Control of synchronization in two-layer power grids

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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

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)]
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:

- 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

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

- \( i \): Node index (=1,...,N)
- \( \theta_i \): Phase
- \( \dot{\theta} \): Frequency
- \( m \): Mass, inertia constant, \( m=10 \)
- \( \Omega_i \): Inherent frequency \( \cong \) power generation/consumption
- \( P_{ci}^c \): 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:**

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

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

- **Time averaged frequency of individual nodes:** \( < \omega_i >_t \)

- **Kuramoto order parameter:**

\[
r(t)e^{i\phi(t)} = \frac{1}{N} \sum_{j} e^{i\theta_j}
\]

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

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

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

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

\( c_{i,j}^{\text{local}}, c_{i,j}^{\text{global}} \)
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


- 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
Single node perturbation

Disconnecting nodes (generators)

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

- **NO**
- **OK**

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

- **OK**
- **NO**

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

- **OK**
- **OK**

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Single node perturbation

Intermittent noise
Single node perturbation

Intermittent noise

\[ (\Delta \omega)_{T_p} \]

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

\[ \text{latitude in } ^\circ \]

\[ \text{longitude in } ^\circ \]
Single node perturbation

\[ f_{i}^{\text{diff}}(c_{i,j}, \{\dot{\theta}_{j}(t)\}) \]  NO

\[ f_{i}^{\text{dir}}(c_{i,j}, \{\dot{\theta}_{j}(t)\}) \]  OK

\[ f_{i}^{\text{comb}}(c_{i,j}, \{\dot{\theta}_{j}(t)\}) \]  OK

Gaussian white noise

\[ \langle \Delta \omega \rangle \] in different states

\[ \text{latitude in } ^{\circ} \]

\[ \text{longitude in } ^{\circ} \]
Single node perturbation

Increasing Load Demand

uncritical

critical
Single node perturbation

Increasing Load Demand

- **no control**
  - $f_{i}^{\text{diff}}(c_{i,j}, \{\dot{\theta}_{j}(t)\})$ NO
  - $f_{i}^{\text{dir}}(c_{i,j}, \{\dot{\theta}_{j}(t)\})$ OK
  - $f_{i}^{\text{comb}}(c_{i,j}, \{\dot{\theta}_{j}(t)\})$ OK

- **no control**
  - $f_{i}^{\text{diff}}(c_{i,j}, \{\dot{\theta}_{j}(t)\})$ OK
  - $f_{i}^{\text{dir}}(c_{i,j}, \{\dot{\theta}_{j}(t)\})$ NO
  - $f_{i}^{\text{comb}}(c_{i,j}, \{\dot{\theta}_{j}(t)\})$ OK

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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
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 $c_i^{global}$
- $f_i^{dir}(c_{i,j}, \{\dot{\theta}_j(t)\})$ 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

- $f_{i}^{diff}(c_{i,j}, \{\dot{\theta}_{j}(t)\}) = \sum_{j}^{N} c_{i,j} [\dot{\theta}_{j} - \dot{\theta}_{i}]$
  
  - Synchronizes the frequency of the controlled nodes with their neighbors
  
  - **Limitation:** not able to prevent the desynchronization between continental/peninsular parts

- **Ineffective in $c_{ij}^{local}$:** able to improve upon frequency synchronization locally

- $f_{i}^{dir}(c_{i,j}, \{\dot{\theta}_{j}(t)\}) = - \frac{1}{N_{i}} \sum_{j}^{N} c_{i,j} \dot{\theta}_{j}$
  
  - Restores the original synchronization frequency in the neighborhood of the controlled node
  
  - **Limitation:** chains are problematic (**frustration**)

- **Ineffective in $c_{ij}^{global}$:** multiple controlled generators compensate each other instead of restoring the nominal frequency

- $f_{i}^{comb}(c_{i,j}, \{\dot{\theta}_{j}(t)\}) = \sum_{j}^{N} c_{i,j} \left\{a[\dot{\theta}_{j} - \dot{\theta}_{i}] - b\dot{\theta}_{j}\right\}$
  
  - Mixed approach
  
  - **Limitation:** the drawback of applying both control schemes at the same time emerges when increasing demand of all loads simultaneously
Topological measures

- 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)].


- Different control schemes tested in a network subject to different realistic perturbation scenarios
  - $f_{diff}$ works always in $c_{ij}^{global}$, $f_{dir}$ is useful in $c_{ij}^{local}$

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)]