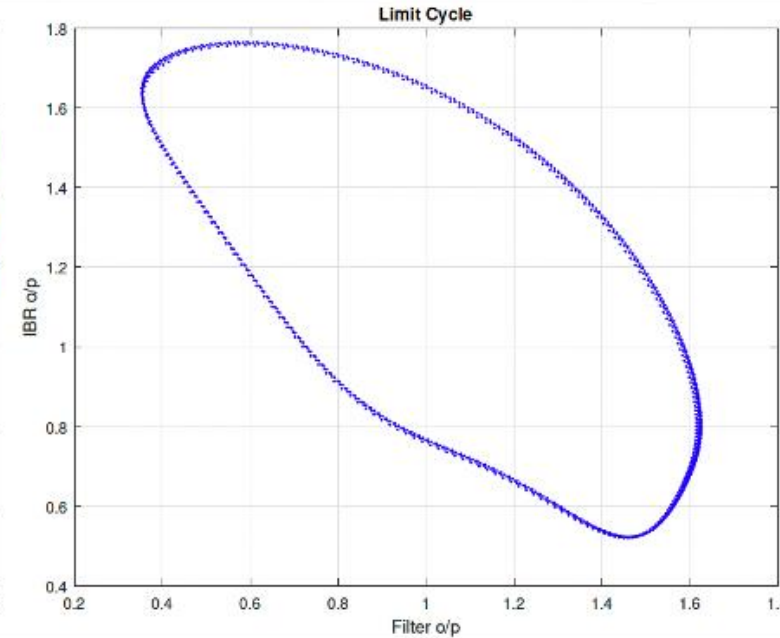
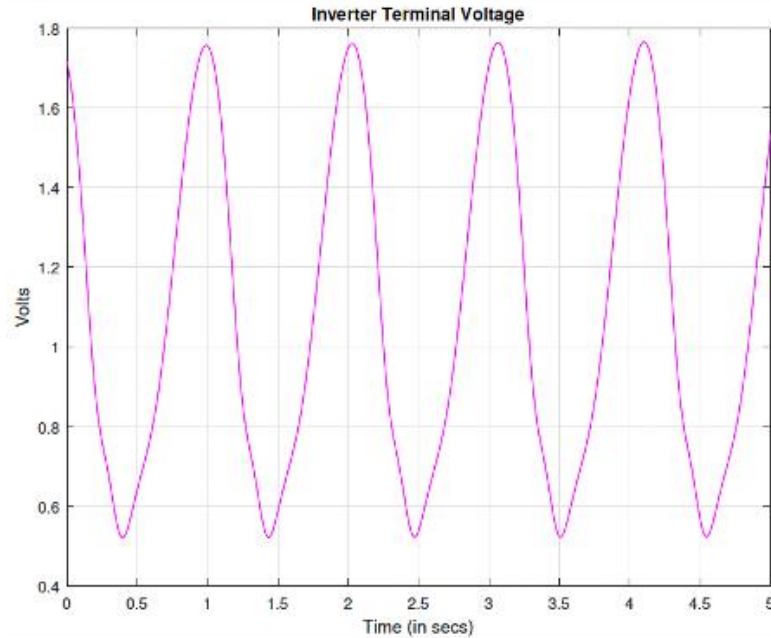
Case 1: Normal Operation ($K_p = 2.5$) $\Rightarrow$ Fixed Point



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

GFM Inverter

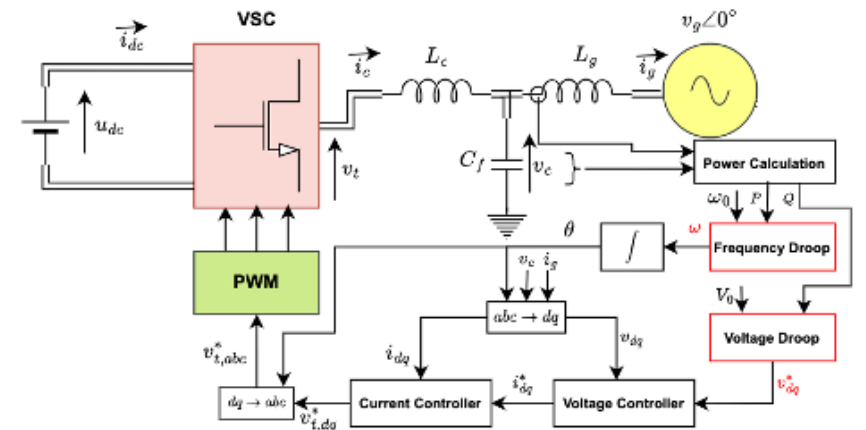
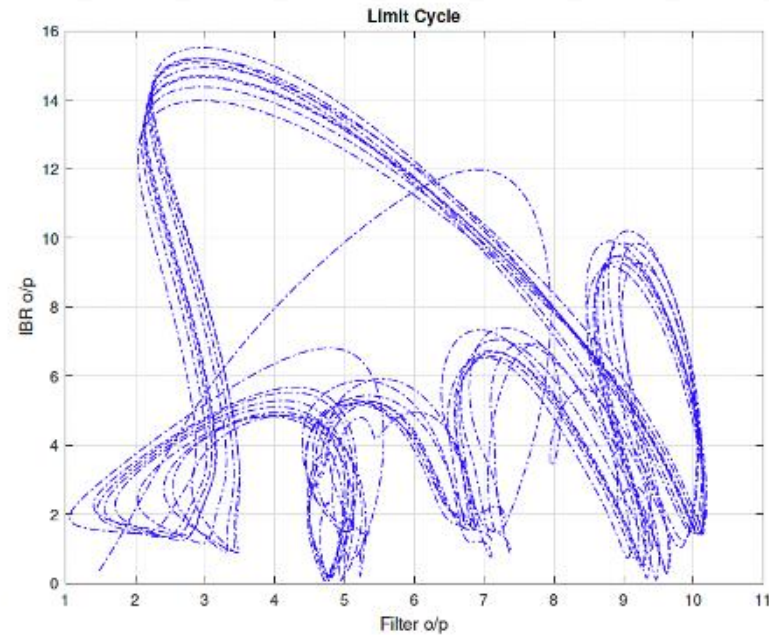
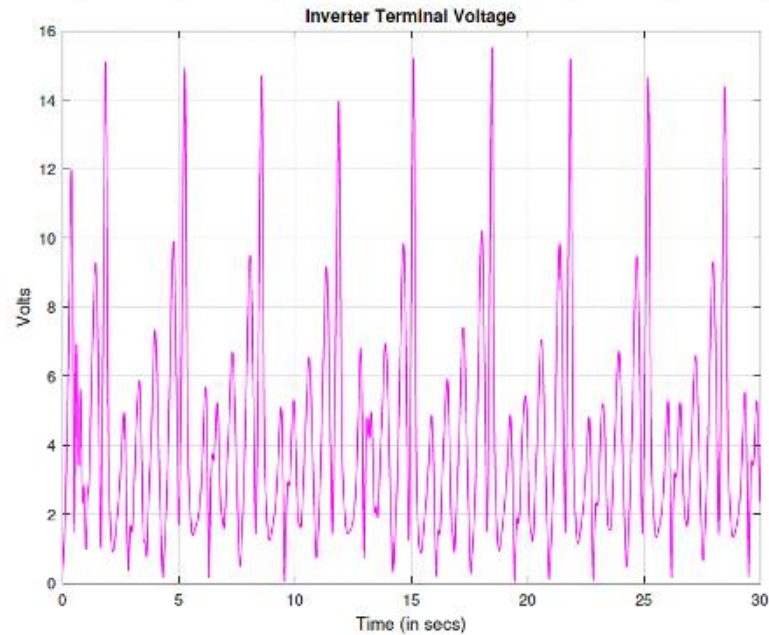
Case 2: ($K_p = 0.636998540037319$) $\Rightarrow$ Period-1 Orbit



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

GFM Inverter

Case 3: ($K_p = 0.636998540037318$) $\Rightarrow$ 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?*
2. *Is there a fundamental difference between GFL and GFL Inverters?*



Observations:

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

Observations: GFM inverters can produce even more complex behavior

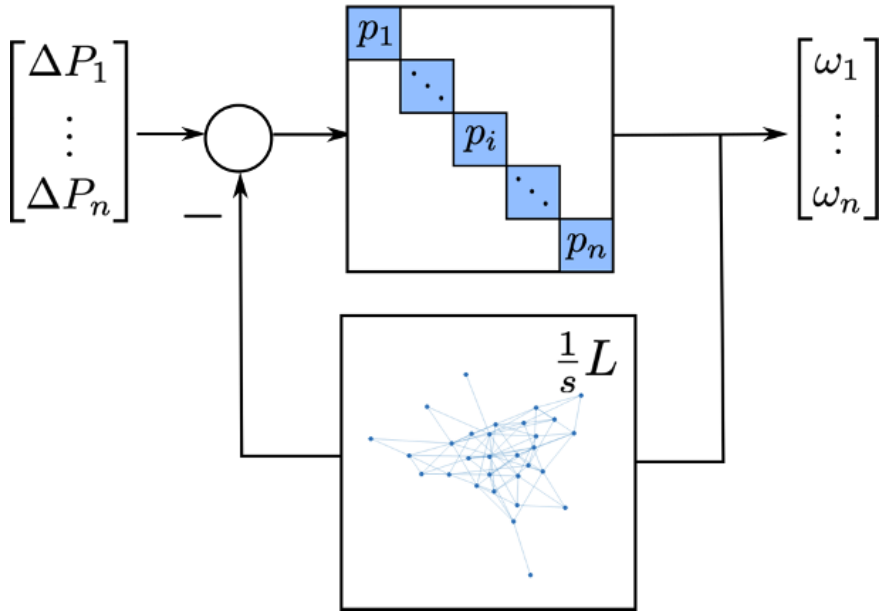
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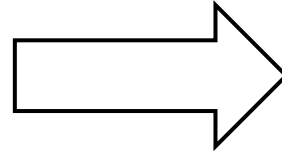
Decentralized Stability Analysis in Power Grids [TCNS 19]



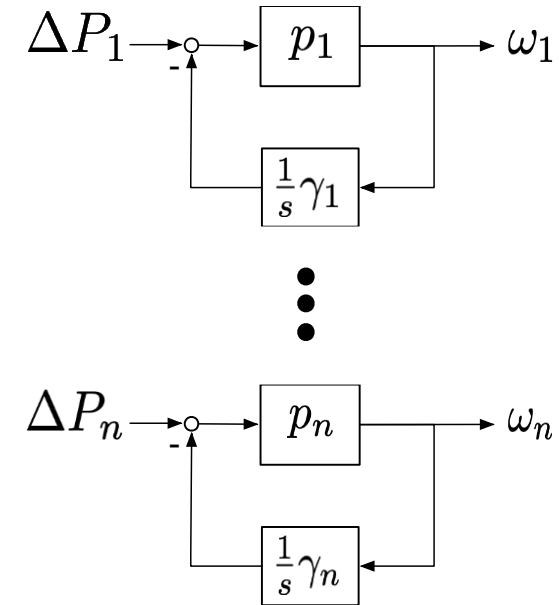
Richard Pates



1. When does this interconnection is stable?



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



Problem Setup:

- Linearized power flows, lossless

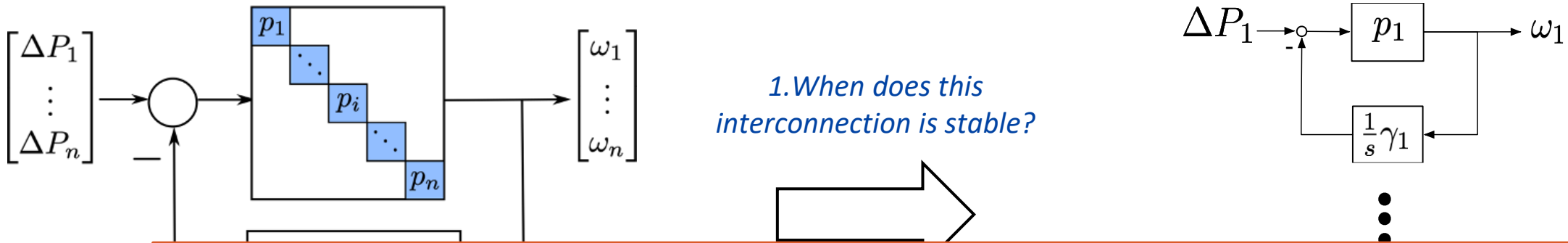
$$L_{ij} = b_{ij}v_i v_j \cos(\theta_i^* - \theta_j^*)$$
- Bus i : arbitrary siso transfer function:

$$\omega_i = p_i(s) \Delta P_i \quad (\text{SGs or IBRs})$$

Decentralized Stability Analysis in Power Grids [TCNS 19]



Richard Pates



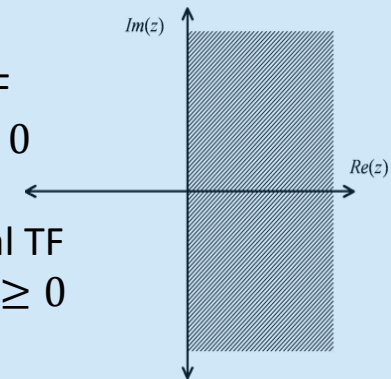
Can we use **network information** to relax passivity conditions?

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

Strictly Positive Real TF
 $\text{Re}[p_i(s - \varepsilon)] \geq 0$



Classical Result: Absolute Stability

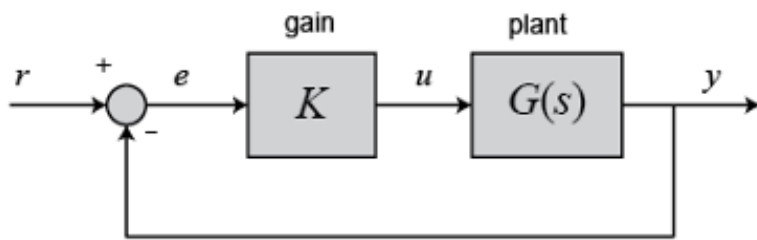
IEEE TRANSACTIONS ON AUTOMATIC CONTROL

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

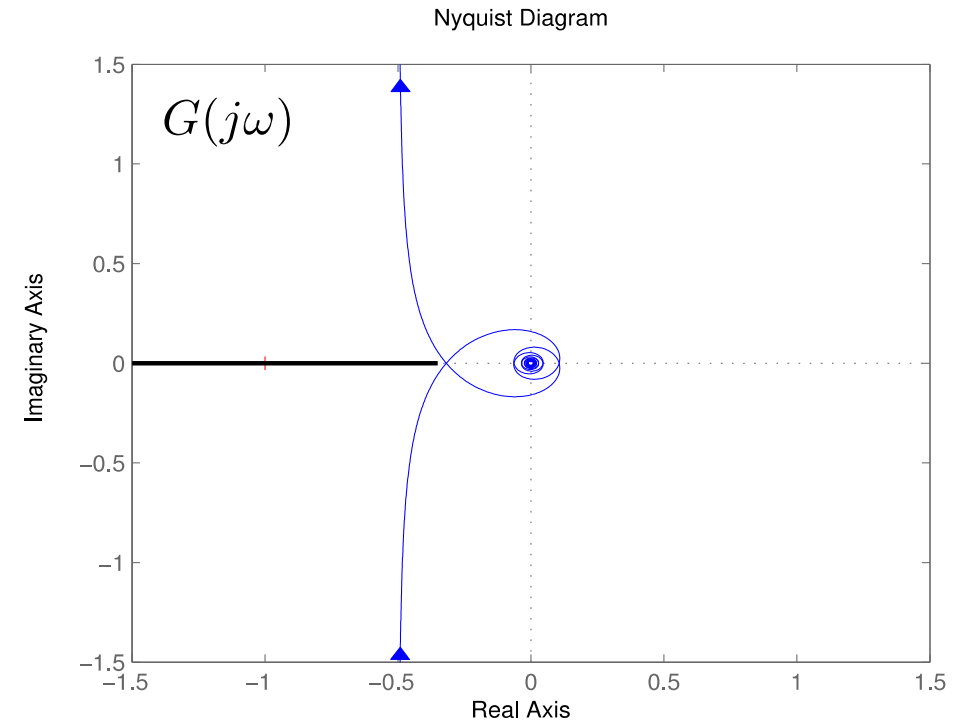


Stable for $0 \leq K \leq k^*$?

Assume: $G(s)$ is stable

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

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



Classical Result: Absolute Stability

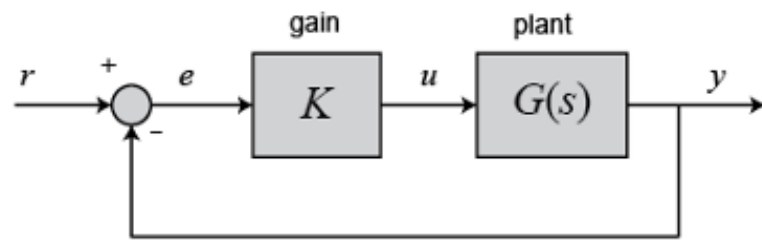
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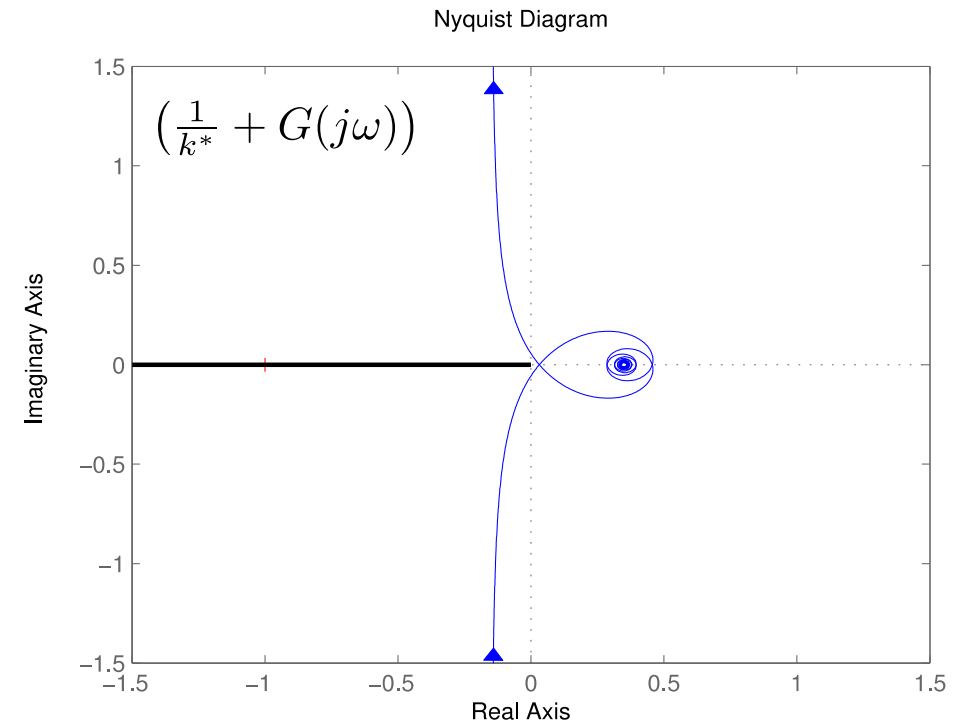


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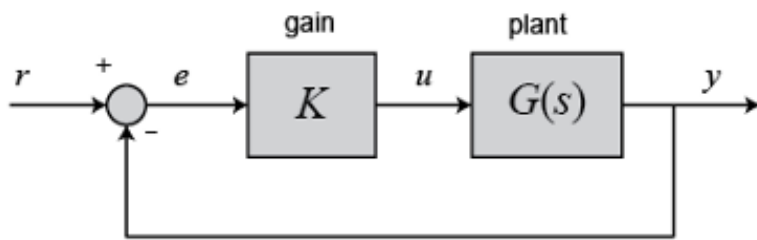
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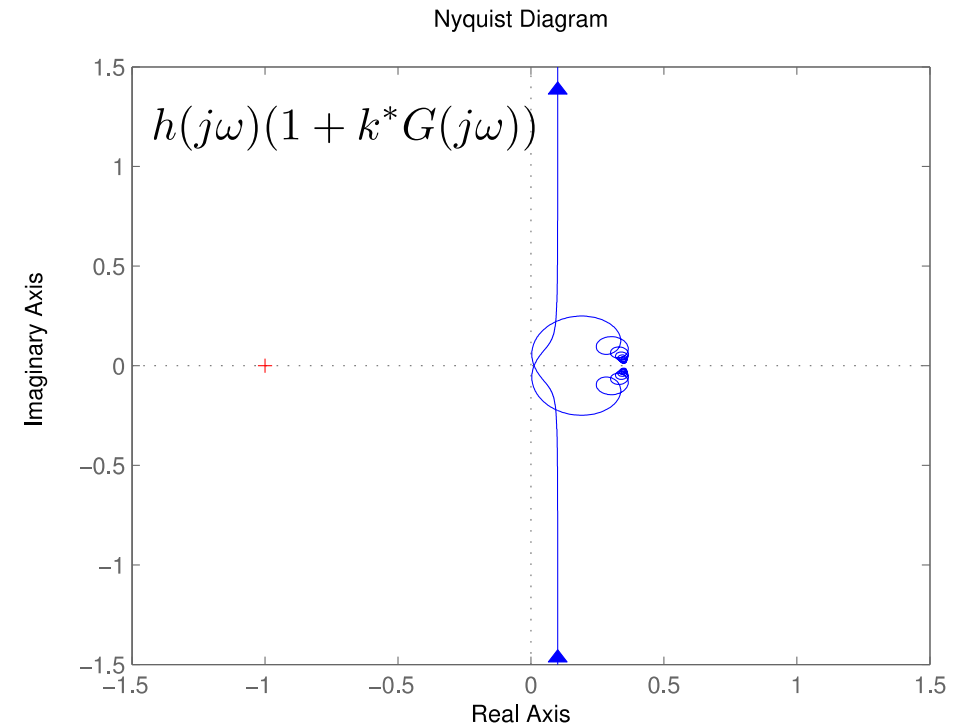


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then, **yes!**



Scale-free Stability Analysis

Key Idea: Exploit limited network information to relax passivity condition

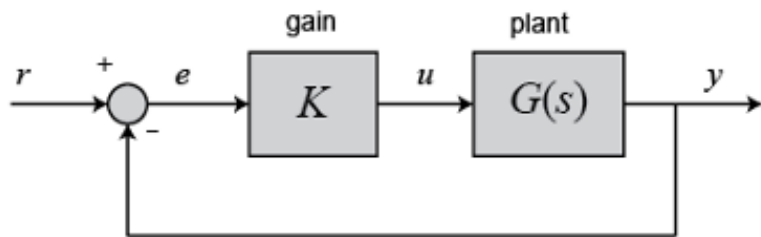
- Let γ_i be a local connectivity bound: $[L]_{ii} = \sum_{j \in N_i} b_{ij} v_i v_j \cos(\theta_i^* - \theta_j^*) \leq \frac{\gamma_i}{2}$

Brockett & Willems '65

Assume: $G(s)$ is stable

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

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

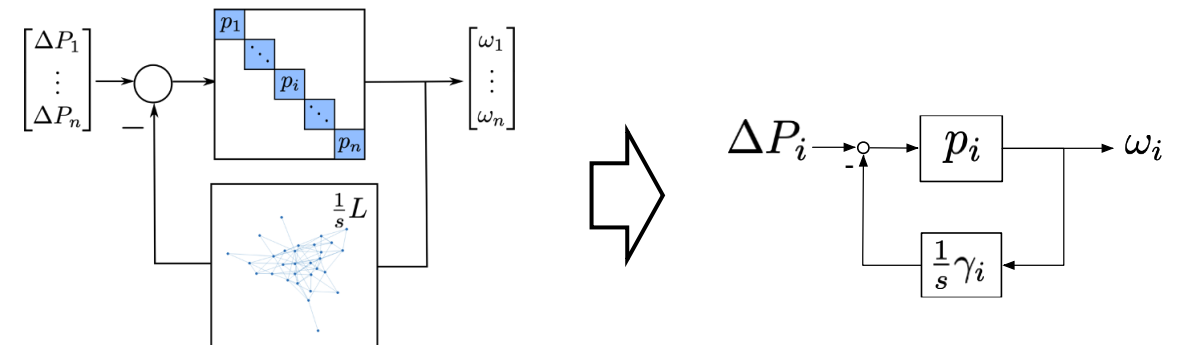


Pates & Mallada 2019

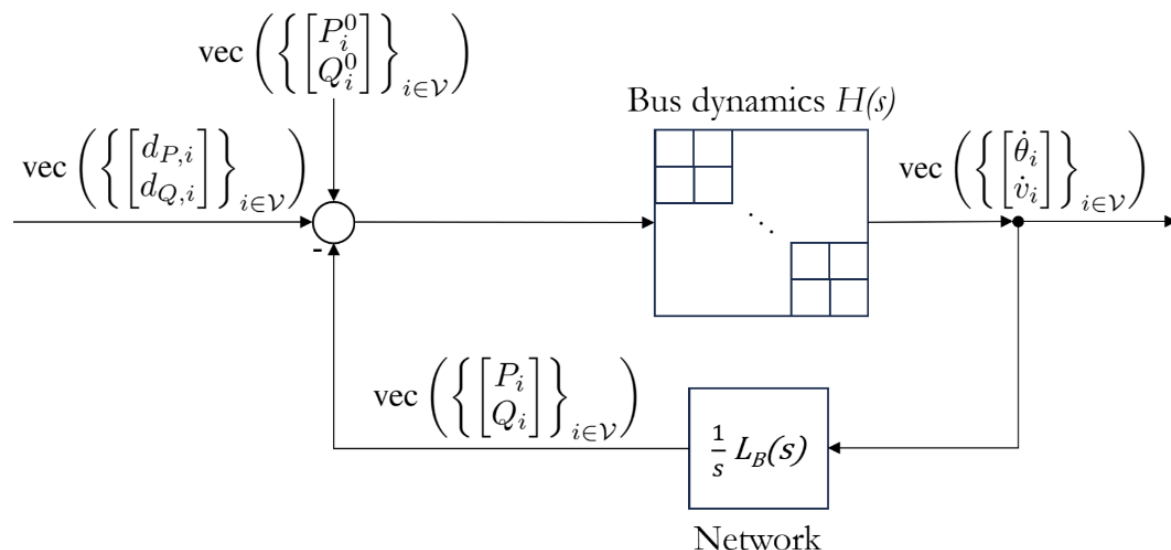
Assume: $p_i(s)$ is stable

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

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



Decentralized Stability Analysis for IBR Power Systems



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

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

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

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

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...

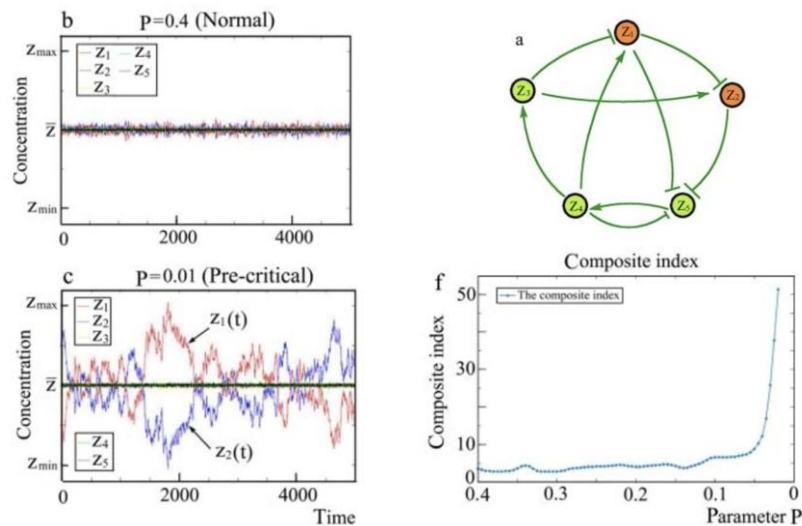
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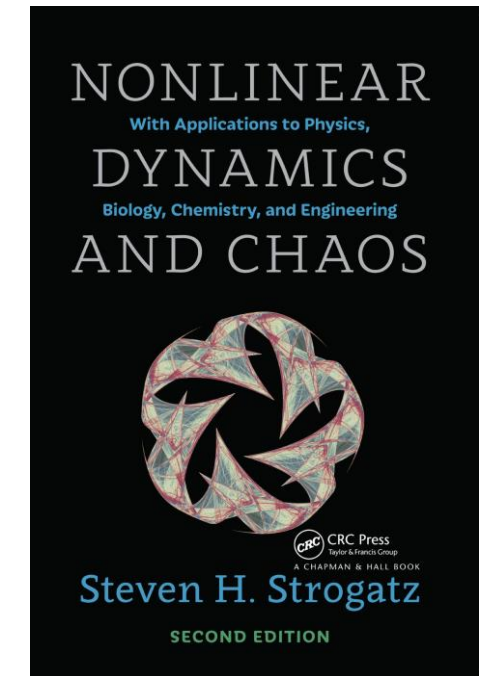
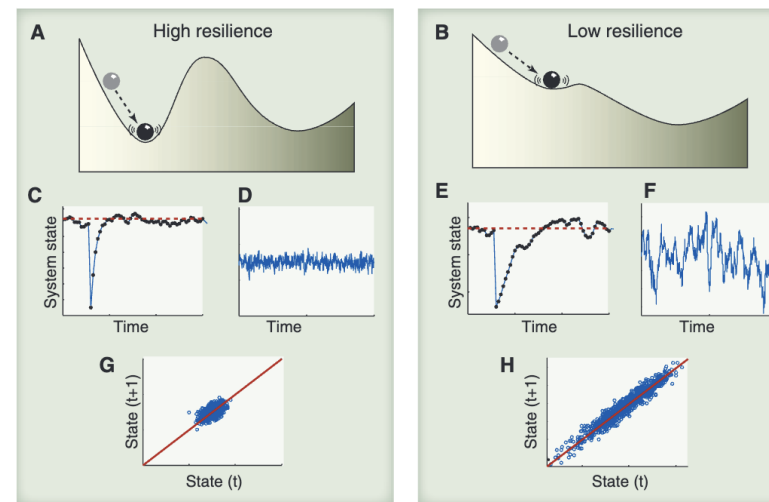
Early Detection via Critical Slowdown

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

Early disease detection^[1]



Loss of resilience^[2]



Research Questions:

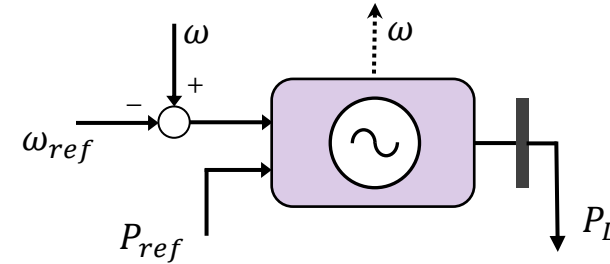
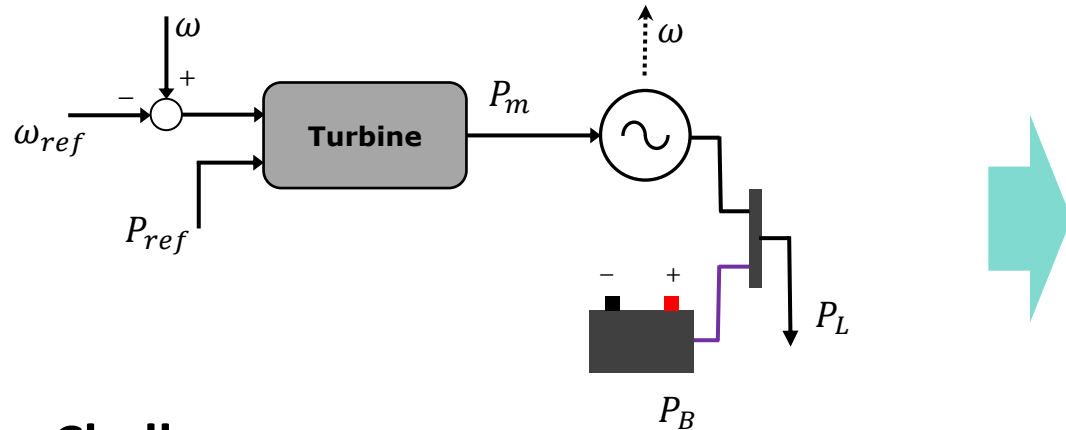
- Is critical slow-down a measurable feature in SSO transition to instability?
- Can we use critical slow down signatures to develop early alarm notifications?
 - What is the role of ML/AI in identifying these signatures?

[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**



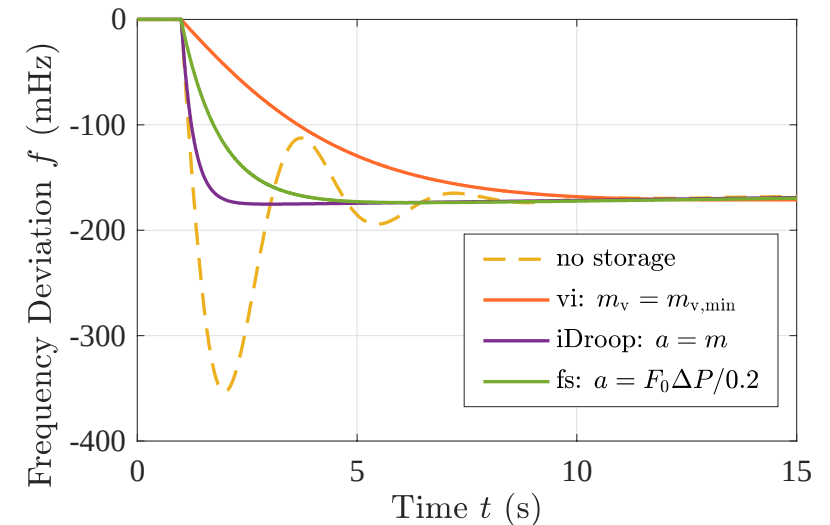
Challenge:

- 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?

Remove Nadir or Tuning RoCoF

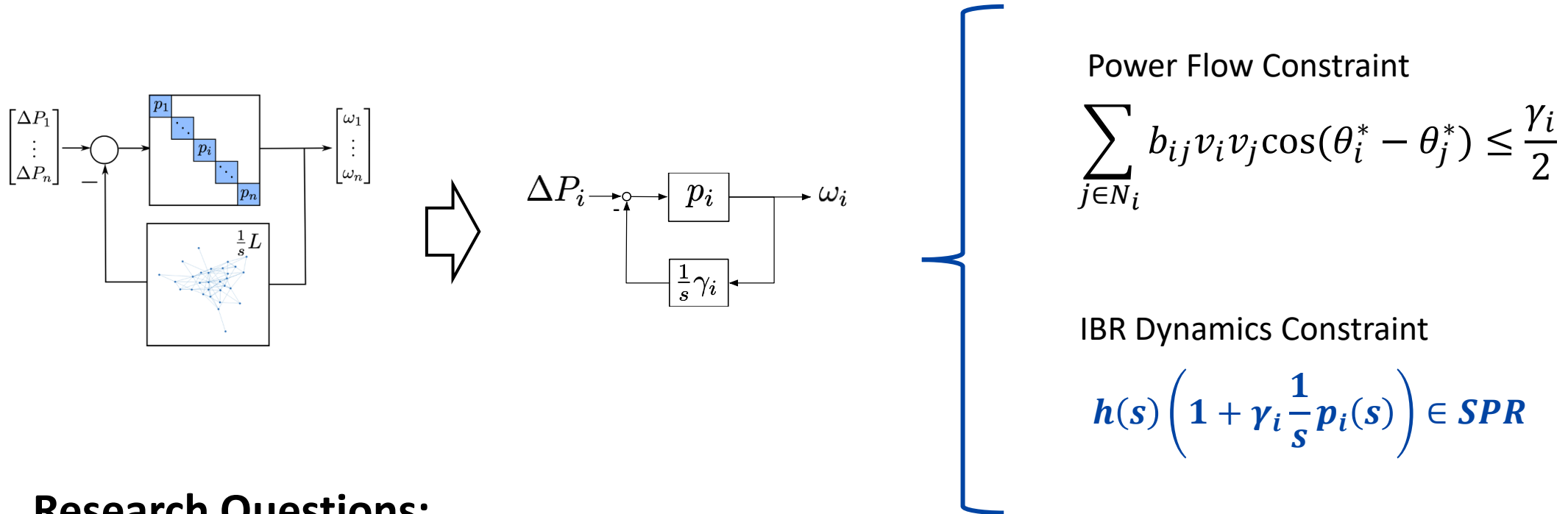


[LCSS 20] Jiang, Bernstein, Vorobev, M. Grid-forming frequency shaping control for low-inertia power systems **IEEE Control Systems Letters** 2020

[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 tuning*



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

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