Control of synchronization in two-layer power grids

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- Ph.D. in Nonlinear Dynamics and Complex Systems (2013) on “Collective dynamics in complex neural networks”- University of Florence (Italy)
- M.Sc. in Theoretical Physics (2009) on “Dynamics of pulse-coupled diluted neural networks” - University of Florence (Italy)
- Publications: $\sim$ 29 journal articles in international peer-reviewed journal - citations 720 (h-index 13)
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Main collaborations: A. Torcini (Cergy Paris Université); E. Schöll (TU Berlin); A. Politi (University of Aberdeen); S. Boccaletti (ISC-CNR); V. Jirsa (Institut de Neurosciences des Systèmes)

Motivation

Introduction of renewable generators

- Transformation of the present power system into a large-scale distributed generation system incorporating thousands of generators
- The increasing complexity and geographical spread, together with the high penetration of renewable, stochastically fluctuating energy generators make the network very vulnerable
  - Security mechanisms [Morante et al, IEEE Trans. Ind. Inform. 2, 165 (2006)]
  - Dynamic stability due to the employment of microgrids [Balaguer et al, IEEE Trans. Ind. Electron. 58, 147 (2011)]

Control requirements:

- Widely distributed intelligent control
- Two-way communication infrastructure (sustaining power flow between intelligent components and information technologies) - Smart Grid [Santacana at al IEEE Power Energy 8, 41 (2010)]
- Wide-area measurement systems [Younis, Iravani, in 2013 IEEE Electrical Power & Energy Conference (IEEE, 2013), 1-6]

Motivation

Goal:

- Integration with the existing network of renewable energy generators
- Investigate the controllability of power networks subject to different realistic perturbation scenarios (disconnecting generators, increasing demand of consumers, or generators with stochastic power output)
- Provide more effective and widely distributed intelligent control
- Propose a quite realistic model which includes a dynamic description of the communication infrastructure

Communication infrastructure:

- Trivial networks, without disconnected nodes [Li and Han, in Proc. 2011 IEEE Intl. Conf. Smart Grid Communications (SmartGridComm) 463-468 (2011); Wei et al, in Proc. 2012 IEEE Power and Energy Society General Meeting, 1-8 (2012)]
- Attention focused on sampling problems or communication constrains (e.g. time delays, packet losses, and sampling and data rate) [Giraldo et al, in 52nd IEEE Conf. Decision and Control, 4638 (2013); Baillieul and Antsaklis, Proc. IEEE 95, 9 (2007)]

The model: Two layer network

Communication infrastructure in a full dynamic description +
Power grid layer : Kuramoto model with inertia

$$m\ddot{\theta}_i(t) = -\dot{\theta}_i(t) + \Omega_i + P_i^c(t) + K\sum^{N} A_{ij}\sin(\theta_j - \theta_i)$$

- i: Node index (=1,...,N)
- θ_i: Phase
- $\dot{\theta}$: Frequency
- m: Mass, inertia constant, m=10
- Ω_i: Inherent frequency $\widehat{=}$ power generation/consumption
- P_i^c: control signal supplied by the communication layer
- A_{ij}: Coupling matrix
- K: Coupling strength

Measures: Real Space

- Average grid frequency:

$$\bar{\omega}(t) := \frac{1}{N}\sum_{i=1}^{N}\omega_i(t) := \frac{1}{N}\sum_{i=1}^{N}\dot{\theta}_i(t)$$

- Standard deviation of frequencies:

$$\Delta\omega(t) := \frac{1}{N}\sqrt{\sum_{i=1}^{N}(\omega_i(t)-\bar{\omega}(t))^2}$$

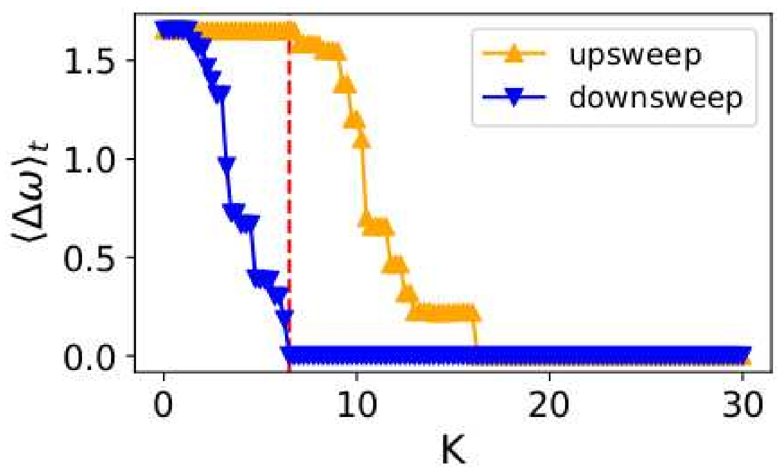
  and it's time average $\langle\Delta\omega\rangle(t)$

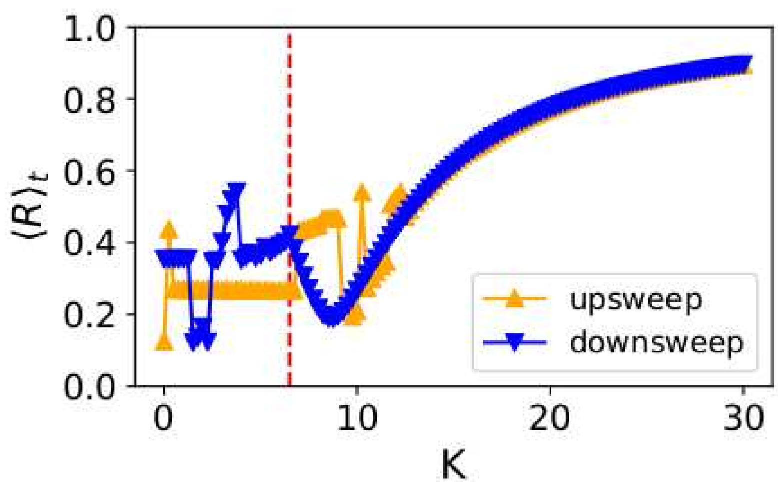
- Time averaged frequency of individual nodes: $<\omega_i>_t$
- Kuramoto order parameter:

$$r(t)e^{i\phi(t)} = \frac{1}{N}\sum_j e^{i\theta_j}$$

Dynamics in absence of control

- Adiabatic variation of the coupling strength K: For each K, the system is initialized with the final conditions found for the previous coupling value
  - Upsweep protocol: starting from $K = 0$, the coupling is increased in steps of ΔK until a maximum coupling strength is reached
  - Downsweep protocol: starting from the maximum coupling strength, K is reduced in steps of ΔK until the asynchronous state is reached
- Operation state: regime of bistability in which both the fully frequency-synchronized state and a partially synchronized state are accessible
- A perturbation displaces the system out of synchrony into an intermediate state





Topology: Italian transmission grid

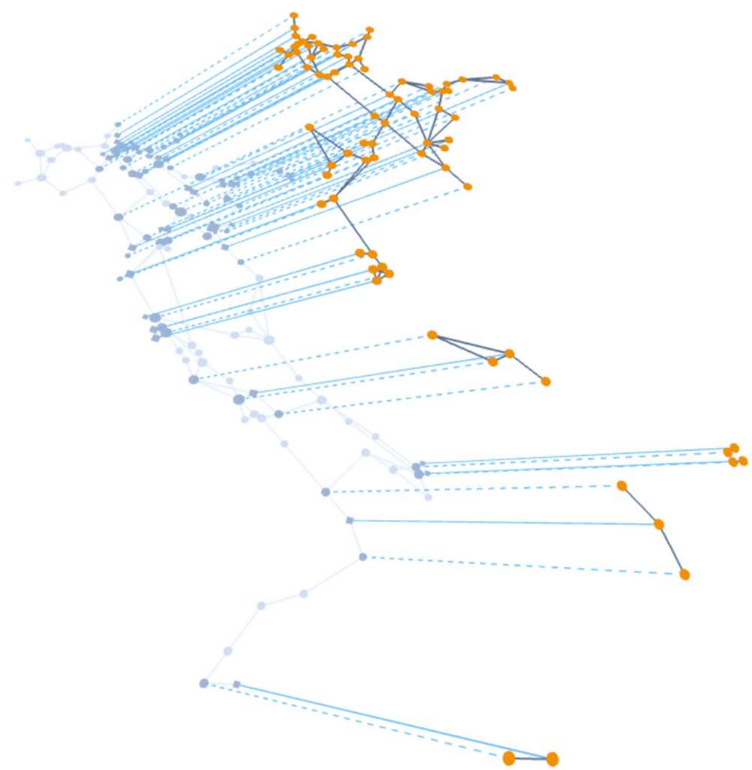
GENI—Global Energy Network Institute, Map of Italian electricity grid: https://www.geni.org/

- 127 nodes
  34 generators
  93 consumers
- 342 transmission lines
  (220 kV & 380 kV)
- Average connectivity 2.865
- Natural frequencies:
  Ω_{gen}= 93/34
  $\Omega_{load} = -1$

The model: Two layer network

Communication layer:

- Phasor measurement units provide information: local controllers integrated with the generators use the information to calculate a control signal $P_i^c \in \mathrm{Re}$
- The loads are not controlled.
- The control signal can be interpreted as power injection for $P_i^c > 0$ or power absorption for $P_i^c < 0$
- The control is realized using storage devices (batteries) that absorb or inject power to the generator buses [H. Qian et al, IEEE Trans. Power Electron. 26, 886 (2010).]



$$\dot{P}_i^c = G_i f_i(c_{i,j}, \{\dot{\theta}_j(t)\})$$

$c_{i,j}$ adjacency matrix of the communication layer

The model

Communication layer:

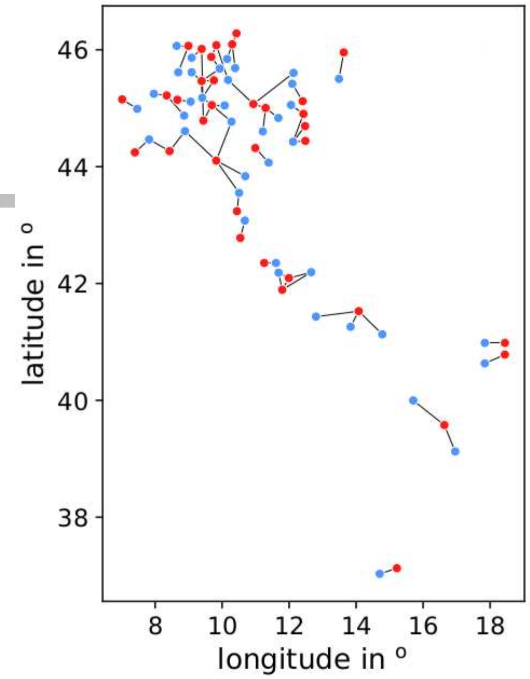
$$\dot{P}_i^c = G_i f_i(c_{i,j}, \{\dot{\theta}_j(t)\})$$

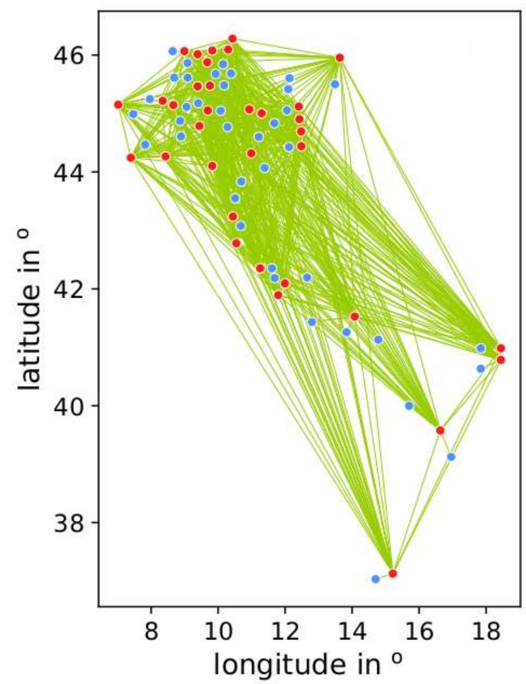
Control function $f_i(c_{i,j}, \{\dot{\theta}_j(t)\})$:

- Frequency droop control
  $f_i^{diff}(c_{i,j}, \{\dot{\theta}_j(t)\}) = \sum_j^N c_{ij}[\dot{\theta}_j - \dot{\theta}_i]$
  [Giraldo et al, in 52nd IEEE Conf. Decision and Control (2013), 4638]
- Proportional control
  $f_i^{dir}(c_{i,j}, \{\dot{\theta}_j(t)\}) = \frac{-1}{N_i} \sum_j^N c_{ij}\dot{\theta}_j$
- Combined control
  $f_i^{comb}(c_{i,j}, \{\dot{\theta}_j(t)\}) = \sum_j^N c_{ij} \left\{a[\dot{\theta}_j - \dot{\theta}_i] - b\dot{\theta}_j\right\}$

Control strength G_i: Effective only for generators

- $c_{ij}^{local}, c_{ij}^{global}$





Applied perturbations

- Disconnecting generators $\begin{cases} a_{ij}(t) &= a_{ji}(t) = 0 \\ c_{ij}(t) &= c_{ji}(t) = 0 \end{cases} \quad t \in T_P$

  T_p duration of the perturbation

- Gaussian white noise

$$\Omega_i(t) = \Omega_{gen} + \sqrt{2D}\xi(t)$$

  ξ = δ-correlated Gaussian random variable, with noise intensity D

- Intermittent noise

$$\Omega_i(t) = \Omega_{gen} + \mu x(t)$$

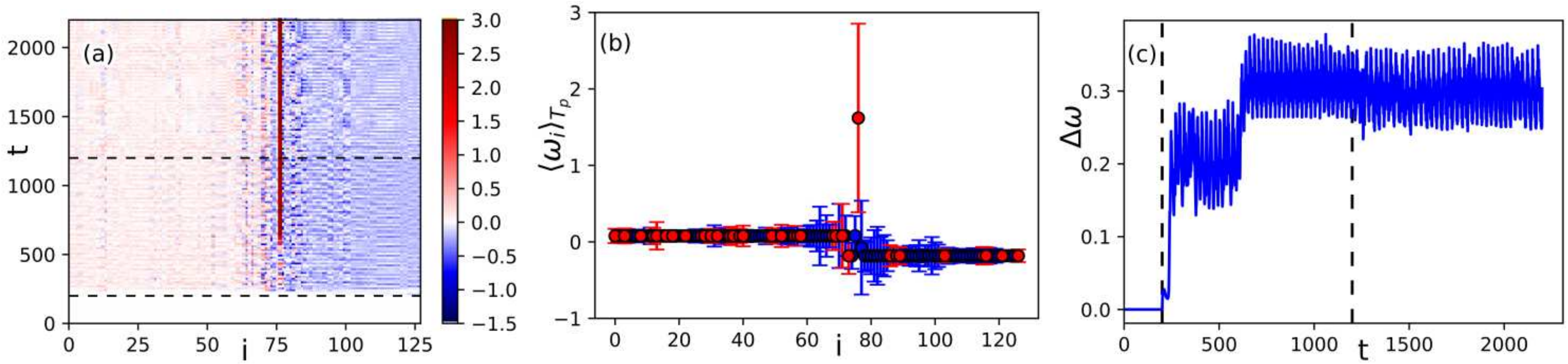
  μ= penetration parameter, $x(t)$= intermittent noise series
  [Schmietendorf, Peinke, Kamps, Eur. Phys. J. B 90, 222 (2017)]

- Increasing demand of loads ($\Omega_{pert} = -3$)

$$\Omega_i(t) = \begin{cases} \Omega_{load}\,, & t < t_{start} \\ \Omega_{load} + (\Omega_{pert} - \Omega_{load})\,\frac{t - t_{start}}{t_{end} - t_{start}}\,, & t_{start} \leq t \leq t_{end} \\ \Omega_{pert}\,, & t < t_{end} \end{cases},$$

Typical perturbation patterns

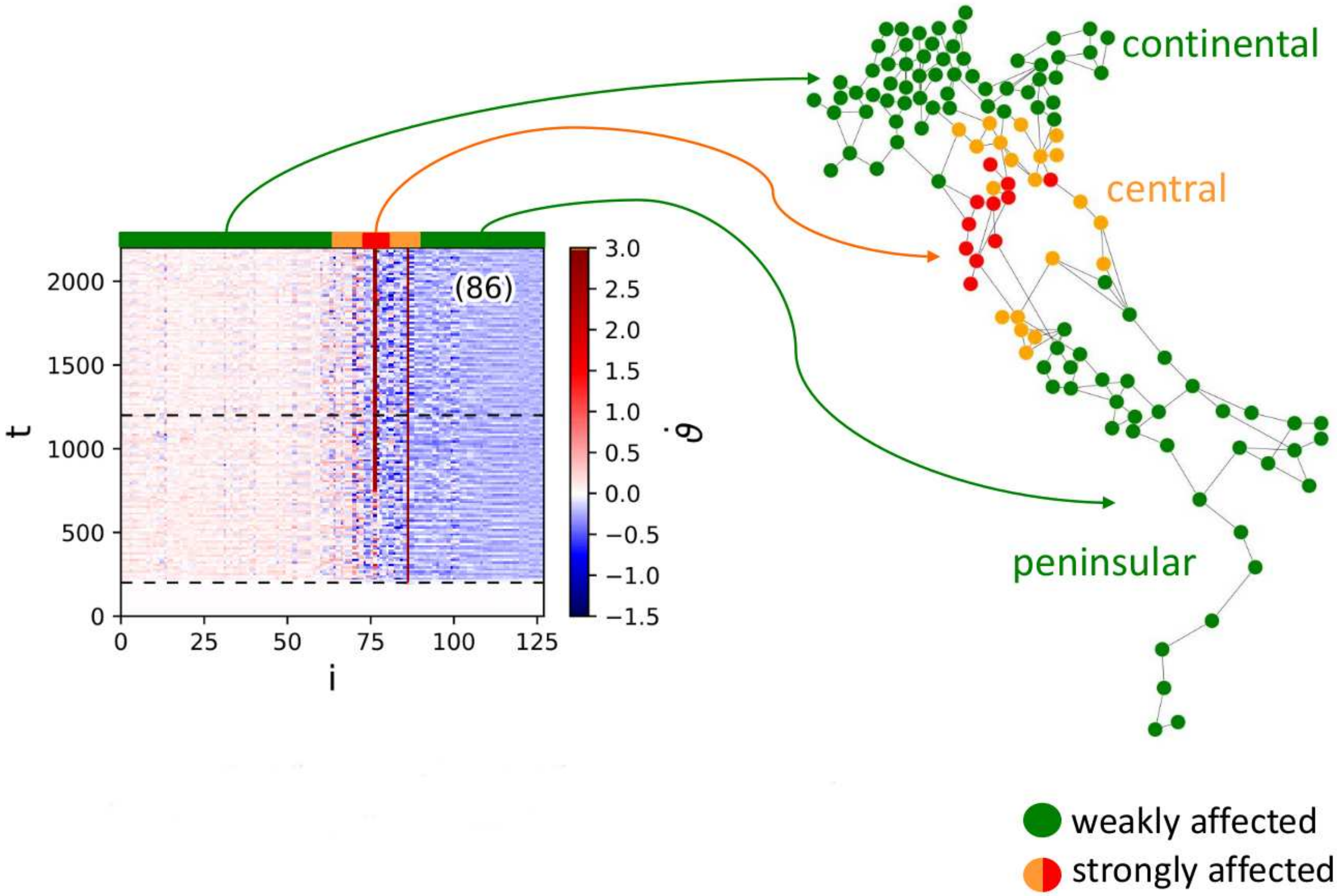
Single node perturbation: increased load demand (i=120)



- Desynchronization between the northern ($i \leq 70$) and southern parts
- Due to the unbalanced distribution of generators (more dense in the north), the network splits in two parts with different average frequency
- Fluctuations become stronger near the boundary of the two parts
- Single-node perturbation can cause the destabilization of a distant node (i=76)
- Macroscopic reaction: $\Delta\omega$ increases drastically and oscillates in time

Typical perturbation patterns

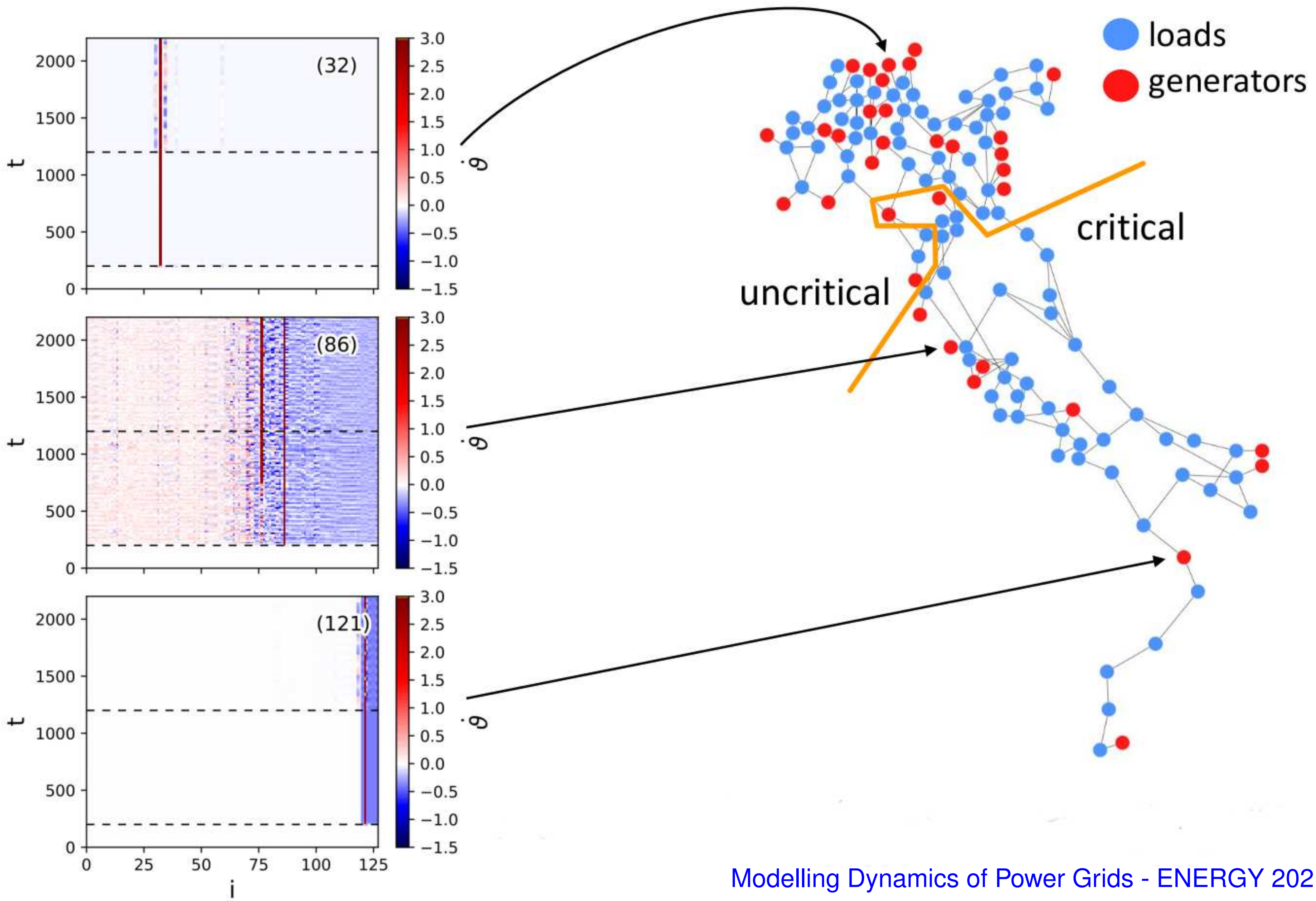
Single node perturbation: disconnection of a generator (i=86)



- Dependence on the topology: Dead ends (trees) are problematic
- Nodes in the south are particularly vulnerable to selected disconnection, nodes in the north can be easily replaced

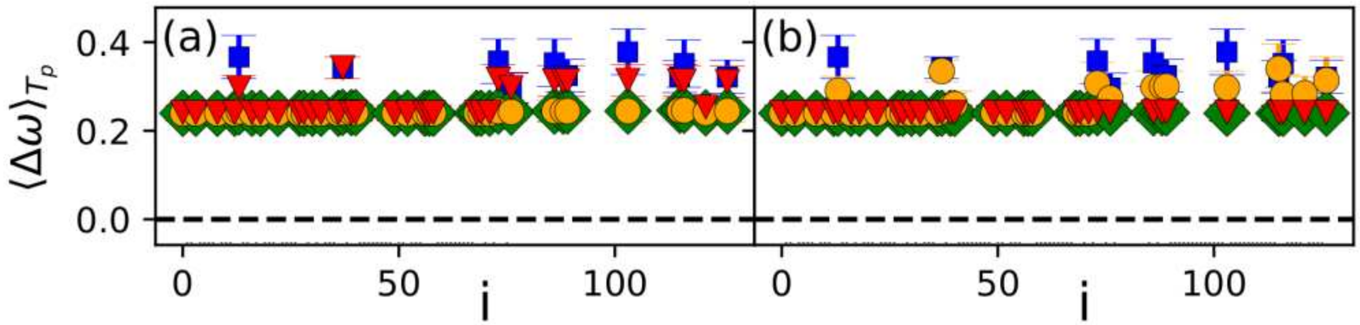
Single node perturbation

Disconnecting nodes (generators)



Single node perturbation

Disconnecting nodes (generators)



■ no control
▲ $f_i^{diff}(c_{i,j}, \{\dot\theta_j(t)\})$ NO
o $f_i^{dir}(c_{i,j}, \{\dot\theta_j(t)\})$ OK
♦ $f_i^{comb}(c_{i,j}, \{\dot\theta_j(t)\})$ OK

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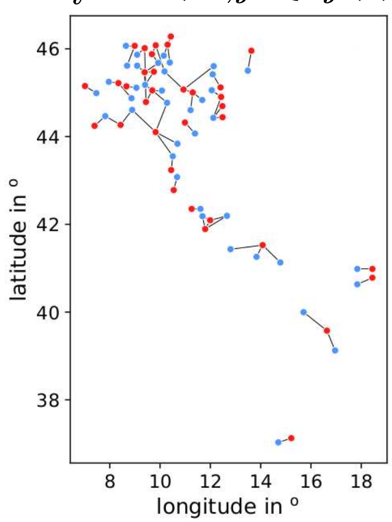
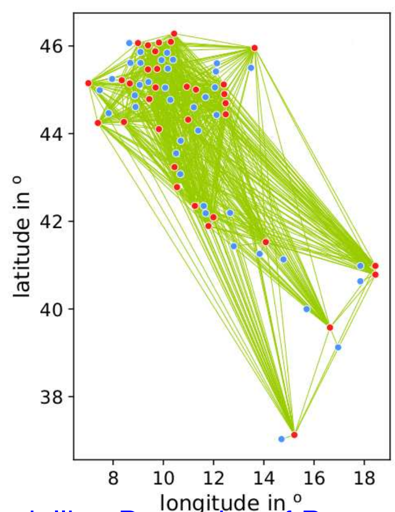
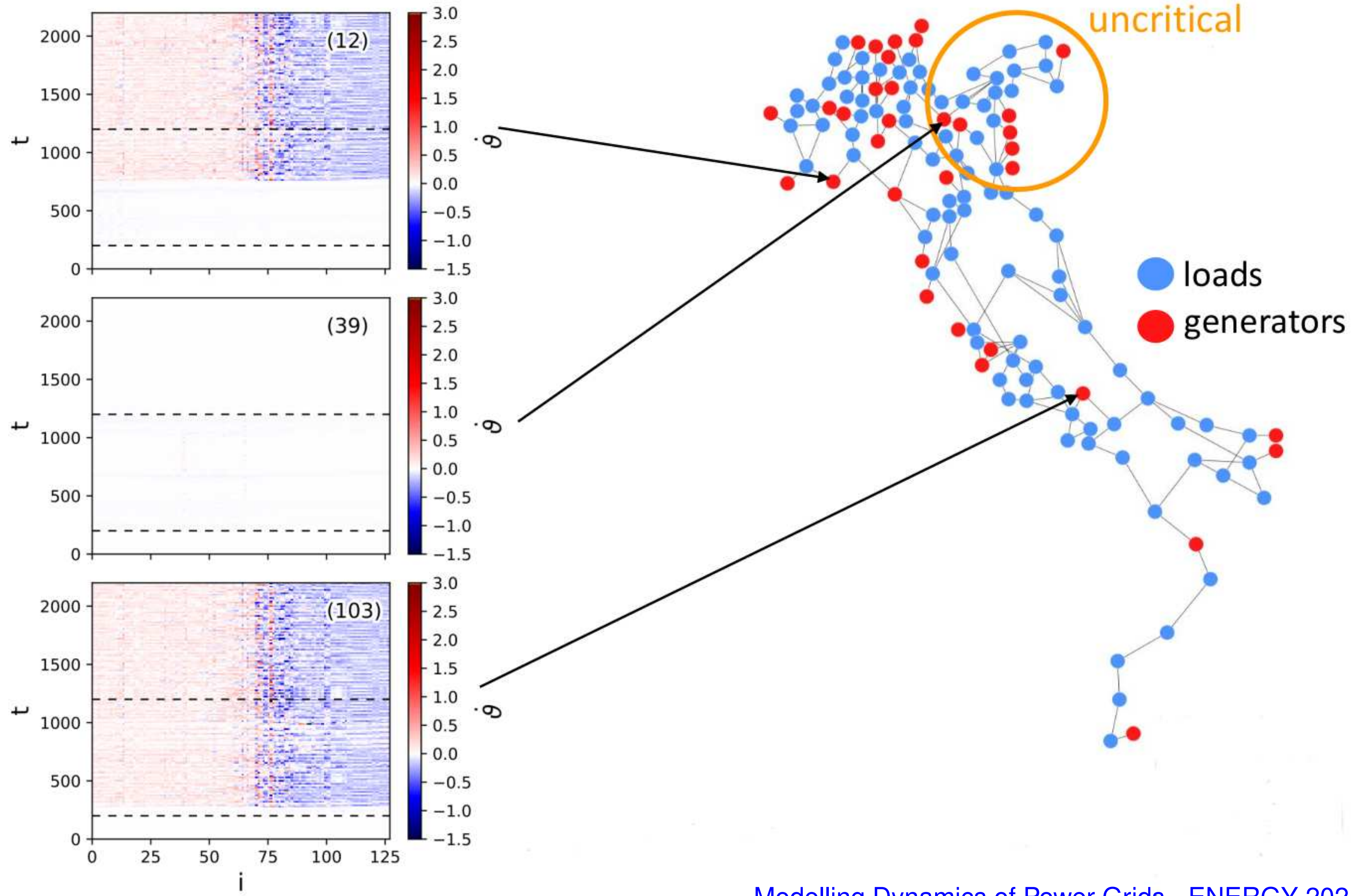


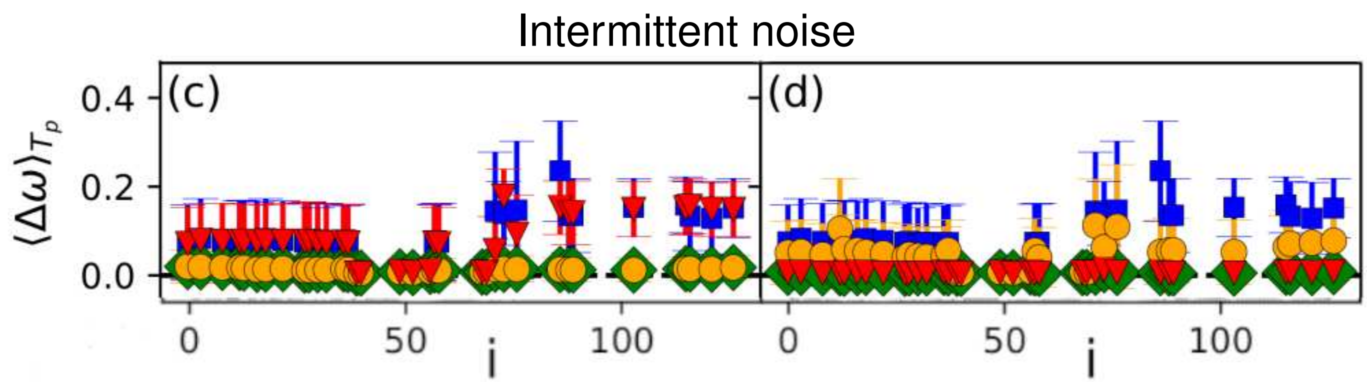


Single node perturbation

Intermittent noise



Single node perturbation



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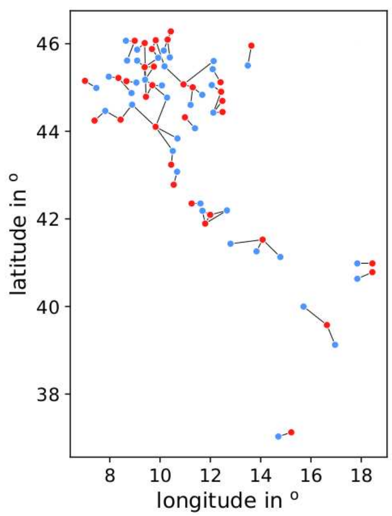

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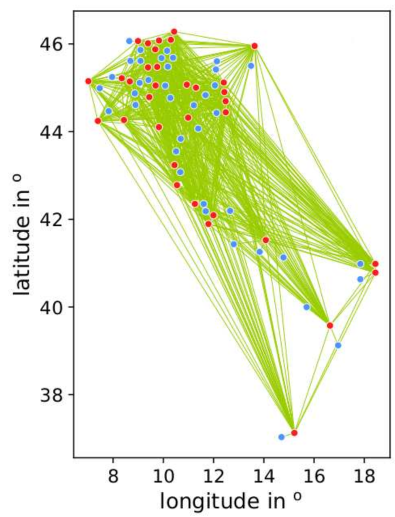
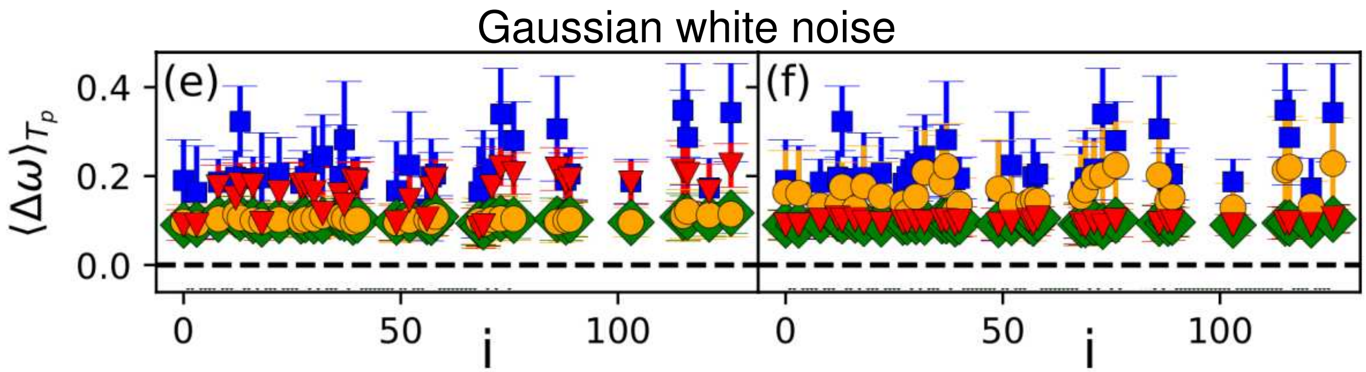


Single node perturbation



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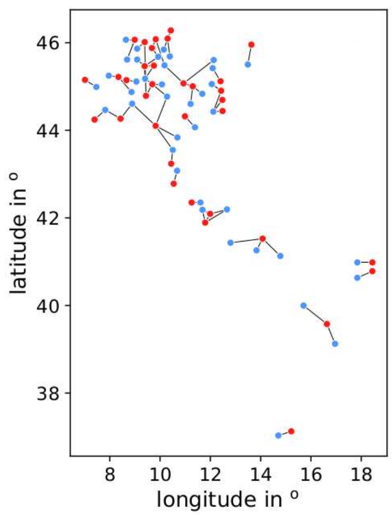

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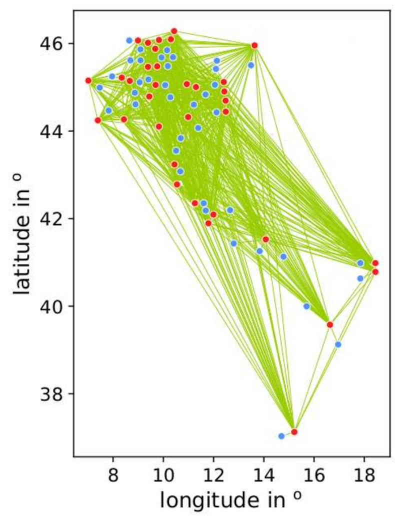
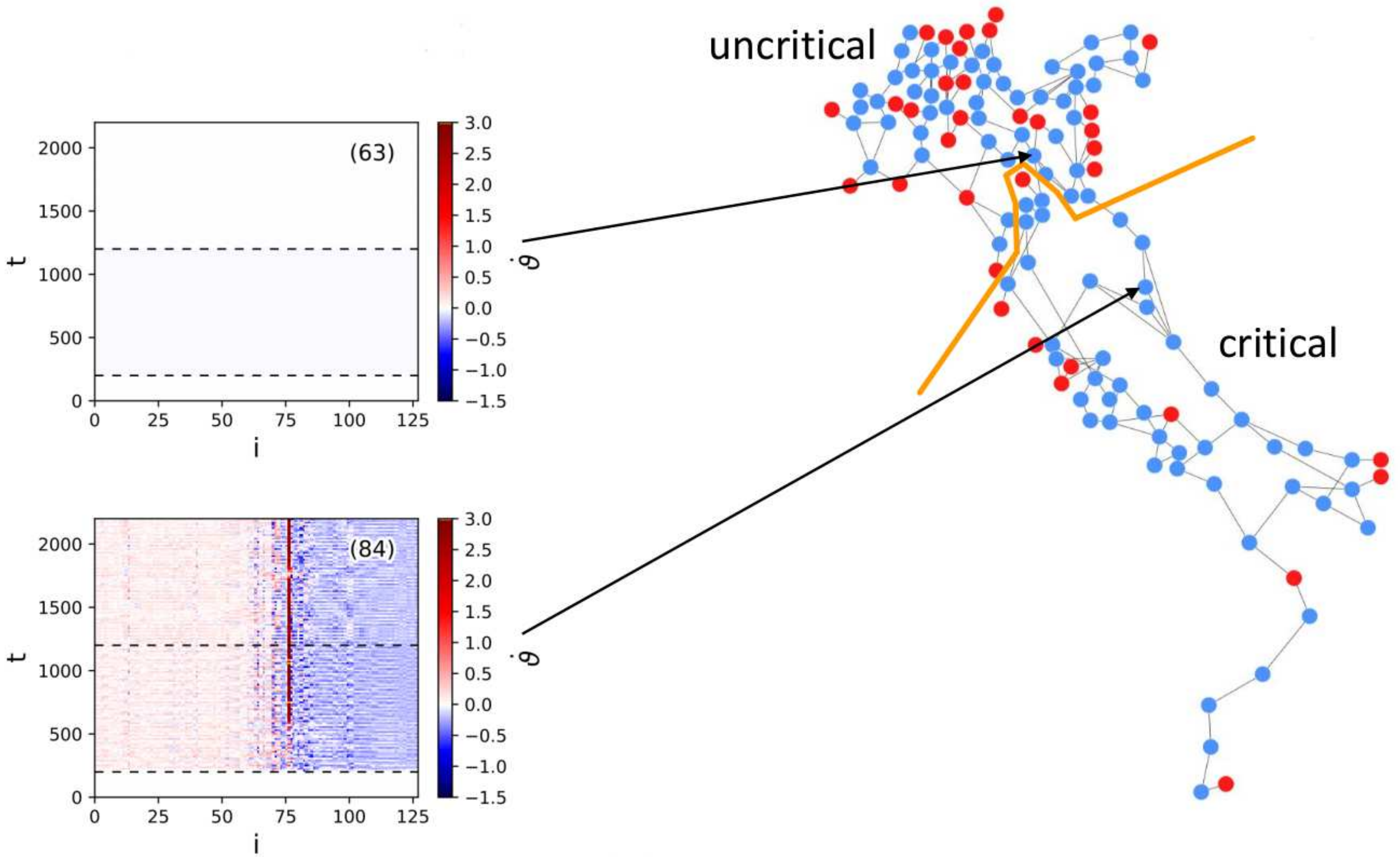
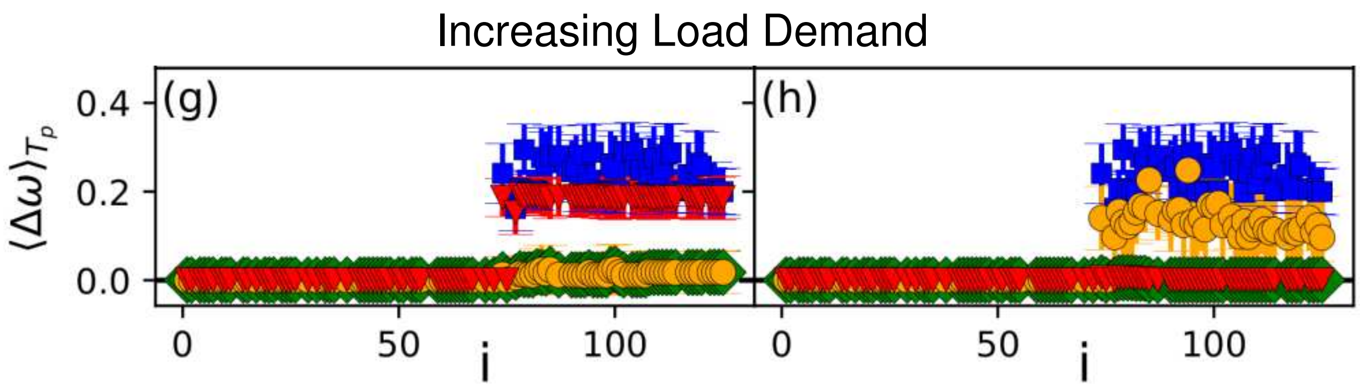


Single node perturbation

Increasing Load Demand



Single node perturbation



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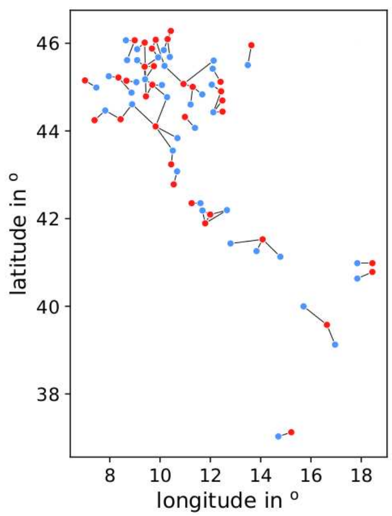

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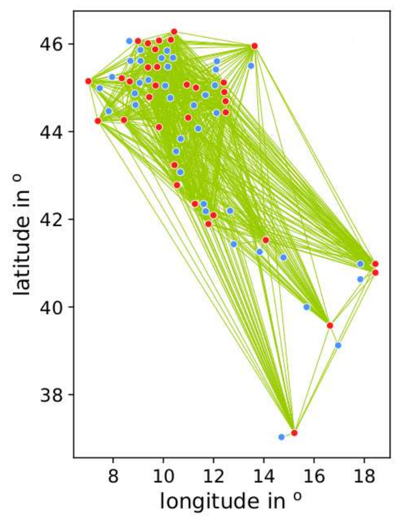
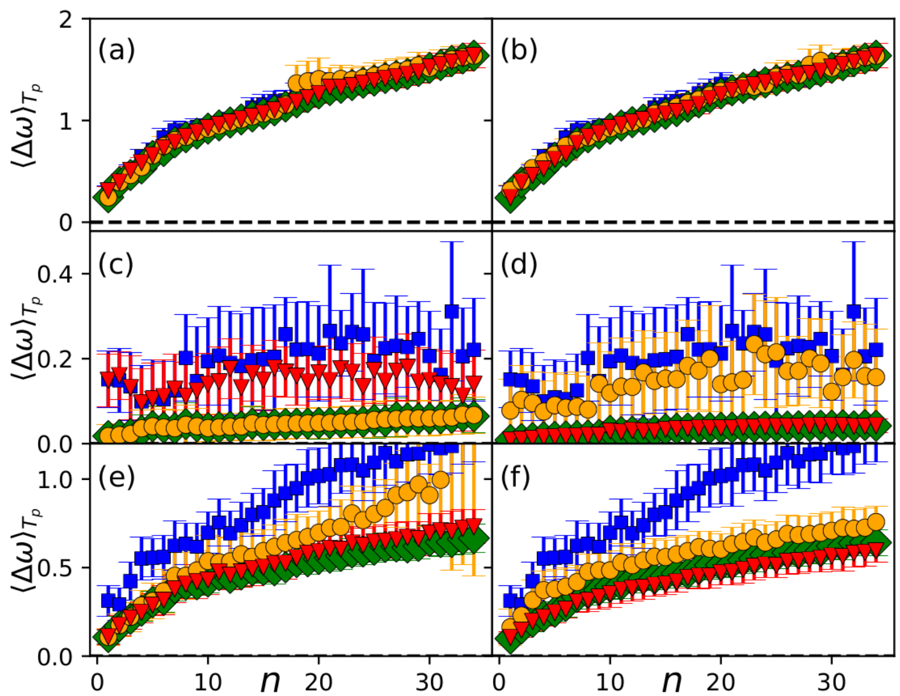


Multiple perturbed generators



(a, b) Disconnecting nodes

(c, d) Intermittent noise

(e, f) Gaussian white noise

(a,c,e) $c_{i,j}^{local}$

(b,d,f) $c_{i,l}^{global}$

■ no control: generators are perturbed successively from south to north

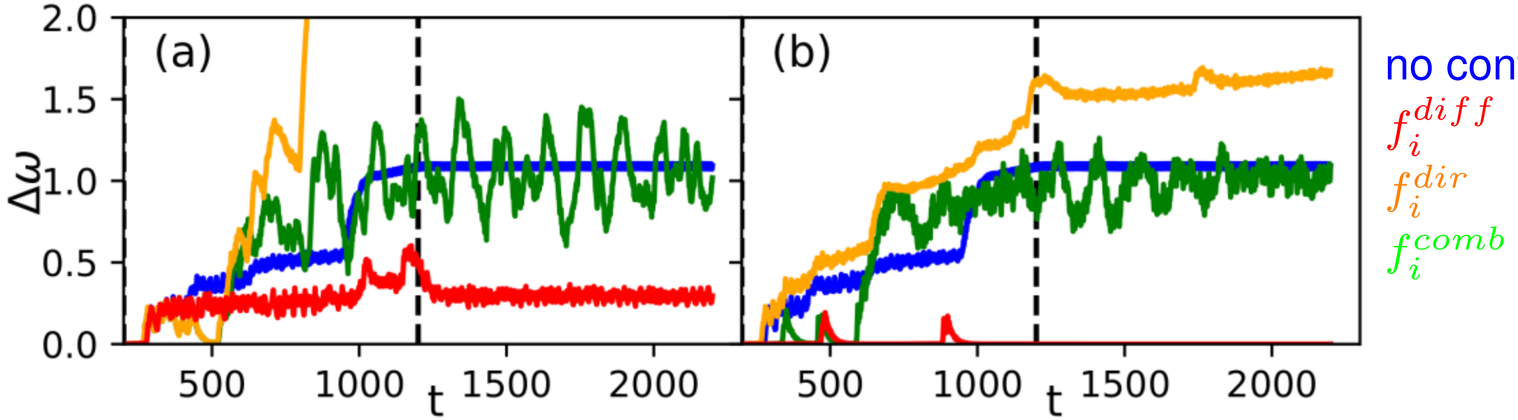
▲ $f_i^{diff}(c_{i,j}, \{\dot{\theta}_j(t)\})$: effective at preserving frequency synchronization if all generators are connected in the communication layer

o $f_i^{dir}(c_{i,j}, \{\dot{\theta}_j(t)\})$: the most effective control scheme in the absence of additional links in the control layer, its reliability deteriorates with the severity of the perturbation

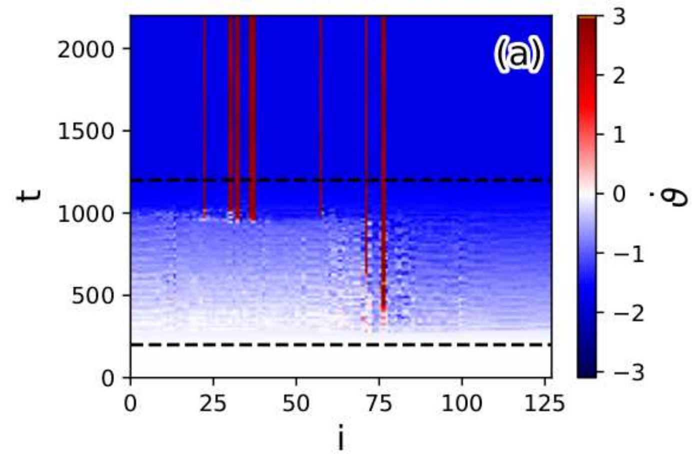
♦ $f_i^{comb}(c_{i,j}, \{\dot{\theta}_j(t)\})$: governed by the interplay of its two components, it improves the effect of the control terms taken separately

Multiple perturbed loads

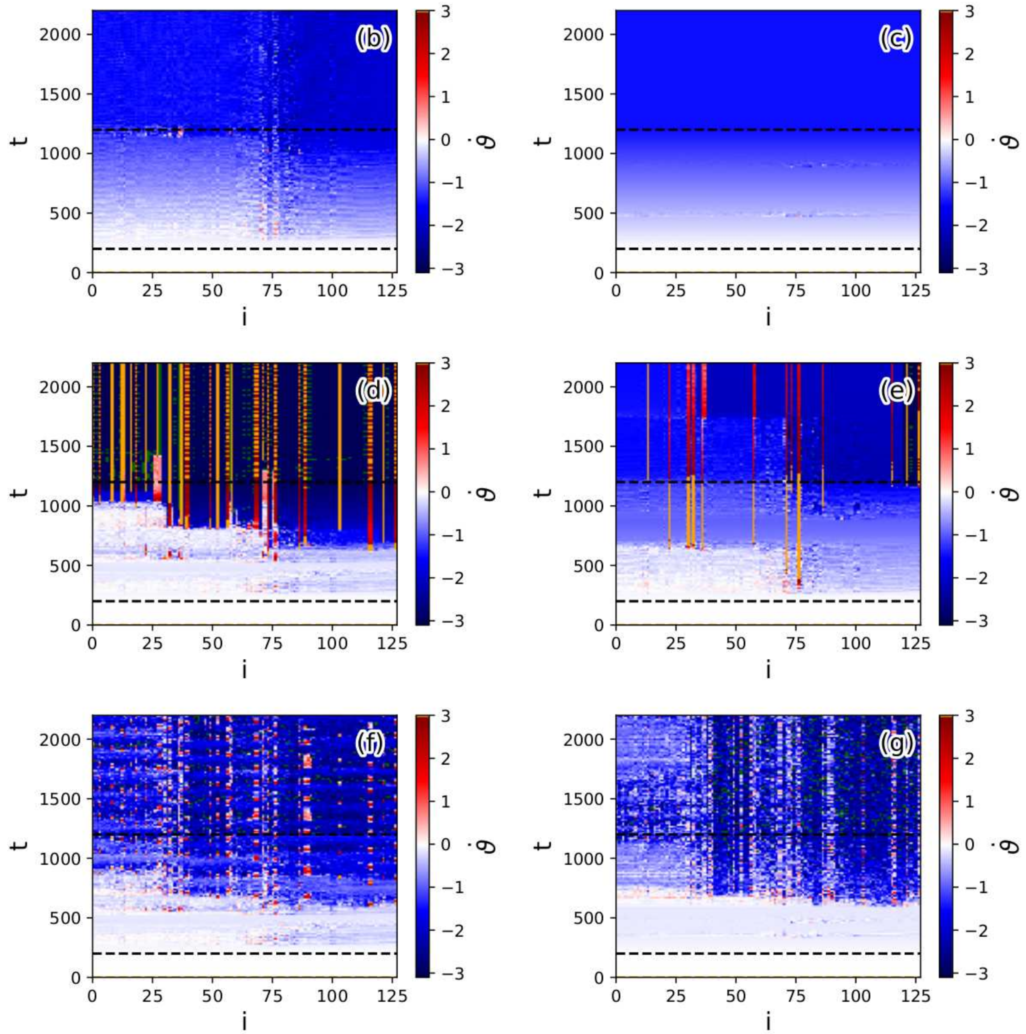
Continuously increasing demand of all nodes simultaneously



- Higher percentage of loads in the southern part of the grid with respect to the north
- Generators at the boundary between north and south are the first to desynchronize
- Desynchronization of multiple generators in the northern part
- Negative average mean frequency trying to compensate the desynchronized generators



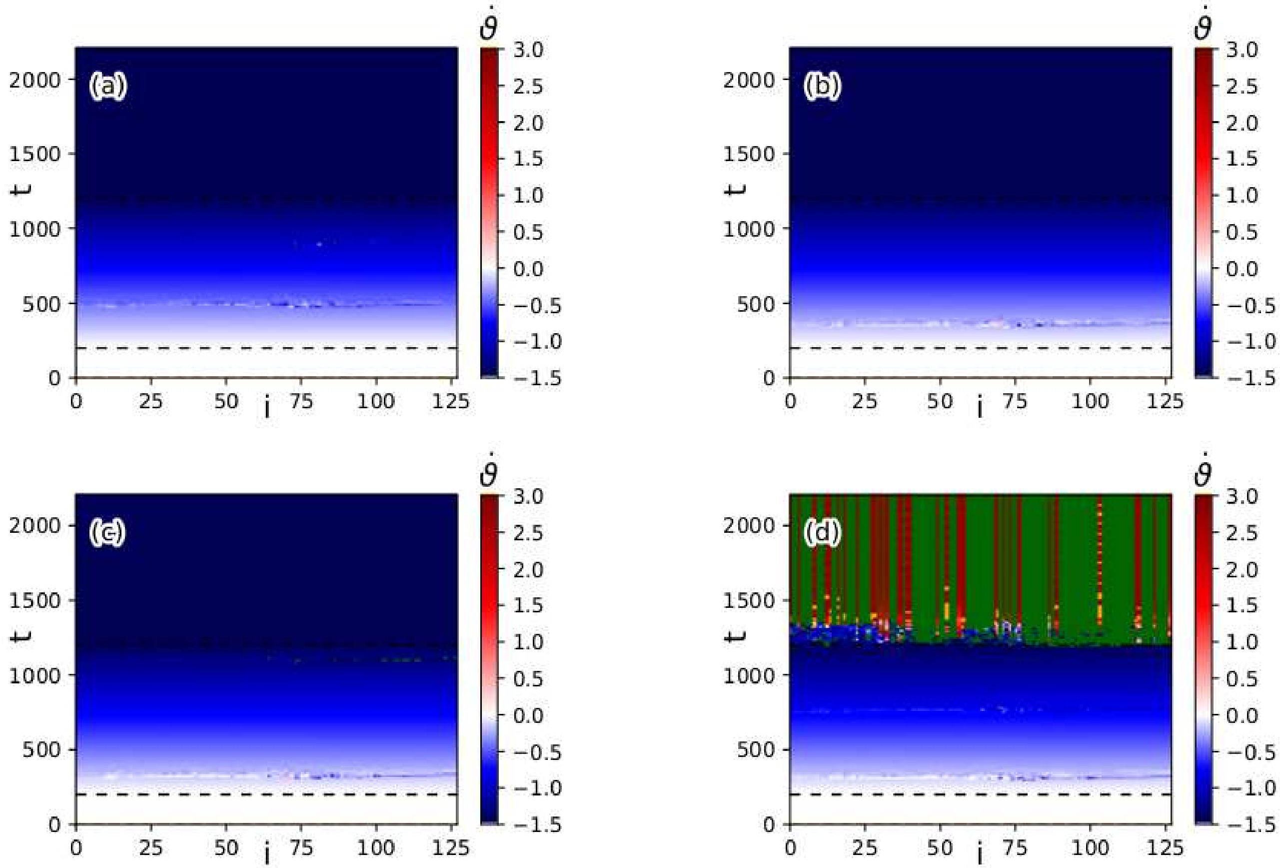
Multiple perturbed loads



- The only efficient control scheme is f_i^{diff}
- The performance is better when considering $c_{i,l}^{global}$
- $f_i^{dir}(c_{i,j}, \{\dot{\theta}_j(t)\})$ fails trying to increase the output of the generators to restore power balance
- $f_i^{comb}(c_{i,j}, \{\dot{\theta}_j(t)\})$ proves ineffective because the two components are competing against each other
- The competition causes the frequencies of the controlled generators to **oscillate**

Multiple perturbed loads

(a) p = 1.0 (b) p = 0.25 (c) p = 0.125 (d) p = 0.07

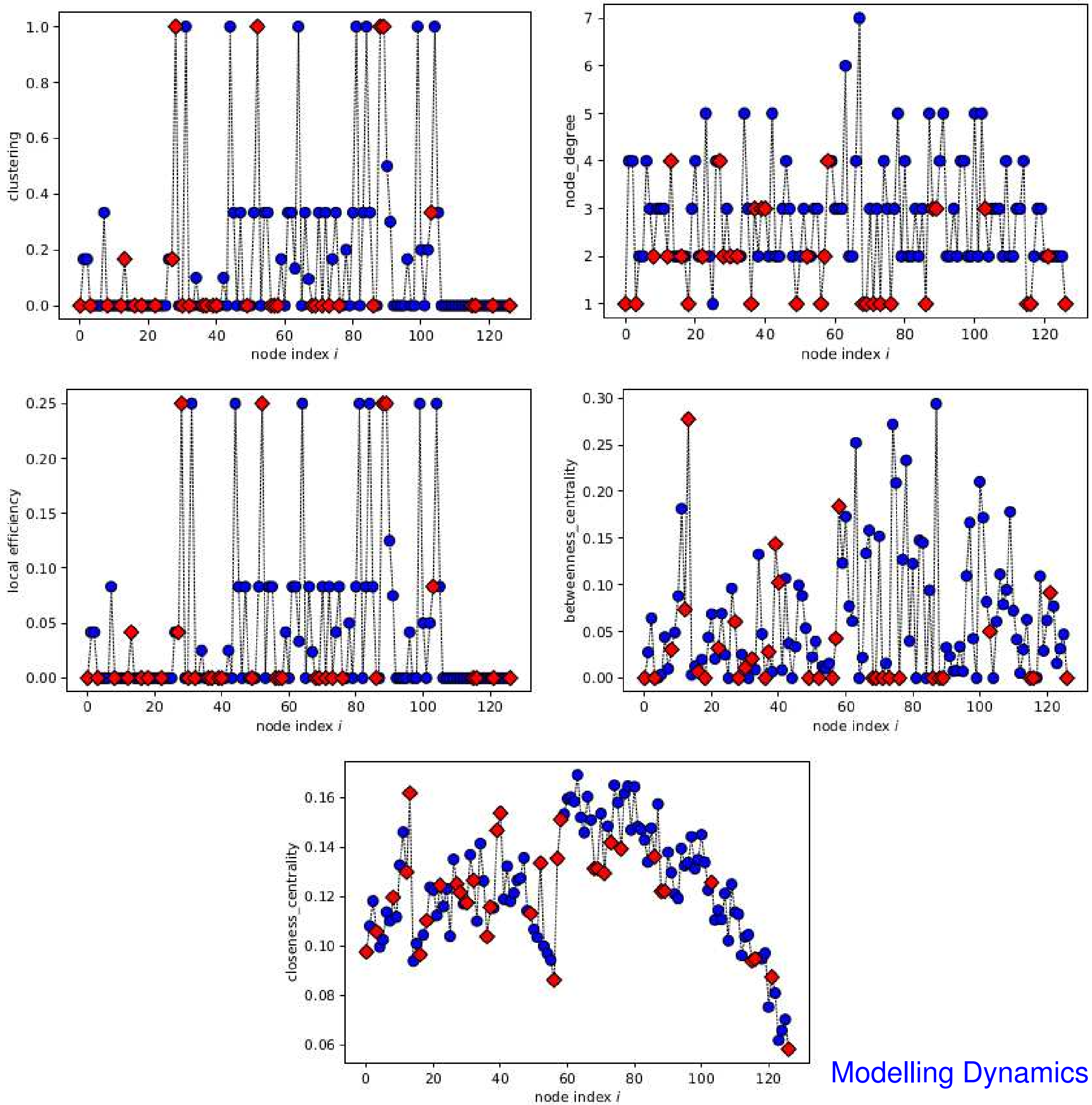


- Global coupling is not a necessary condition for the control scheme to work efficiently
- A few percent of the links ($p > 7\%$) are sufficient to ensure synchronization

Comparison of the control schemes

- $f_i^{diff}(c_{i,j}, \{\dot{\theta}_j(t)\}) = \sum_j^N c_{ij}[\dot{\theta}_j - \dot{\theta}_i]$
  - Synchronizes the frequency of the controlled nodes with their neighbors
  - Limitation: not able to prevent the desynchronization between continental/ peninsular parts
  - **Ineffective in c_{ij}^{local}:** able to improve upon frequency synchronization locally
- $f_i^{dir}(c_{i,j}, \{\dot{\theta}_j(t)\}) = -\frac{1}{N_i}\sum_j^N c_{ij}\dot{\theta}_j$
  - Restores the original synchronization frequency in the neighborhood of the controlled node
  - Limitation: chains are problematic (**frustration**)
  - **Ineffective in c_{ij}^{global}:** multiple controlled generators compensate each other instead of restoring the nominal frequency
- $f_i^{comb}(c_{i,j}, \{\dot{\theta}_j(t)\}) = \sum_j^N c_{ij}\left\{a[\dot{\theta}_j - \dot{\theta}_i] - b\dot{\theta}_j\right\}$
  - Mixed approach
  - Limitation: the drawback of applying both control schemes at the same time emerges when increasing demand of all loads simultaneously

Topological measures



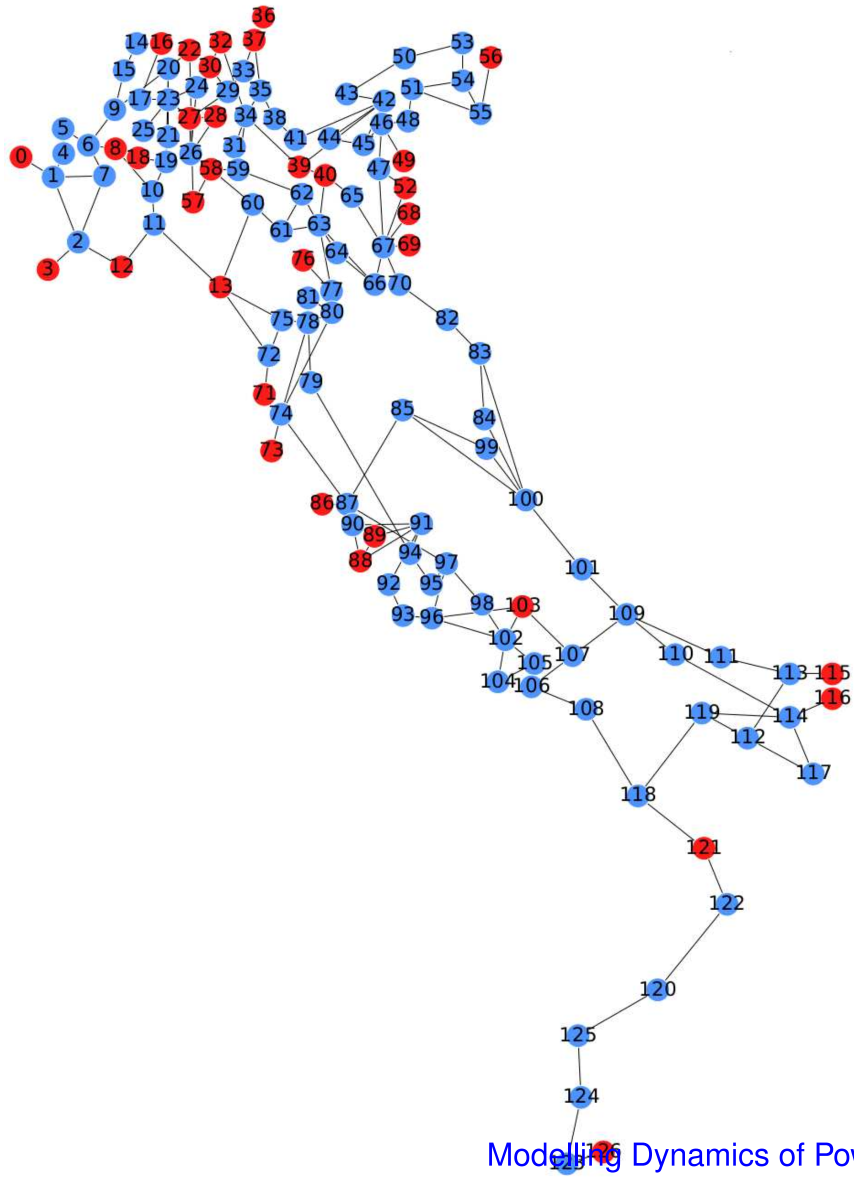
- Dead ends and dead trees [Menck et al. Nature communications 5.1 (2014): 1-8]
- No specific topological measure for most affected nodes
- Northen part: high average connectivity
- Southern part: low average connectivity

Conclusions

- A novel approach by considering the dynamics of a power grid in a two-layer network model, using a **fully dynamical description** for the communication layer
- Multiple-layer power grids have been performed by taking into account only static nodes without dynamics, focusing on topological effects [Buldyrev, Parshani, Paul, Stanley, Havlin, Nature 464, 1025 (2010)].
- Investigations of the dynamics of the (Italian) power grid are usually conducted only in a single layer [Olmi et al, Phys. Rev. E 90, 042905 (2014); Corsi et al IEEE Trans. Power Syst. 19, 1723 (2004); Fortuna et al Int. J. Mod. Phys. B 26, 1246011 (2012)]
- Different control schemes tested in a network subject to different realistic perturbation scenarios
  - f^{diff} works always in c_{ij}^{global}, f^{dir} is usefull in c_{ij}^{local}

Totz, Olmi, Schöll, *Control of synchronization in two-layer power grids*, Physical Review E 102.2 (2020): 022311.

Italian high voltage power grid



Design modern power grids

Decentralization effects:

- Increased vulnerability when adding dead-nodes or dead trees [Menck et al, Nat. Commun. 5, 3969 (2014)]
- Sensitivity to dynamical perturbations and topological failures [Rohden et al, Phys. Rev. Lett. 109, 064101 (2012)]
- Braess's paradox [Witthaut and Timme, New J. Phys. 14, 083036 (2012); Tchuisseu et al, New Journal of Physics 20, 083005 (2018)]
- Single critical nodes [Hellmann et al, Nat. Commun. 11, 592 (2020); Taher et al, Phys. Rev. E 100, 062306 (2019)]

Cascade of failures:

- Localized events such as line overload, voltage collapse or desynchronization [Ewart, IEEE Spectrum 15, 36 (1978)]
- Importance of considering transient dynamics of the order of few seconds, since the distance of a line failure from the initial trigger and the time of the line failure are highly correlated [Schäfer et al, Nat. Commun. 9, 1975 (2018)]