



Submission no. 44

# The influence of load characteristics on early warning signs in power systems

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## Outline

- CIS and critical transitions: System stress. State of knowledge.
- Early warning signs: Open questions.
- Power system: Modelling approach.

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- Early warning signs in power systems: Results.
- New findings: Some thoughts and conclusions.

















### CIS and critical transitions: System stress.

- Increased stress pushes CIS towards critical conditions
- Critical loading conditions can cause system collapse
- Failures/contingencies can cause premature collapse













[Figures: Noun Project]



## CIS and critical transitions: General state of knowledge.



- Complex dynamical systems: generic characteristics prior to critical transitions
- Transitions are related to bifurcations
- Some systems emit early warnings signs that the critical transition is imminent















### CIS and critical transitions: The theory.



#### Bifurcation analysis













#### (FRS) FUTURE RESILIENT SYSTEMS 系统

### CIS and critical transitions: The theory.

- System behaviors:
  - Critical slowing down
  - Flickering

#### Indicators:

- (Increase in) Autocorrelation
- (Increase in) Variance
- Skewness
- Kurtosis
- Spatial autocorrelation



#### 0.3 0.95 Freq. (Hz) a window size, T 0.85 -6 Time before critical transition (minutes)

PSD windo

a(V.

 $d(|V_3|)$ 

0.9

3

[Cotilla-Sanchez, et al., IEEE Trans. Smart Grid, 2012]

 $d(P_5)$ 



[Ghanavati, et al., IEEE Trans. Power Sys., 2016]



. . .











d(IV<sub>3</sub>I)

x 10

0.8

ND

0.2

0



#### [Scheffer, et al., Nature, 2009]



#### Early warning signs: Open questions.



Effects of stressor characteristics on the behavior of networked systems and their early warning signs?













#### Power system: Modelling approach.



- 10-machine, 39-bus New England test case
- Time-domain simulation in Power System Analysis Toolbox (PSAT)



#### Power system: Modelling approach.



- Hopf bifurcation: Detectable from eigenvalue analysis
- A complex eigenvalue pair crosses the imaginary axis from the left to the right half plane



### Power system: Modelling approach.



- Determine autocorrelation coefficients
- Aggregate coefficients into median and measure of the spread
- Assess responses under different load scenarios given by load homogeneity and connectivity

$$\begin{aligned} p_{L_{n,i}} &= p_{L_{n,0}} \lambda_i + \eta_{p_{n,i}} = p_{L_{n,0}} \lambda_i + \sigma^2 \xi_{n,i} \\ q_{L_{n,i}} &= q_{L_{n,0}} \lambda_i + \eta_{q_{n,i}} = q_{L_{n,0}} \lambda_i + \sigma^2 \xi_{n,i} \end{aligned}$$

$$\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{y}, \boldsymbol{\eta}, \dot{\boldsymbol{\eta}})$$
$$0 = g(\mathbf{x}, \mathbf{y}, \boldsymbol{\eta})$$
$$\dot{\boldsymbol{\eta}} = \alpha(\mathbf{x}, \mathbf{y}, \boldsymbol{\eta}) + b(\mathbf{x}, \mathbf{y}, \boldsymbol{\eta})\boldsymbol{\xi}$$















### Power system: Load homogeneity and connectivity.



 Homogeneity: parameterizes "spatial" load distribution  Connectivity: modulates the coupling between the stochastic load perturbations across network buses

















### Early warning signs in power systems: Results.



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- Shifts the bifurcation point
- Does not affect increase in autocorrelation



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### Early warning signs in power systems: Results.



- Shifts the bifurcation point
- Does not affect increase in autocorrelation

#### BUT:

- A given absolute value is not indicative of the proximity of the bifurcation
- Not a universal indicator applicable under unknown load conditions

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### Early warning signs in power systems: Results.



#### Changes in perturbation type:



### Early warning signs in power systems: Results.

- The effect of load connectivity
  - Does not influence the degree to which individual loads may be correlated with past samples over time
  - > Autocorrelation coefficients not sensitive to load connectivity.













### Conclusions: Final thoughts.



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- Defined aggregate metrics to determine system-wide indicators of critical transitions
- Confirm previous findings of critical slowing down in power systems
- Load connectivity does not influence autocorrelation indicator
- Indicators may falsely alert about a critical condition in case of limited knowledge and misinformation about system stressors – Predictability?

## Thank you!

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#### References



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Noun Project artists: Chameleon Design, Juan Pablo Bravo, Becris, Artem Kovyazin, Yorlmar Campos, iconsphere, Vectors Market, hash









