Control of synchronization in two-layer power grids

Simona Olmi\textsuperscript{1}, Carl Totz\textsuperscript{2}, Eckehard Schöll\textsuperscript{2,3}

(1) Istituto dei Sistemi Complessi - CNR - Firenze, Italy
(2) Technische Universität Berlin - Germany
(3) Potsdam Institute for Climate Impact Research - Germany

simona.olmi@fi.isc.cnr.it
Simona Olmi

- **Researcher** at Istituto dei Sistemi Complessi (ISC)-CNR since 2019
  
  [https://www.isc.cnr.it/staff-members/simona-olmi/](https://www.isc.cnr.it/staff-members/simona-olmi/)

- **Previous Positions:** Inria Sophia Antipolis Méditerranée (France); Institut für Theoretische Physik, TU Berlin (Germany); Weierstrass Institute for Applied Analysis and Stochastics (Berlin, Germany); Institut de Neurosciences des Systèmes (Marseille, France)

- **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:** ~ 29 journal articles in international peer-reviewed journal - citations 720 (h-index 13)

- **Scientific expertises:** nonlinear dynamics, computational neuroscience, power grids, stability analysis of collective solutions, epileptic seizure prediction

**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 et 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

\[ m \ddot{\theta}_i(t) = -\dot{\theta}_i(t) + \Omega_i + P^c_i(t) + K \sum_{j=1}^{N} A_{ij} \sin(\theta_j - \theta_i) \]

- \( i \): Node index (=1,...,N)
- \( \theta_i \): Phase
- \( \dot{\theta} \): Frequency
- \( m \): Mass, inertia constant, \( m=10 \)
- \( \Omega_i \): Inherent frequency \( \cong \) power generation/consumption
- \( P^c_i \): 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 $\Delta K$ until a maximum coupling strength is reached
  - **Downsweep protocol**: starting from the maximum coupling strength, $K$ is reduced in steps of $\Delta K$ 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:
  \[ \Omega_{gen} = \frac{93}{34} \]
  \[ \Omega_{load} = -1 \]
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 $P^c_i \in \mathbb{R}$
- The loads are not controlled.
- The control signal can be interpreted as power injection for $P^c_i > 0$ or power absorption for $P^c_i < 0$
- 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)].

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

$c_{i,j}$ 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**
  \[ f_{i}^{diff}(c_{i,j}, \{\dot{\theta}_j(t)\}) = \sum_{j}^N c_{i,j} [\dot{\theta}_j - \dot{\theta}_i] \]
  [Giraldo et al, in 52nd IEEE Conf. Decision and Control (2013), 4638]

- **Proportional control**
  \[ f_{i}^{dir}(c_{i,j}, \{\dot{\theta}_j(t)\}) = -\frac{1}{N_i} \sum_{j}^N c_{i,j} \dot{\theta}_j \]

- **Combined control**
  \[ f_{i}^{comb}(c_{i,j}, \{\dot{\theta}_j(t)\}) = \sum_{j}^N c_{i,j} \left\{ a[\dot{\theta}_j - \dot{\theta}_i] - b\dot{\theta}_j \right\} \]

Control strength \( G_i \): Effective only for generators

- \( c_{ij}^{local}, c_{ij}^{global} \)
Applied perturbations

- Disconnecting generators

\[
\begin{align*}
    a_{ij}(t) &= a_{ji}(t) = 0 \\
    c_{ij}(t) &= c_{ji}(t) = 0
\end{align*}
\]

\( t \in T_P \)

\( T_P \) duration of the perturbation

- Gaussian white noise

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

\( \xi = \delta \)-correlated Gaussian random variable, with noise intensity \( D \)

- Intermittent noise

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

\( \mu = \) 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)

- Blue dots: loads
- Red dots: generators

Critical vs. uncritical nodes

Modelling Dynamics of Power Grids - ENERGY 2021 – p. 14
Single node perturbation

Disconnecting nodes (generators)

\[ \Delta \omega \]

\[ \hat{\theta}_j(t) \]

\[ f_i^{\text{diff}}(c_{i,j}, \{\hat{\theta}_j(t)\}) \]

\[ f_i^{\text{dir}}(c_{i,j}, \{\hat{\theta}_j(t)\}) \]

\[ f_i^{\text{comb}}(c_{i,j}, \{\hat{\theta}_j(t)\}) \]

no control

OK

NO

OK

OK

OK

Modelling Dynamics of Power Grids - ENERGY 2021 – p. 15
Single node perturbation

Intermittent noise
Single node perturbation

Intermittent noise

(c)

(d)

- no control
- $f_i^{diff}(c_{i,j}, \{\dot{\theta}_j(t)\})$ NO
- $f_i^{dir}(c_{i,j}, \{\dot{\theta}_j(t)\})$ OK
- $f_i^{comb}(c_{i,j}, \{\dot{\theta}_j(t)\})$ OK

- no control
- $f_i^{diff}(c_{i,j}, \{\dot{\theta}_j(t)\})$ OK
- $f_i^{dir}(c_{i,j}, \{\dot{\theta}_j(t)\})$ NO
- $f_i^{comb}(c_{i,j}, \{\dot{\theta}_j(t)\})$ OK
Single node perturbation

Gaussian white noise

\begin{align*}
\langle \Delta \omega \rangle_{T_p} & \\
\text{no control} & \\
\bigtriangledown f_i^{diff} (c_{i,j}, \{\dot{\theta}_j(t)\}) & \text{NO} \\
\bigcirc f_i^{dir} (c_{i,j}, \{\dot{\theta}_j(t)\}) & \text{OK} \\
\bigstar f_i^{comb} (c_{i,j}, \{\dot{\theta}_j(t)\}) & \text{OK} \\
\end{align*}

\begin{align*}
\text{no control} & \\
\bigtriangleup f_i^{diff} (c_{i,j}, \{\dot{\theta}_j(t)\}) & \text{OK} \\
\bigcirc f_i^{dir} (c_{i,j}, \{\dot{\theta}_j(t)\}) & \text{NO} \\
\bigstar f_i^{comb} (c_{i,j}, \{\dot{\theta}_j(t)\}) & \text{OK} \\
\end{align*}
Single node perturbation

Increasing Load Demand

uncritical

critical

Modelling Dynamics of Power Grids - ENERGY 2021 – p. 19
Single node perturbation

[Diagrams showing different scenarios with color-coded indicators for no control and various functions involving $c_{i,j}$ and $\dot{\theta}_j(t)$]

- $f^\text{diff}_i(c_{i,j}, \{\dot{\theta}_j(t)\})$ NO
- $f^\text{dir}_i(c_{i,j}, \{\dot{\theta}_j(t)\})$ OK
- $f^\text{comb}_i(c_{i,j}, \{\dot{\theta}_j(t)\})$ OK
Multiple perturbed generators

- **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.

- **$f_{i}^{dir}(c_{i,j}, \{\dot{\theta}_{j}(t)\})$:** 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.

(a, b) Disconnecting nodes
(c, d) Intermittent noise
(e, f) Gaussian white noise
(a,c,e) $C_{i,j}^{local}$
(b,d,f) $C_{i,l}^{global}$
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 $f_{i, \text{diff}}$
- The performance is better when considering $c_{i, l}^{\text{global}}$
- $f_{i, \text{dir}}(c_{i,j}, \{\dot{\theta}_j(t)\})$ fails trying to increase the output of the generators to restore power balance
- $f_{i, \text{comb}}(c_{i,j}, \{\dot{\theta}_j(t)\})$ 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

\[ f_{i \text{diff}}^{\text{diff}}(c_{i,j}, \{\dot{\theta}_j(t)\}) = \sum_j^N c_{i,j}[\dot{\theta}_j - \dot{\theta}_i] \]
- Synchronizes the frequency of the controlled nodes with their neighbors
- **Limitation:** not able to prevent the desynchronization between continental/peninsular parts
- **Ineffective in** \( c_{i,j}^{\text{local}} \): able to improve upon frequency synchronization locally

\[ f_{i \text{dir}}^{\text{dir}}(c_{i,j}, \{\dot{\theta}_j(t)\}) = -\frac{1}{N_i} \sum_j^N c_{i,j} \dot{\theta}_j \]
- Restores the original synchronization frequency in the neighborhood of the controlled node
- **Limitation:** chains are problematic (**frustration**)
- **Ineffective in** \( c_{i,j}^{\text{global}} \): multiple controlled generators compensate each other instead of restoring the nominal frequency

\[ f_{i \text{comb}}^{\text{comb}}(c_{i,j}, \{\dot{\theta}_j(t)\}) = \sum_j^N c_{i,j} \left\{ a[\dot{\theta}_j - \dot{\theta}_i] - b \dot{\theta}_j \right\} \]
- 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
- Northern 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 [Withaut 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)]