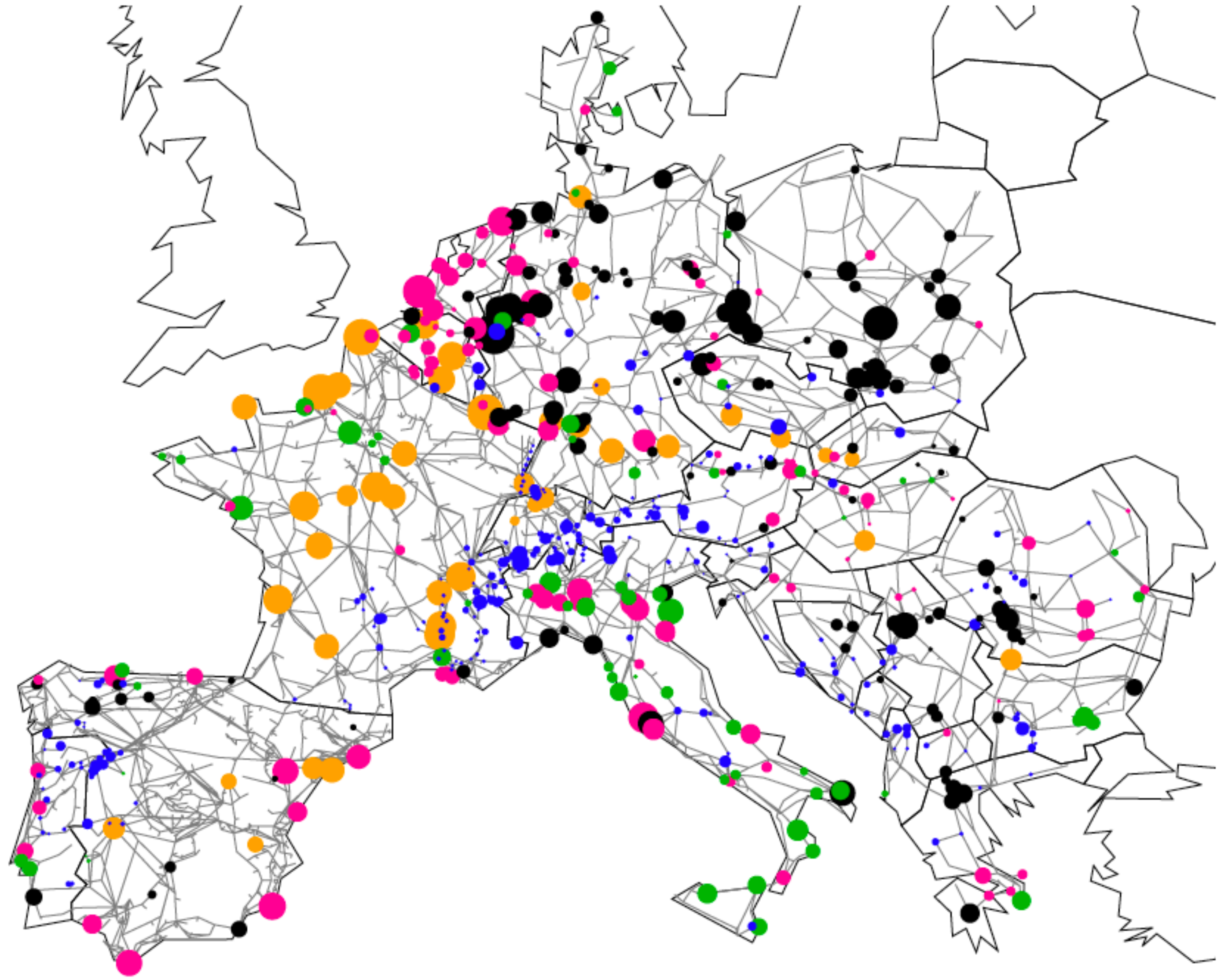
The Physics of Electric Power Systems



Philippe Jacquod

Physics Colloquium - U Basel - 10.04.2019

The team

Philippe

Robin, Melvyn André

Laurent

Tommaso
(now with Sophia genetics)

Glory

Koen

swissgrid

FNSNF

Outline

- Electric power systems - past and present
- Operating steady-state : power flow equations
- Electric power systems - future
- Power system dynamics : swing equations
    - frequency wave propagation
    - optimal placement of inertia

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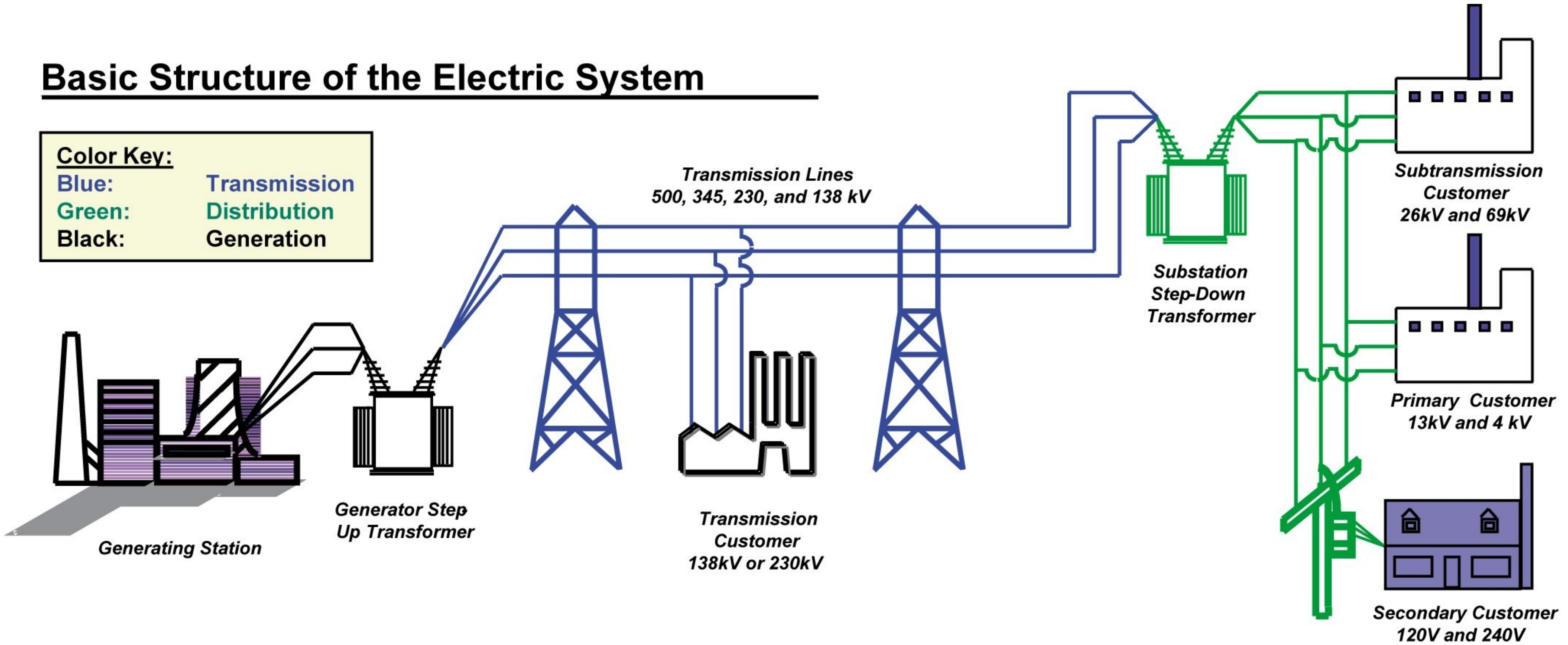
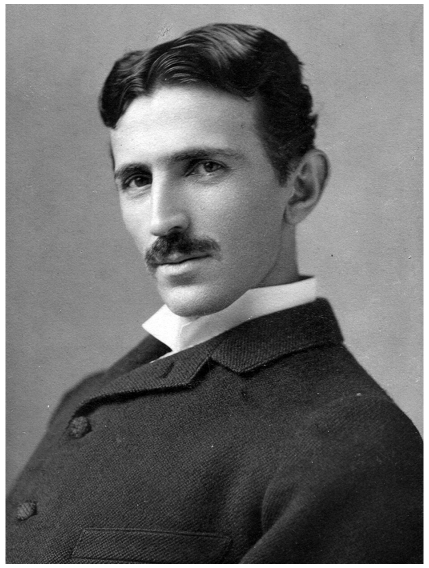
What are electric power systems ?





N Tesla 1856-1943

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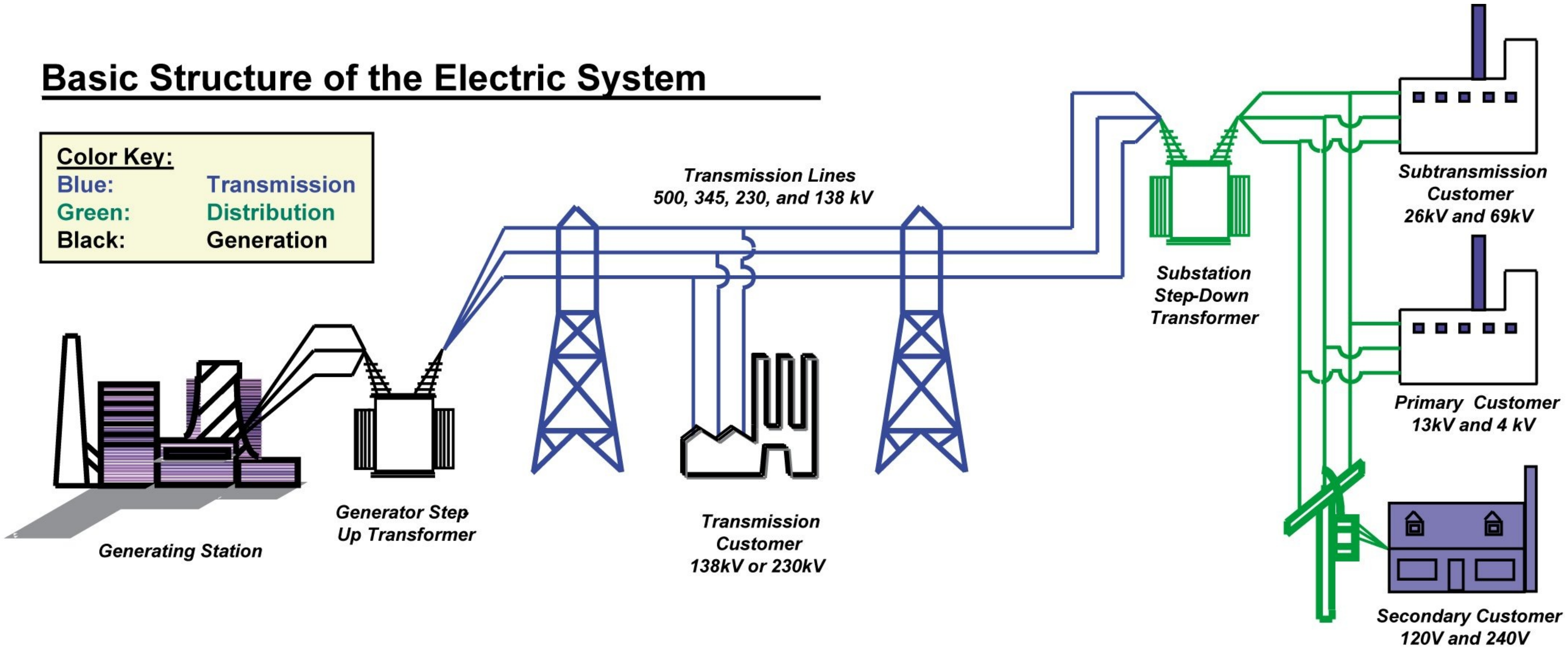

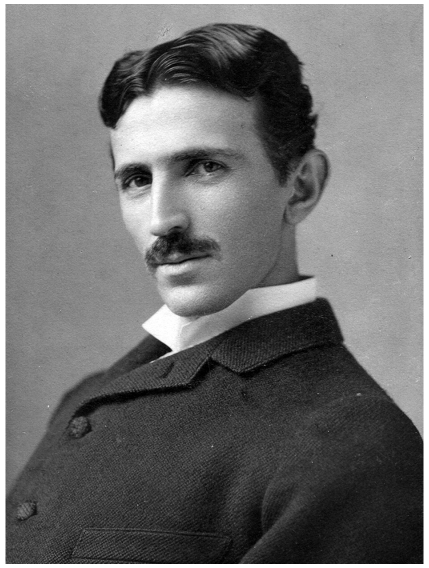

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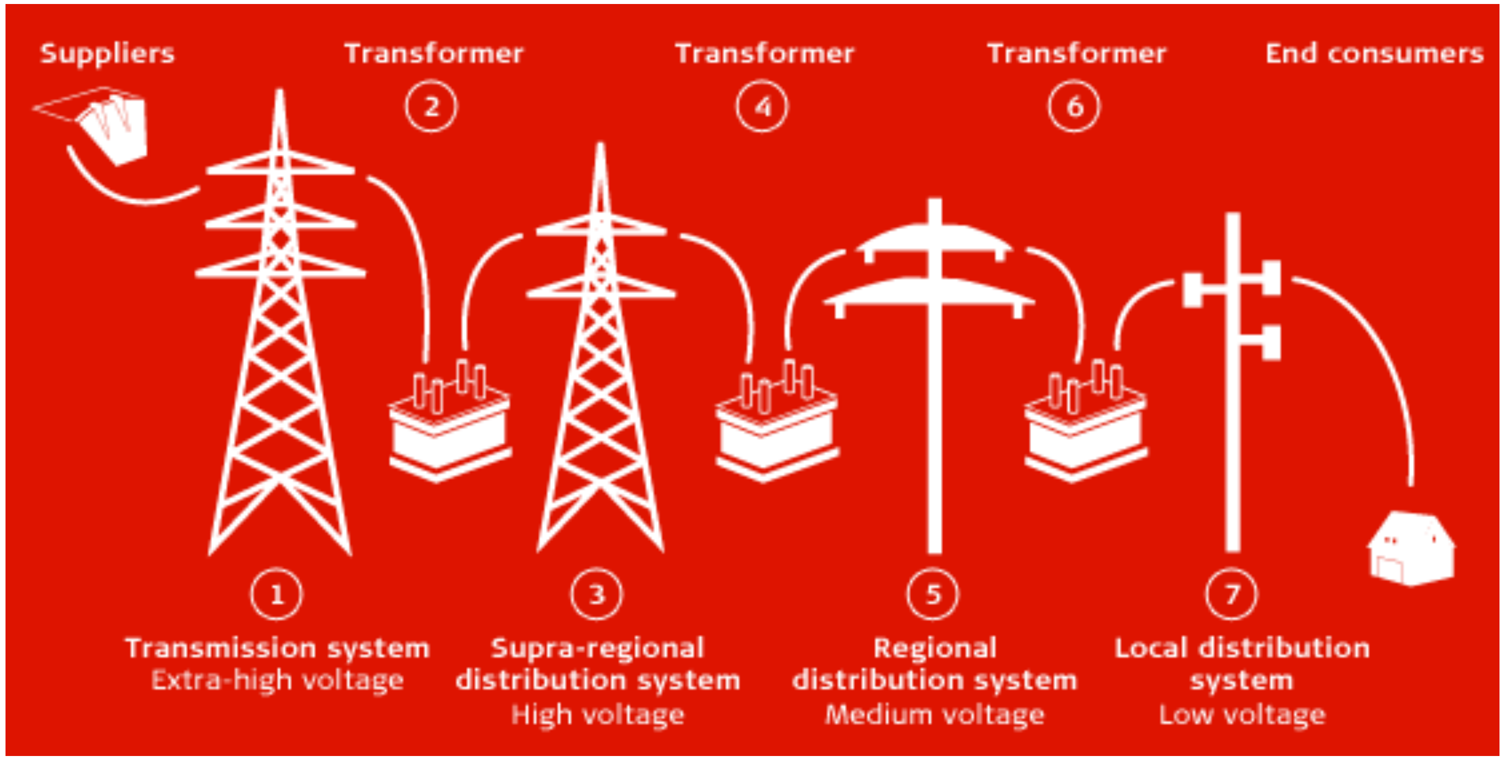
Seven levels of electric power systems



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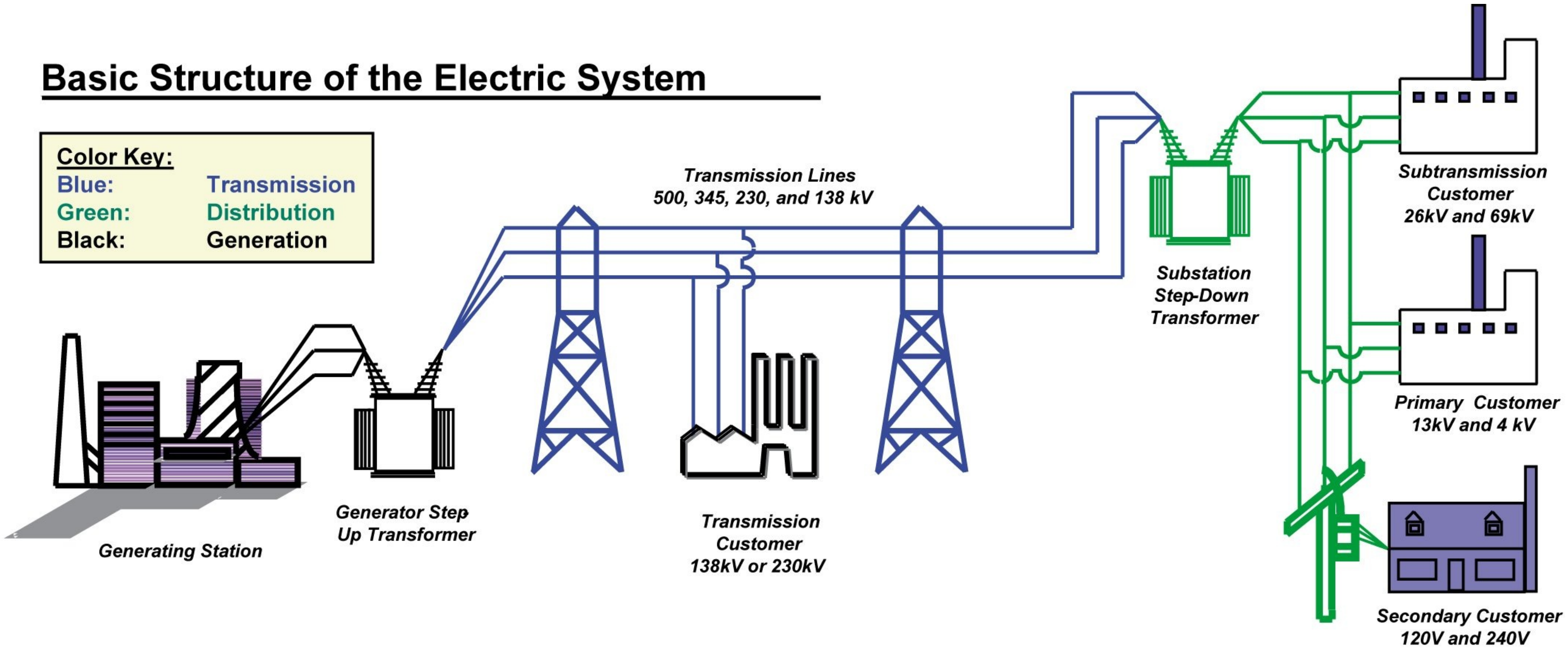

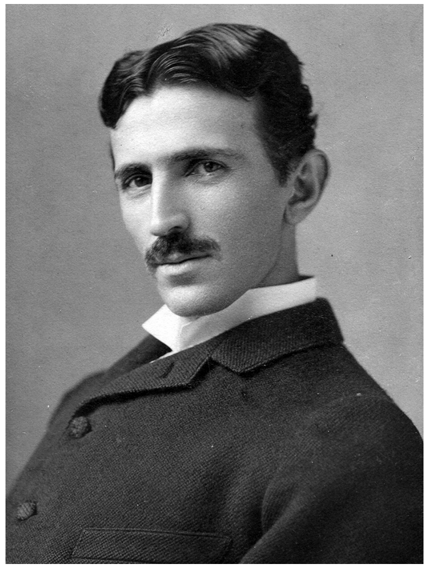

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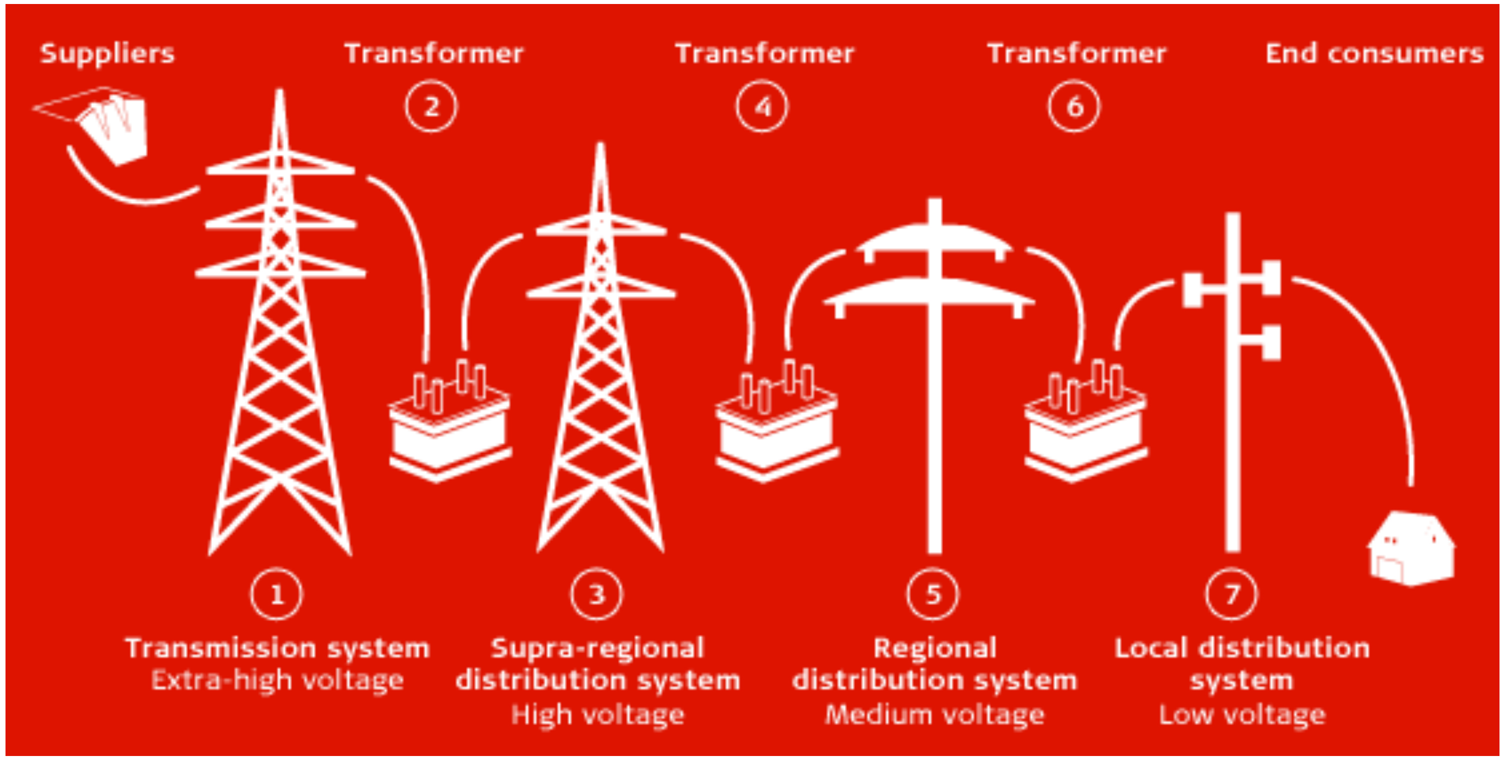


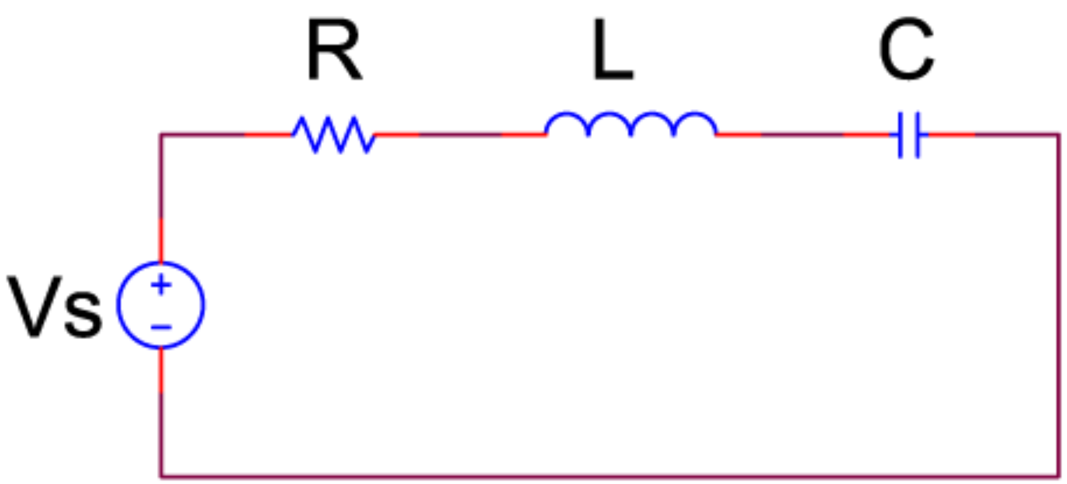
Power :

* conserved (~)
* control parameter

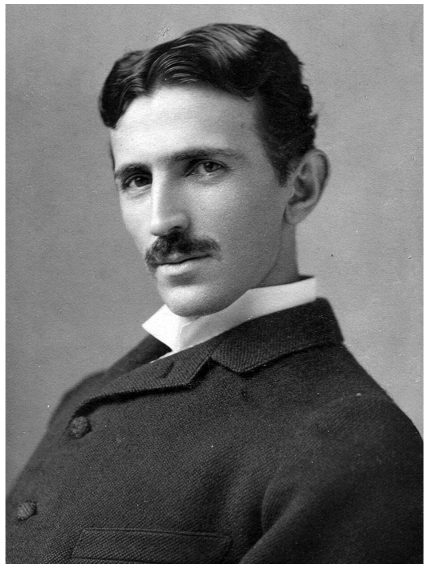
"write Eq. for power"

What are electric power systems ?

- AC electric current/voltages
  (minimize losses ~ high voltages,
  but then need transformers)
- current and voltage not in phase



$$u(t) = u_0 \exp[i\omega t]$$
$$i(t) = i_0 \exp[i(\omega t + \phi)]$$
$$\tan(\phi) = (\omega L - 1/\omega C)/R$$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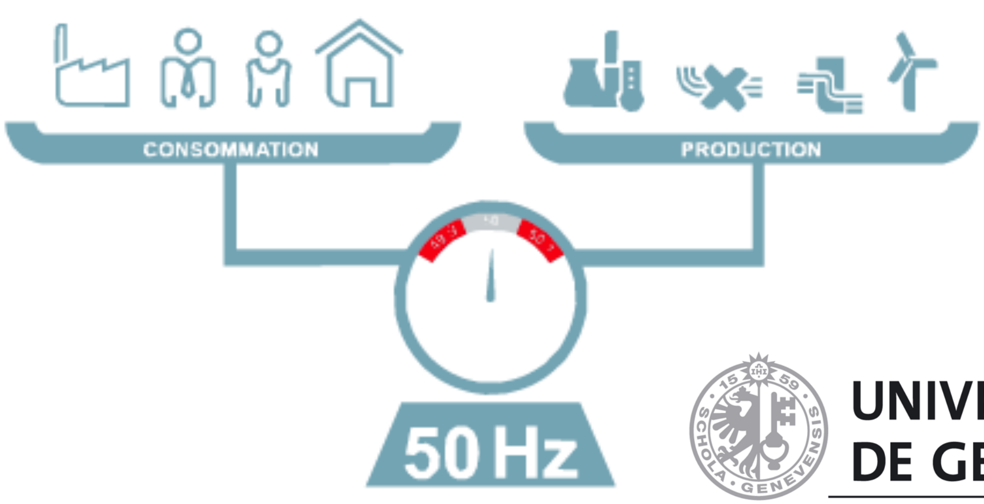
- complex impedance $u(\omega) = Z(\omega)\, i(\omega) \qquad Z(\omega) = R + i\omega L - i/\omega C$

- AC ~ frequency coupled
  to power balance



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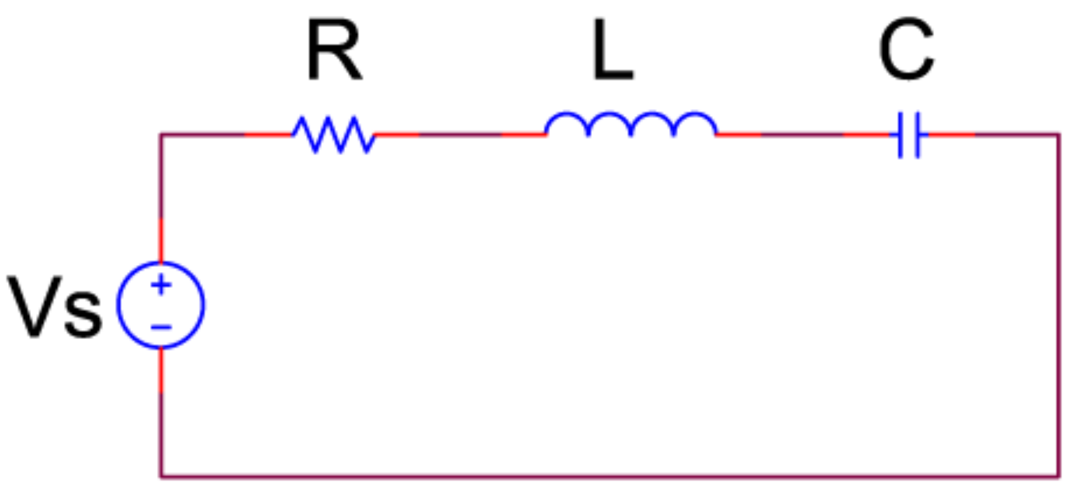

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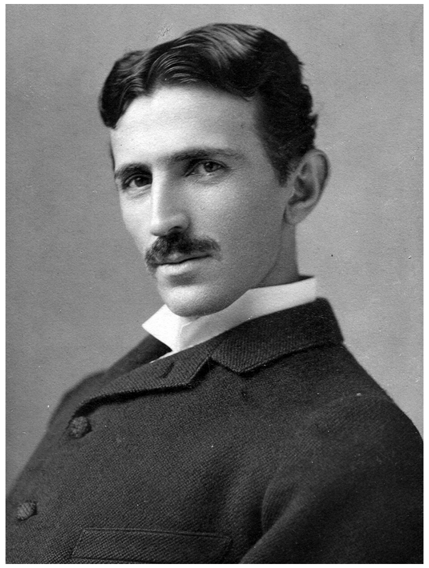
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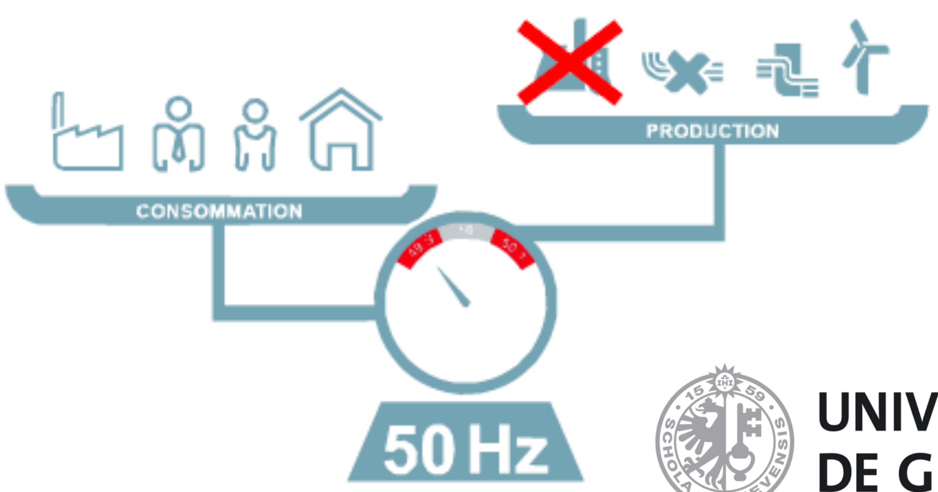

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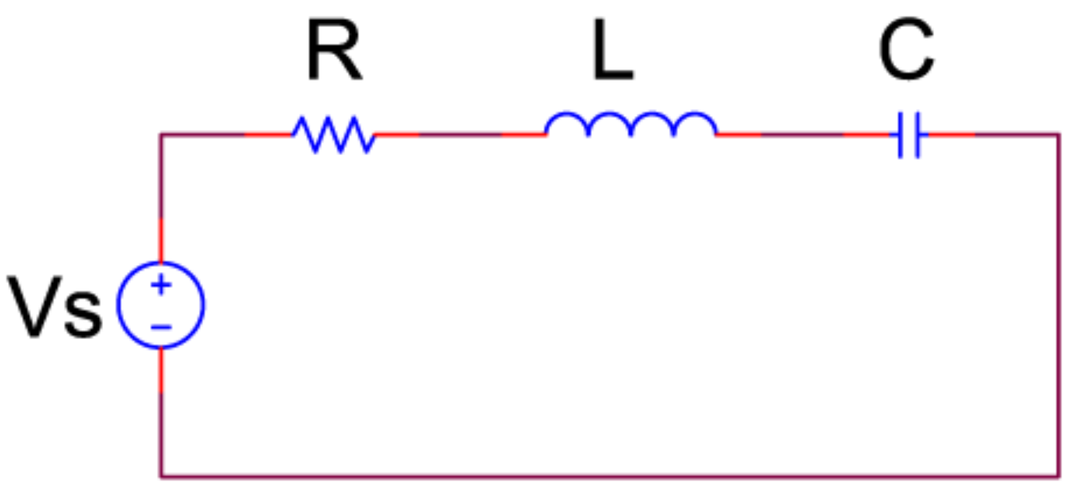

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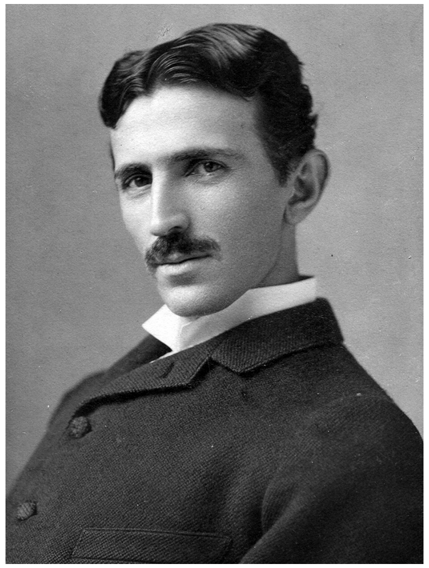

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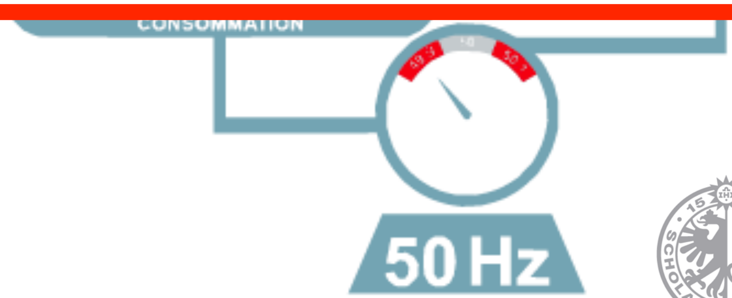
Very high voltage grid (220kV, 380 kV)
$R \ll \omega L$



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Steady-state operation : synchrony over 1000's of kms

Figures from : www.swissgrid.ch

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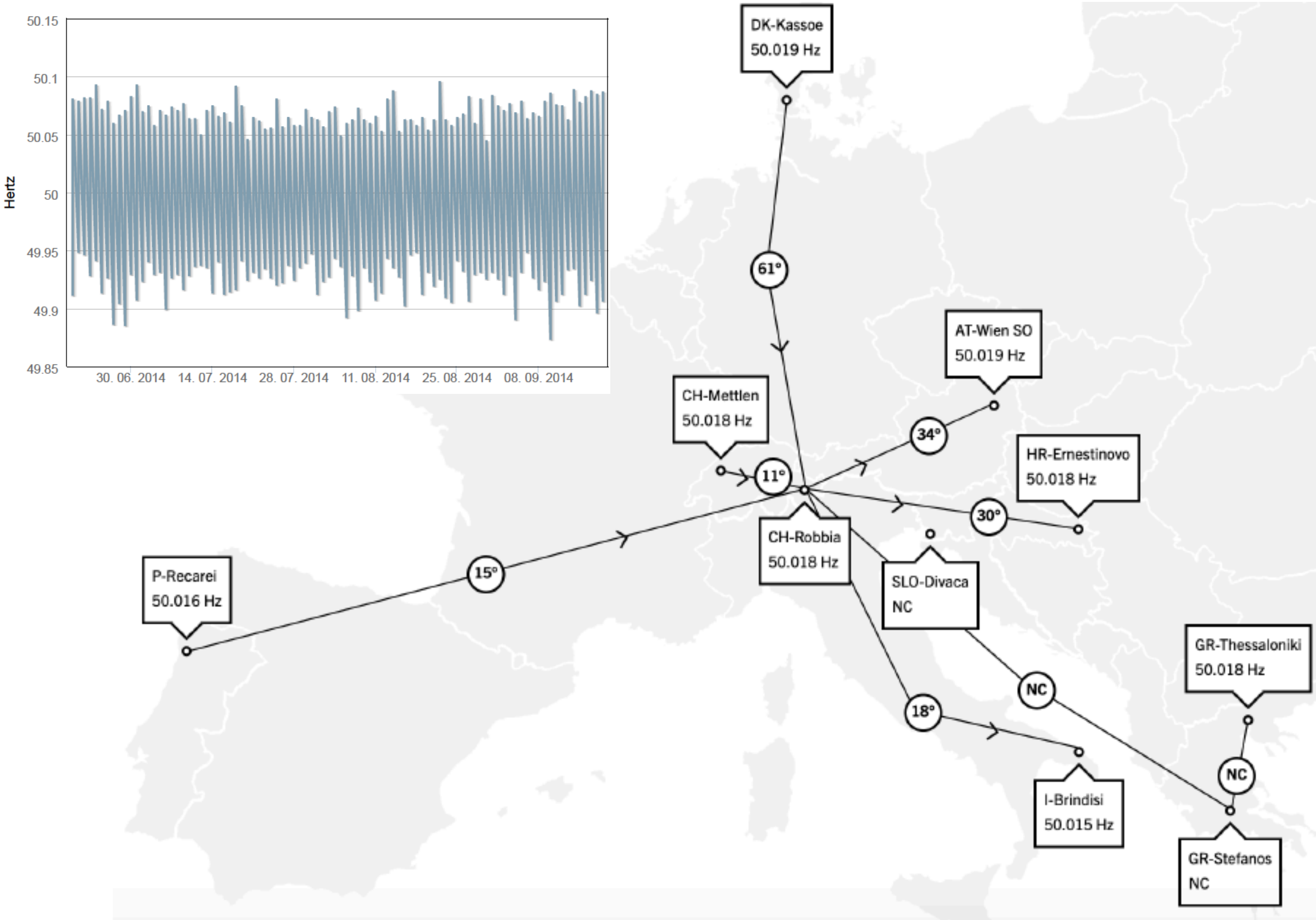

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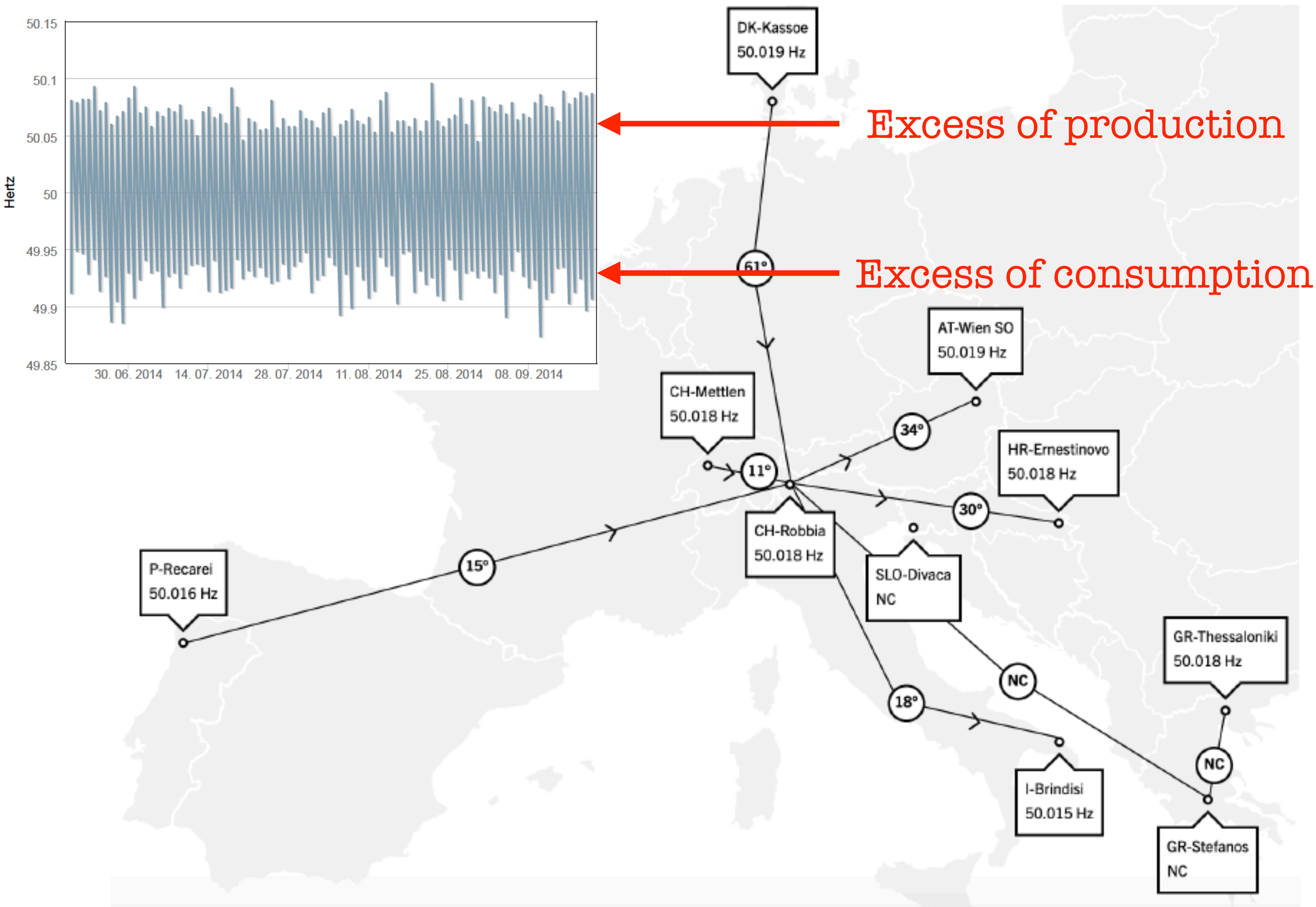

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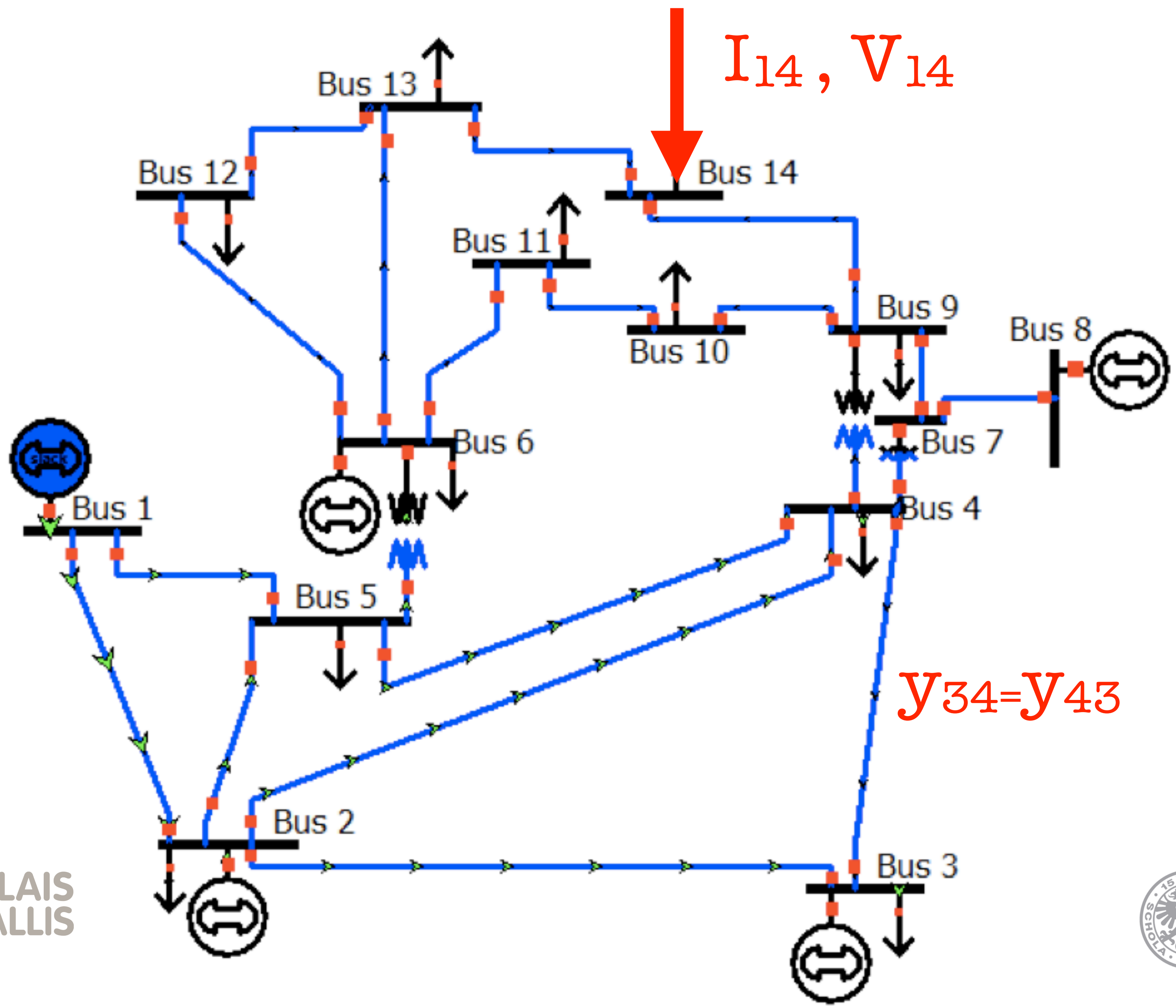
Operating steady-state of AC power grids

- Ohm's law $\boxed{I_i = \sum_j Y_{ij} V_j}$

I_i : current injected/collected at node i
V_i : voltage at node i
Y_{ij} : admittance matrix



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- Active power vs. reactive power

Active power	vs.	reactive power
P=Re(S)		Q=Im(S)
finite time-average		zero time-average
"transmitted power"		"oscillating in the circuit"
(injected and consumed)		

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Voltages at buses i and j

Conductance matrix

Voltage angles at buses i and j

Susceptance matrix

Approximated power flow equations : very high voltage

- Admittance dominated by its imaginary part
  for large conductors ~ high voltage
  G/B < 0.1 for 200kV and more

neglect conductance →

$$P_i \simeq \sum_j |V_i V_j| B_{ij} \sin(\theta_i - \theta_j)$$

$$Q_i \simeq -\sum_j |V_i V_j| B_{ij} \cos(\theta_i - \theta_j)$$

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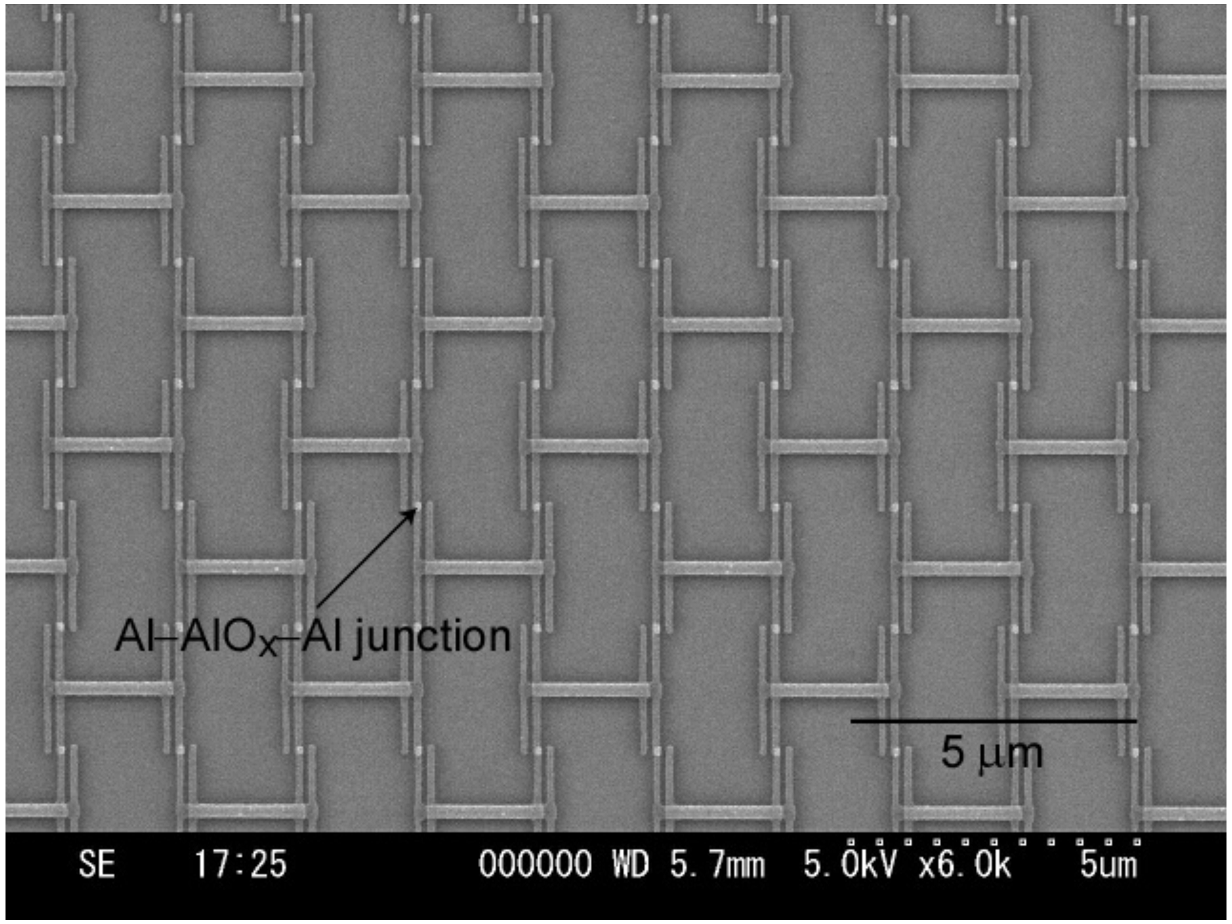
- No conductance ~no voltage drop

consider constant voltage

  * decoupling between P and Q
  * consider P only
    (a.k.a. lossless line approx.) →

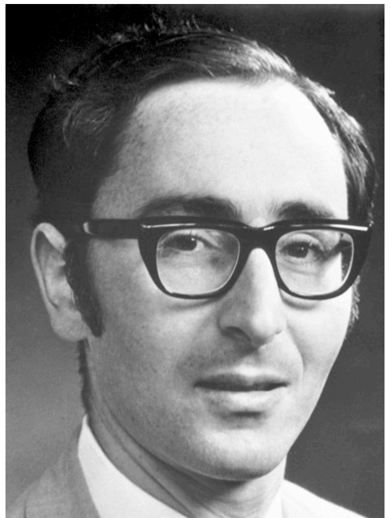
$$P_i = \sum_j B_{ij} \sin(\theta_i - \theta_j)$$

Synchronous fixed points vs. Josephson junctions



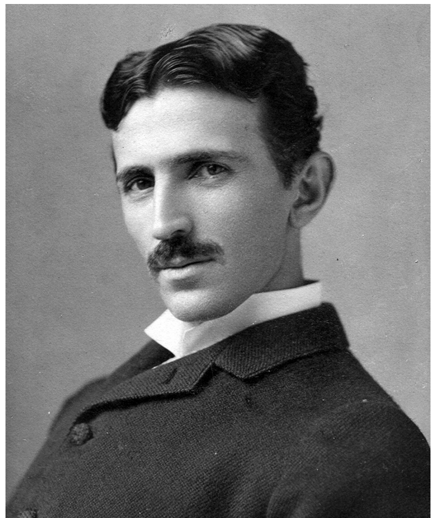
Josephson current

$$I_{ij} = I_c \sin(\theta_j - \theta_i)$$



High voltage
AC transmitted power

$$P_{ij} = B_{ij} \sin(\theta_i - \theta_j)$$



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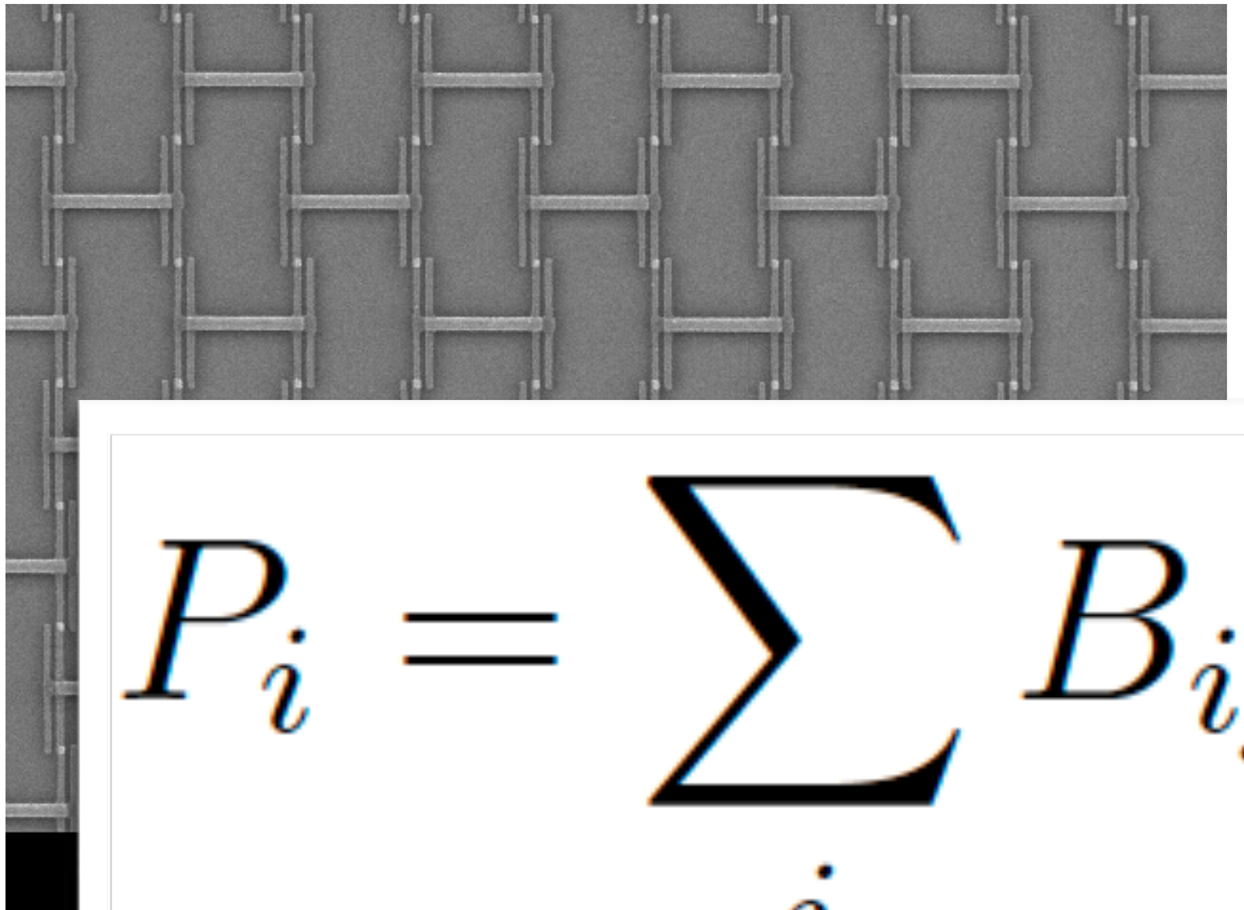

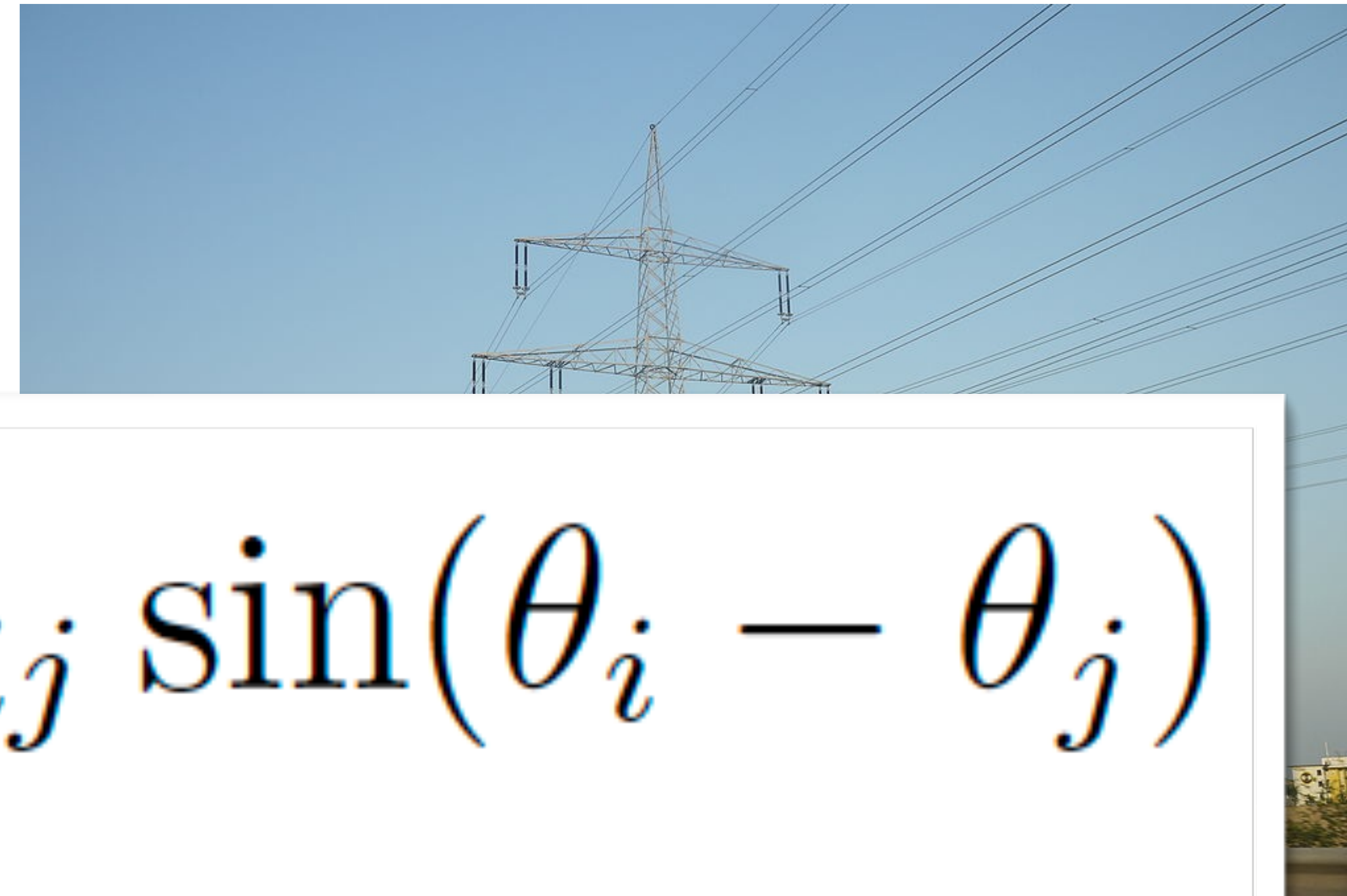

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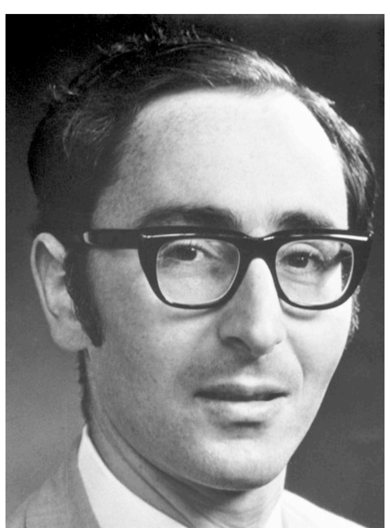

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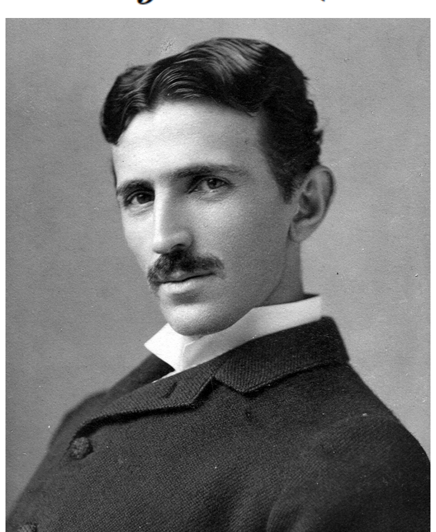
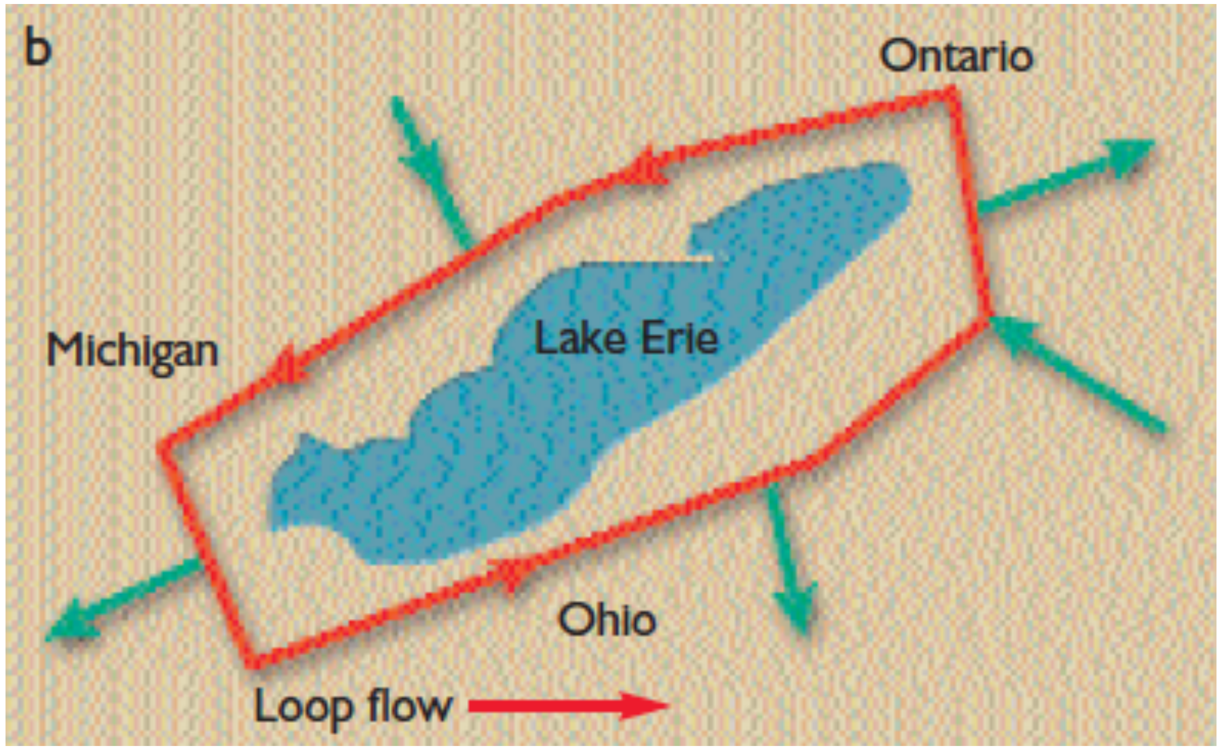


Circulating loop flows



"Where the network jogs around large geographical obstacles, such as the Rocky Mountains in the West or the Great Lakes in the East, loop flows around the obstacle are set up that can drive as much as 1 GW of power in a circle, taking up transmission line capacity without delivering power to consumers."

Casazza, Electrical World (1998)
Lerner, The industrial physicist (2003)

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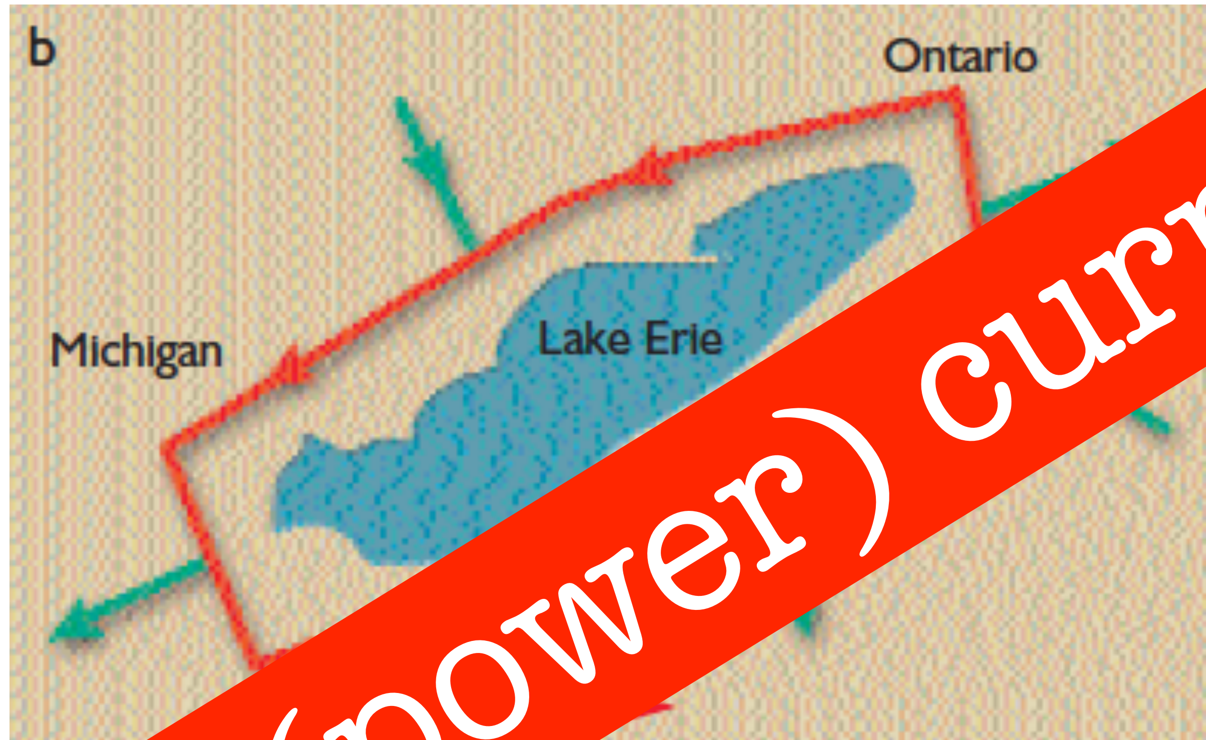

Persistent (power) current ?

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Circulating loop flows

* Thm: Different solutions to the simplified power-flow problem

$$P_i = \sum_j B_{ij} \sin(\theta_i - \theta_j)$$

may differ only by circulating loop current(s) **in any network**

Dörfler, Chertkov, Bullo, PNAS ’13; Delabays, Coletta and PJ, JMP ’16

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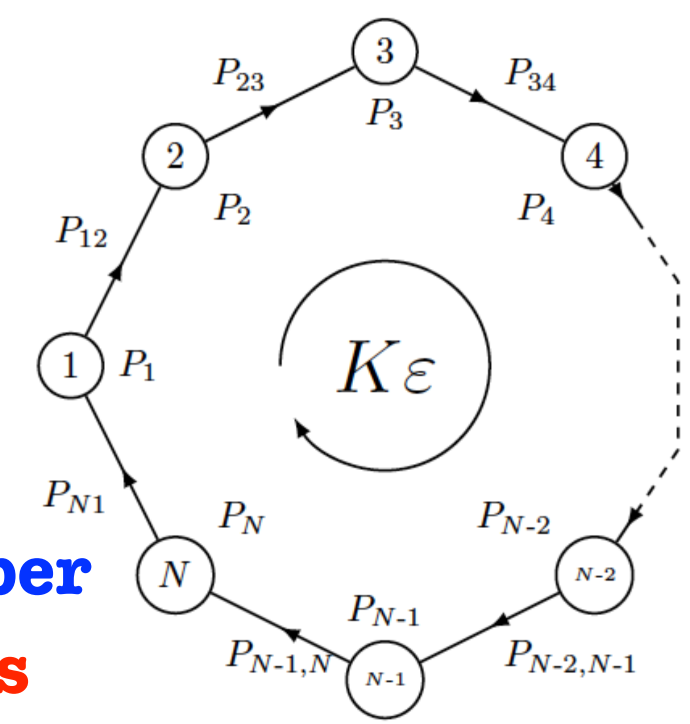

*Voltage angle $V_i = |V_i| e^{i\theta_i}$ uniquely defined

→ $q = \Sigma_i |\theta_{i+1} - \theta_i|_{2\pi} / 2\pi \in \mathbb{Z}$ **~topological winding number**

→ discretization of these loop currents **~vortex flows**

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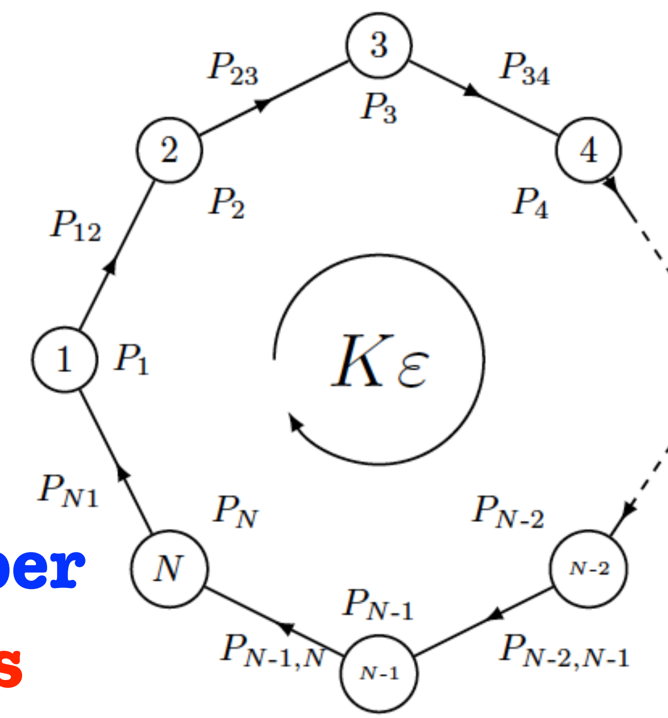

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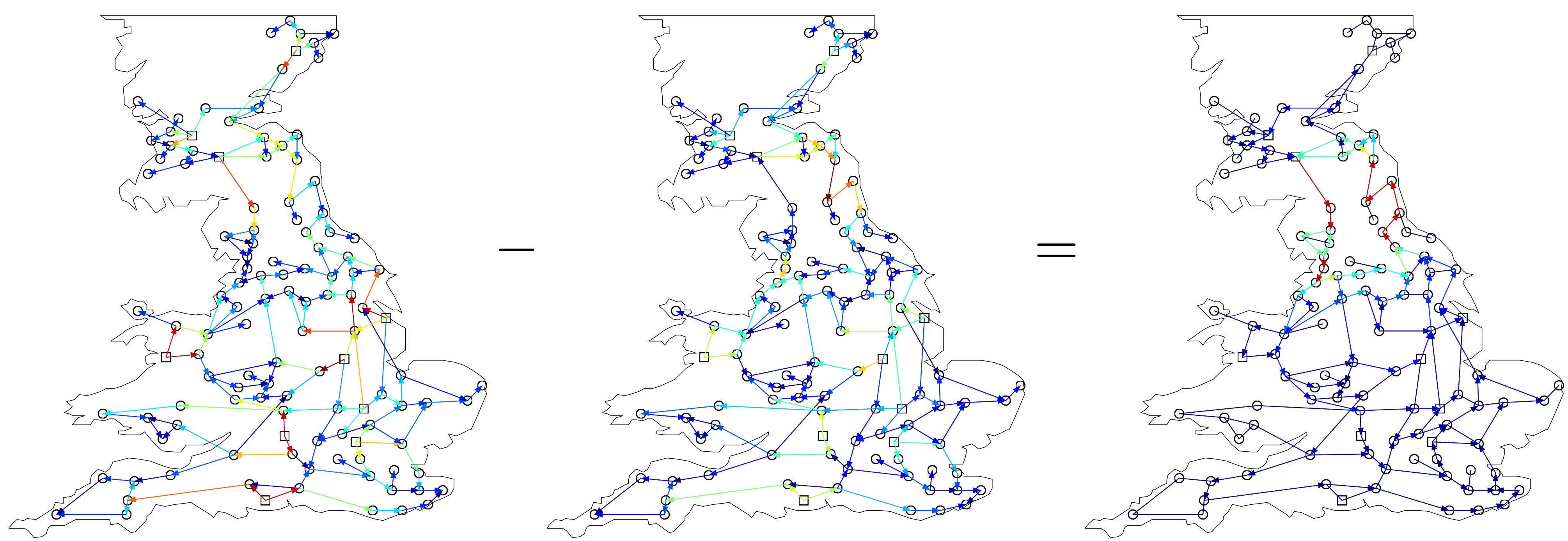

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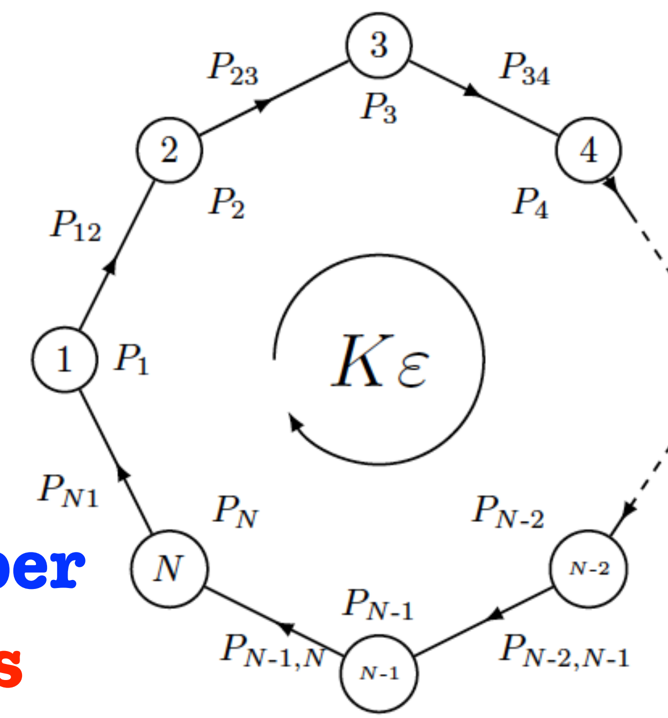

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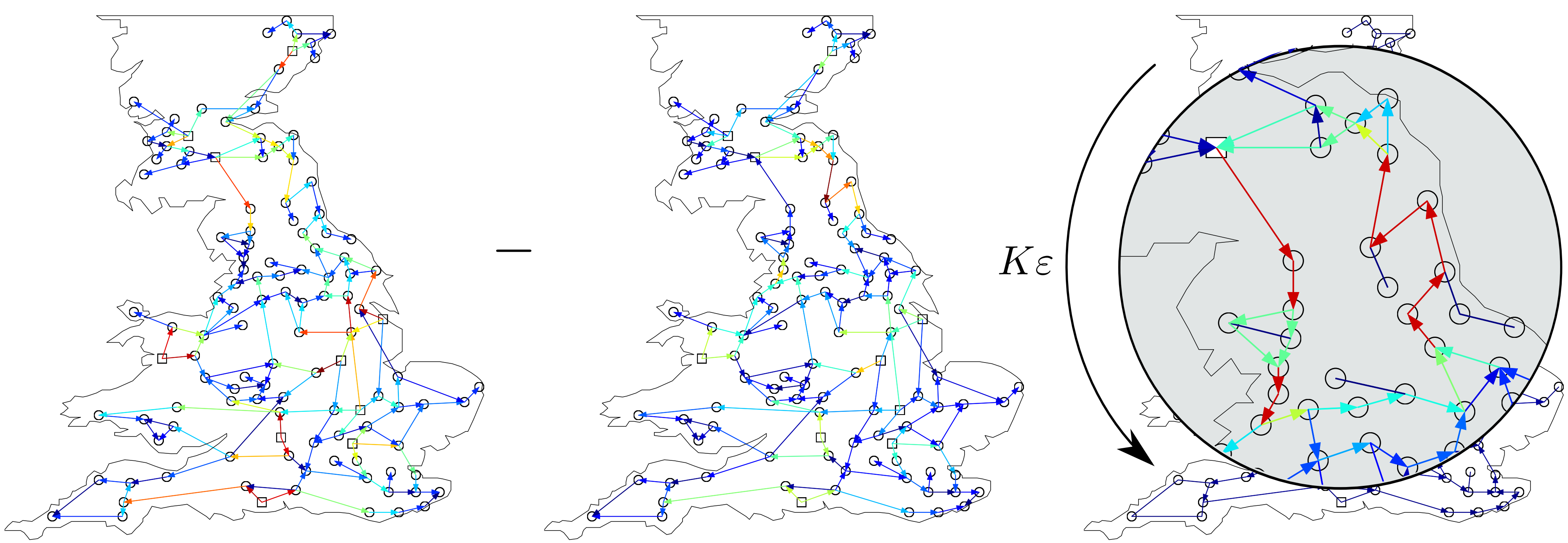

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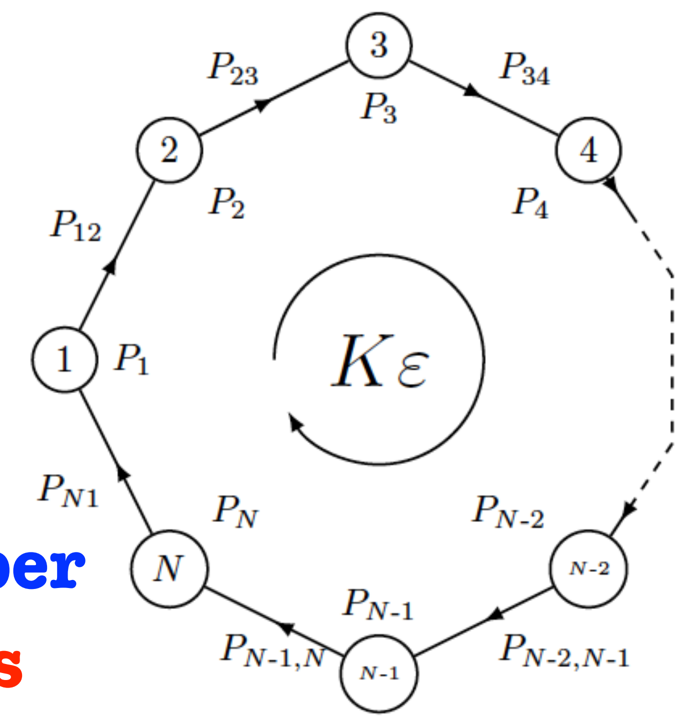

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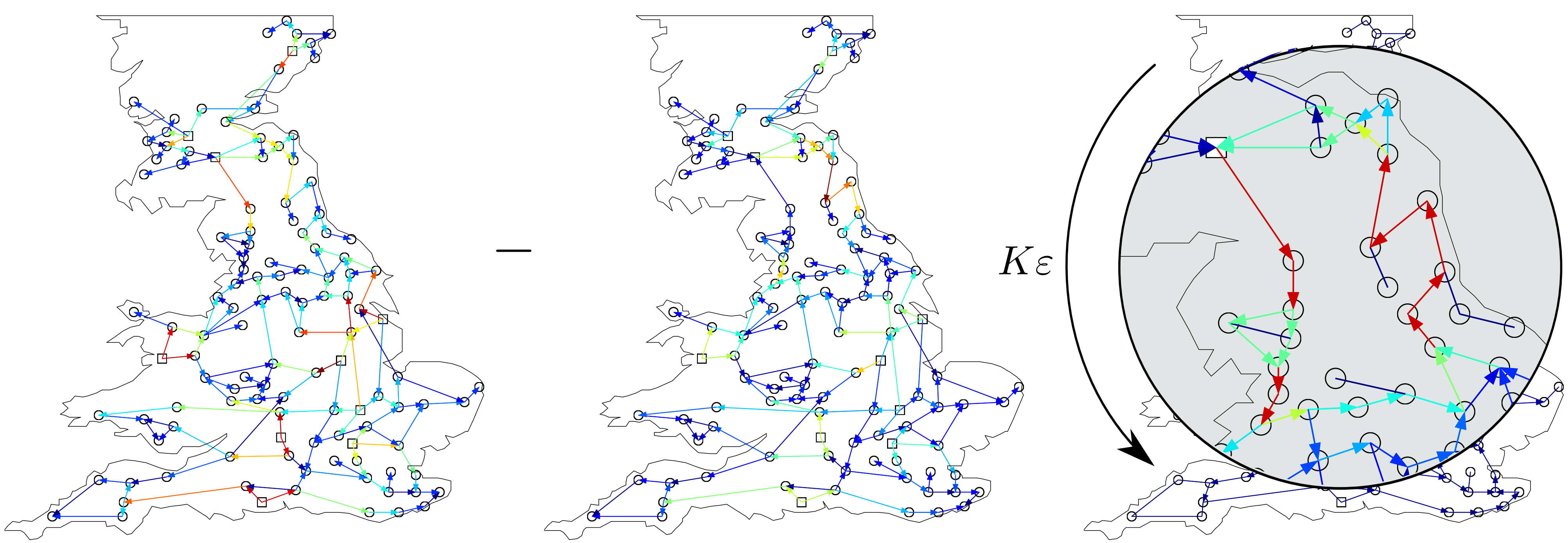

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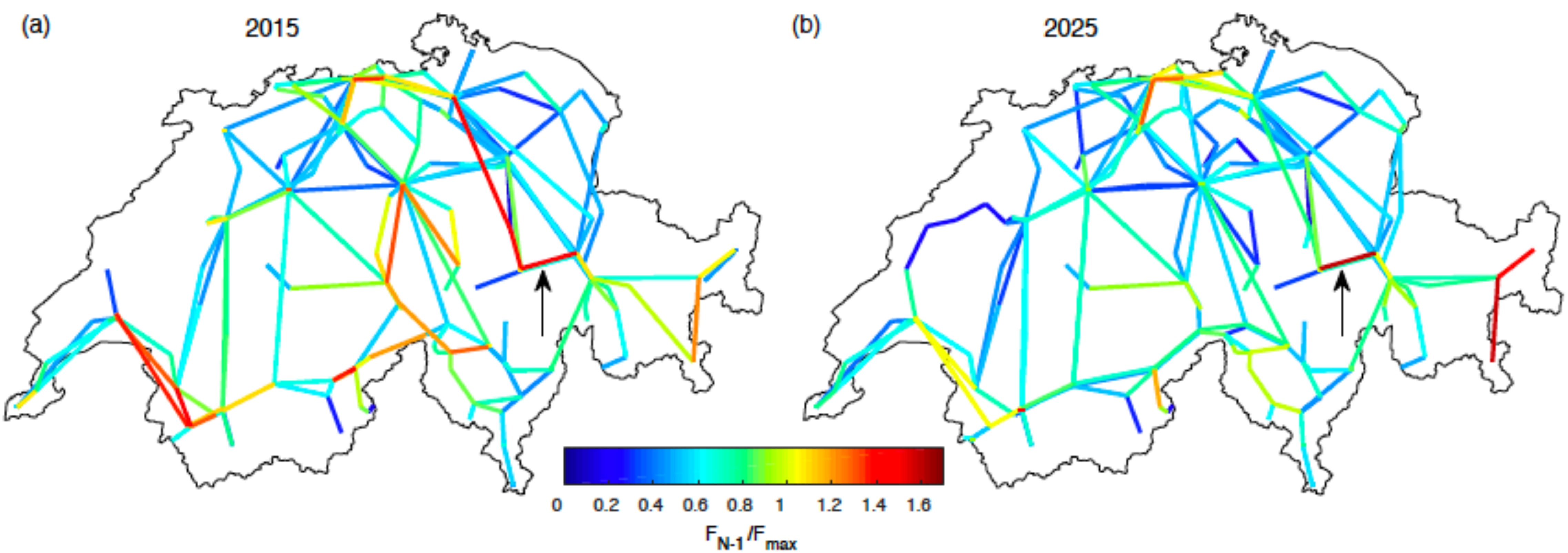
They are used for :

(i) planning future expansions/upgrade



- www.swissgrid.ch/en/home/projects/strategic-grid.html
- L Pagnier and PJ, “Swissgrid's strategic grid 2025 : an independent analysis”

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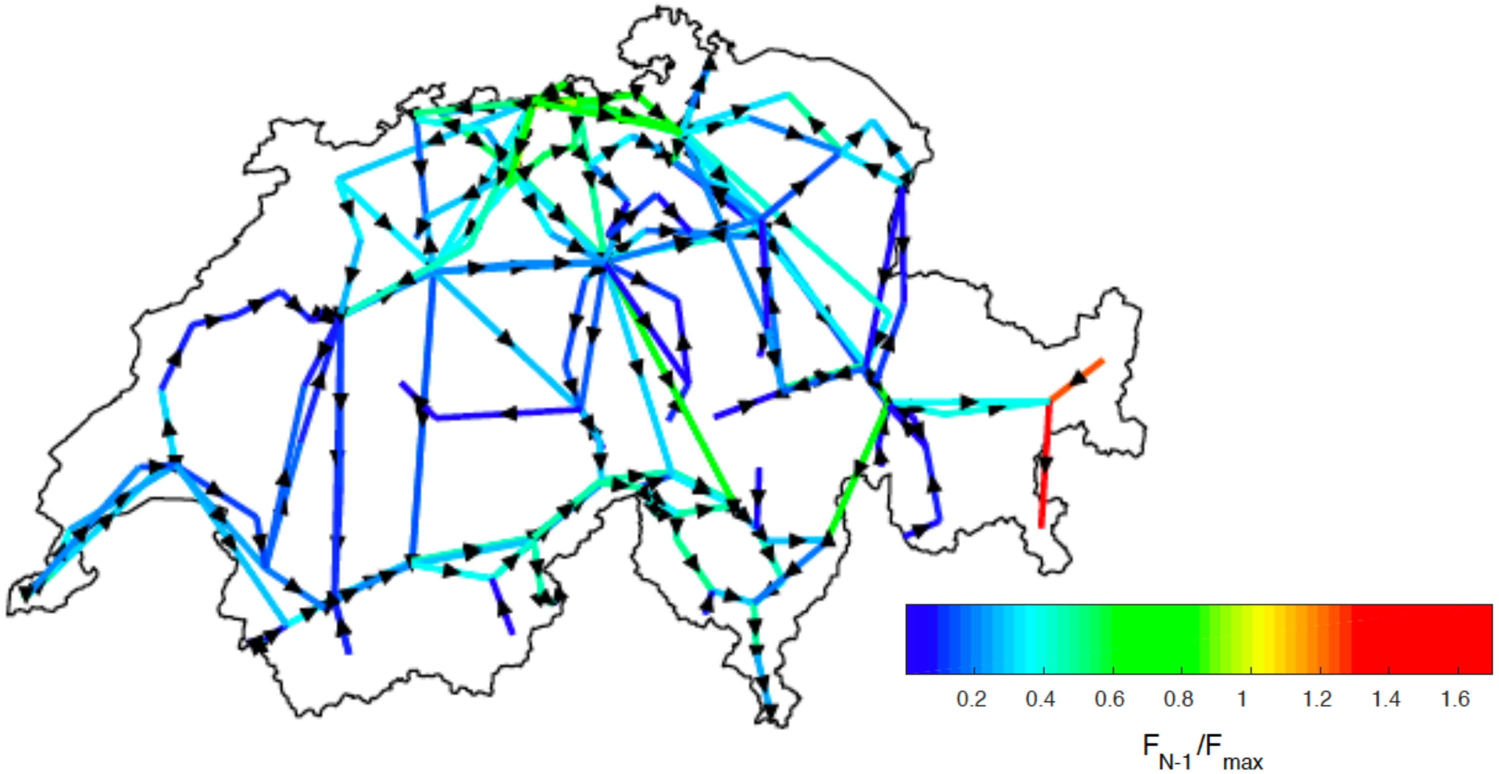
They are used for :

(ii) running the existing system as well as possible

- is the current state of the grid problematic ?
- can it tolerate one fault (N-1 assessment) ?
- is the scheduled state (say in 5 mins) problematic ?



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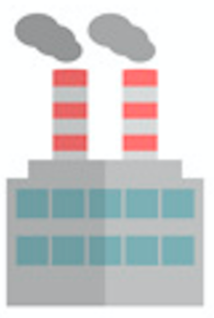
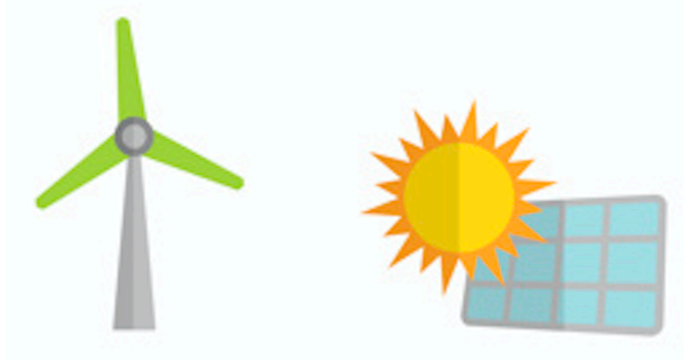
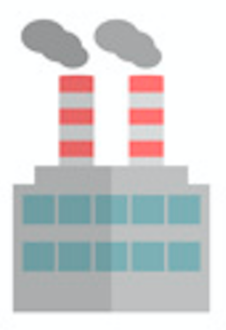
Today’s vs. tomorrow’s power grids

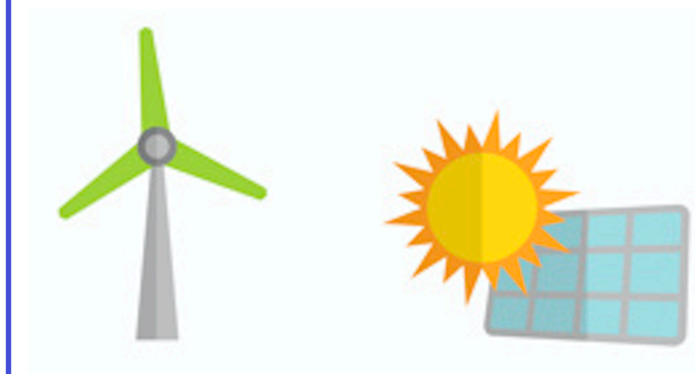




Today’s vs. tomorrow’s power grids

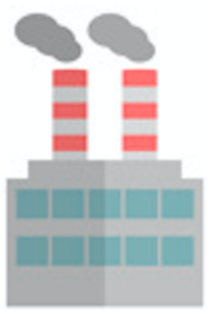


- Centralized



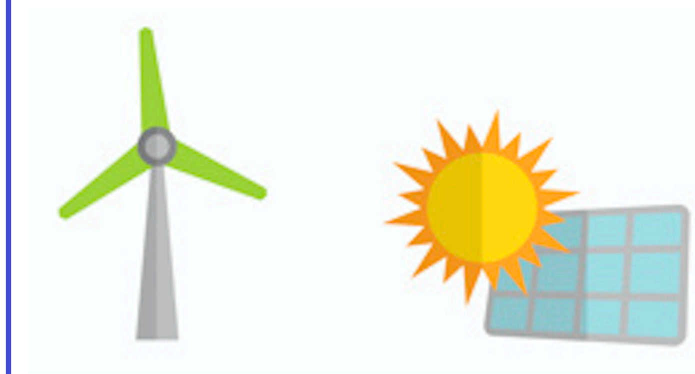
- Decentralized
  - -issues at distribution level
  - -easier at transmission level (=reduction in load)

Today’s vs. tomorrow’s power grids



- Centralized

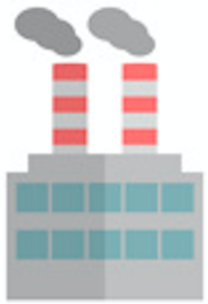
- Dispatchable/predictable



- Decentralized
  - -issues at distribution level
  - -easier at transmission level (=reduction in load)

- Uncertain
  - -power / energy reserve

Today's s



• Centr

• Dispa

Aaron Rupar
@atrupar
Suivre

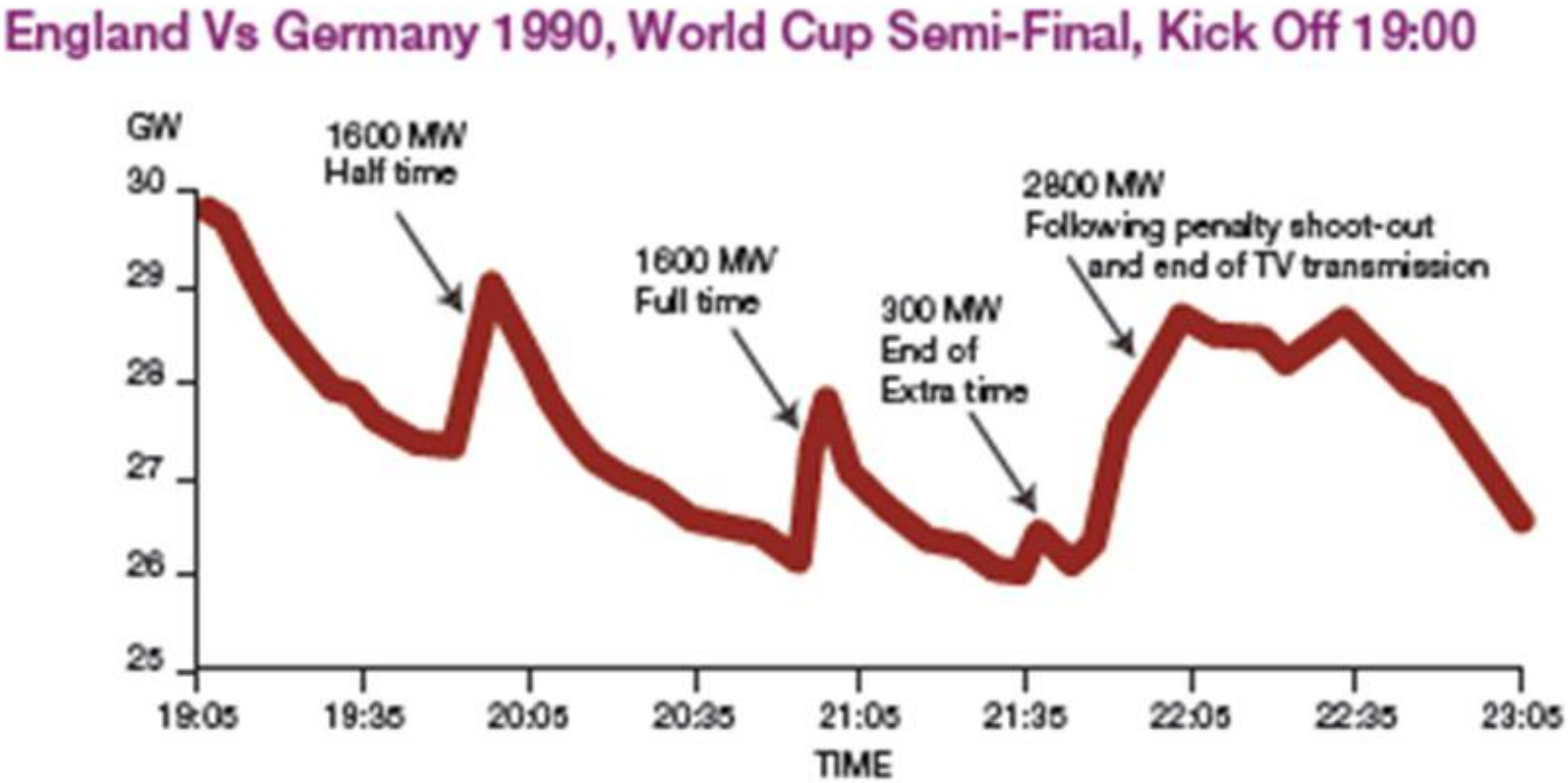
TRUMP: "If Hillary got in... you'd be doing wind. Windmills. Weeeee. And if it doesn't blow, you can forget about television for that night. 'Darling, I want to watch television.' 'I'm sorry! The wind isn't blowing.' I know a lot about wind."

Traduire le Tweet

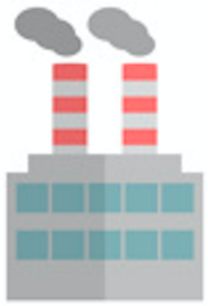
n level
on level

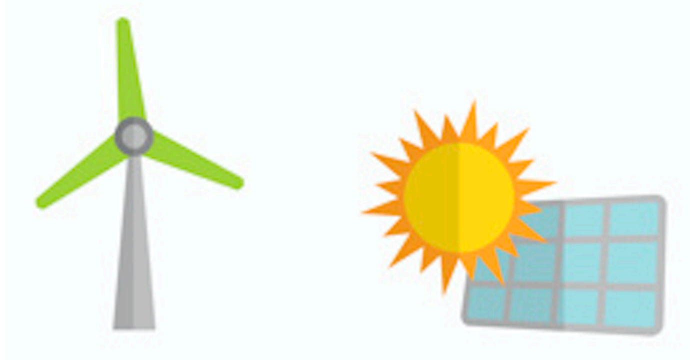
erve

Variability and uncertainty are nothing new for grid operators



Old vs. new productions

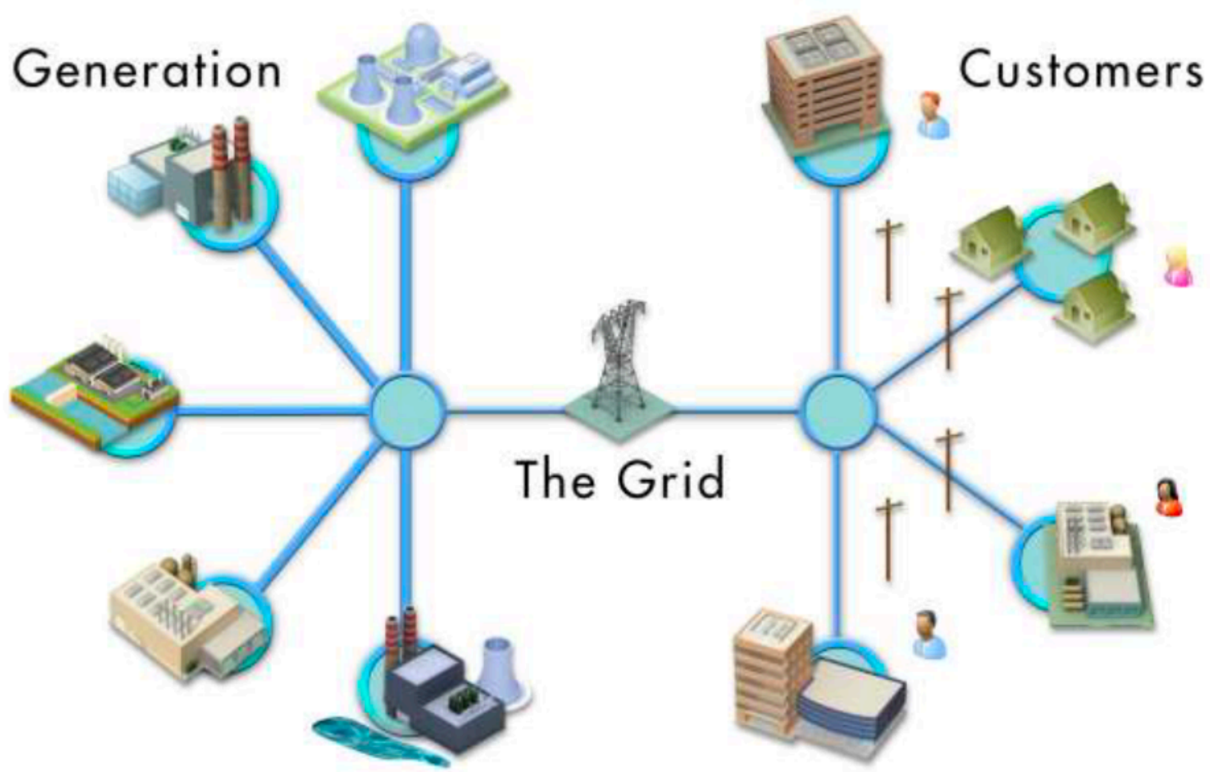


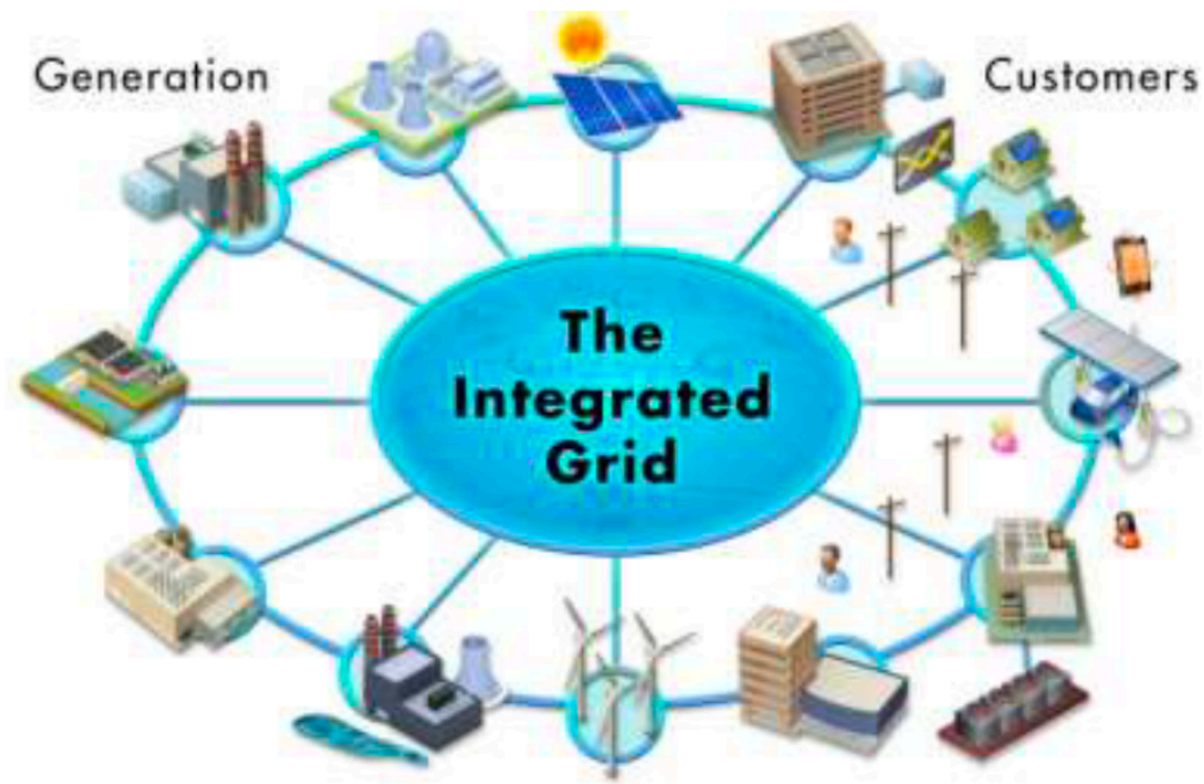


- Rotating machine with inertia
  - -frequency definition
  - -grid stability :
    - * energy reserve
    - * droop control

- No or much less inertia (inverter-connected)

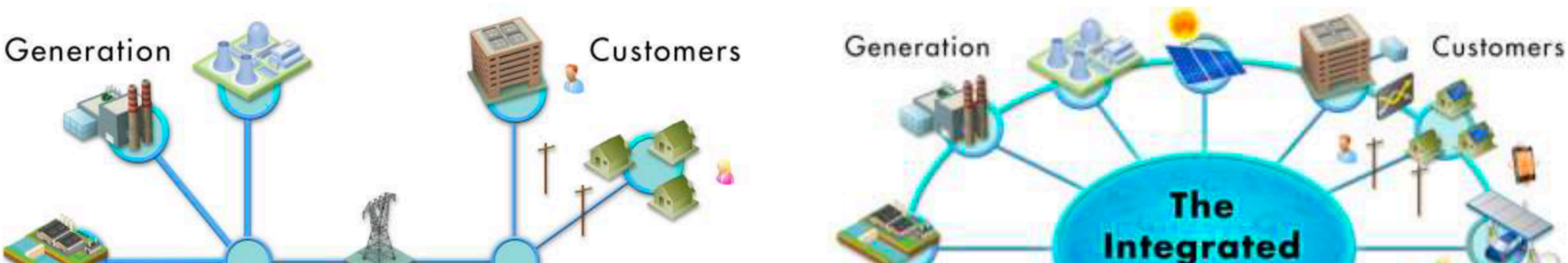
Today's vs. tomorrow's electric power systems





Tomorrow's grid will be : -less dispatchable
-less forecastable
-more dynamic (less inertia)
-bi-directional
-based on power electronics

Today’s vs. tomorrow’s electric power systems



?? Would substituting traditional plants with new renewables jeopardize grid stability ??

Tomorrow’s grid will be : -less dispatchable
-less forecastable
-more dynamic (less inertia)
-bi-directional
-based on power electronics

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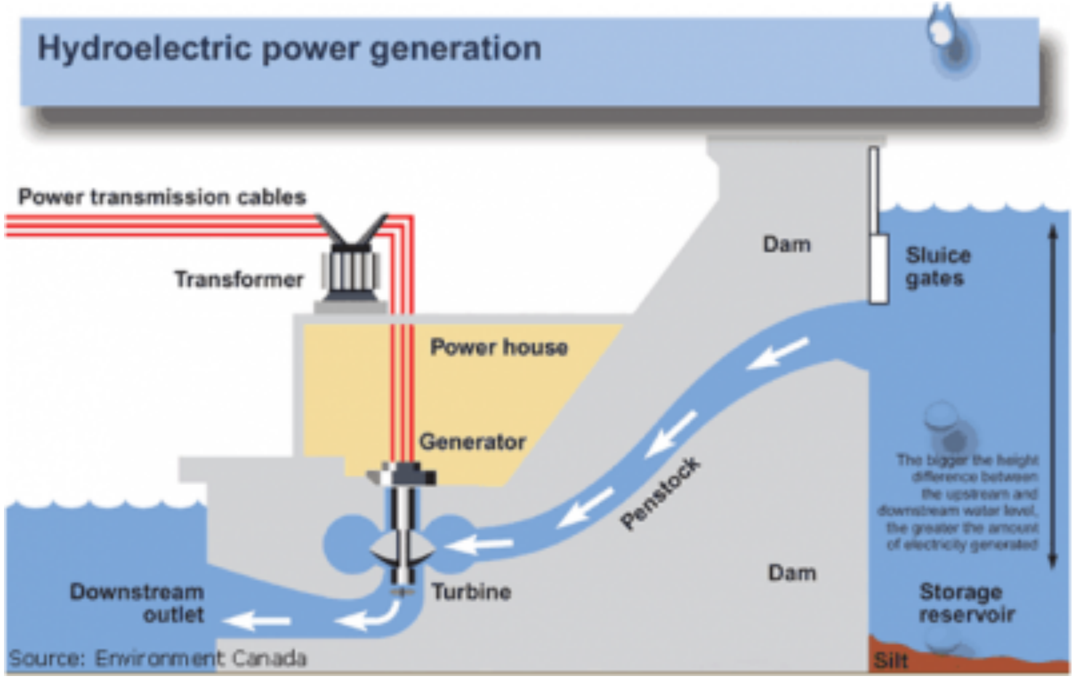
Outline

- Electric power systems - past and present
- Operating steady-state : power flow equations
- Electric power systems - future
- Power system dynamics : swing equations

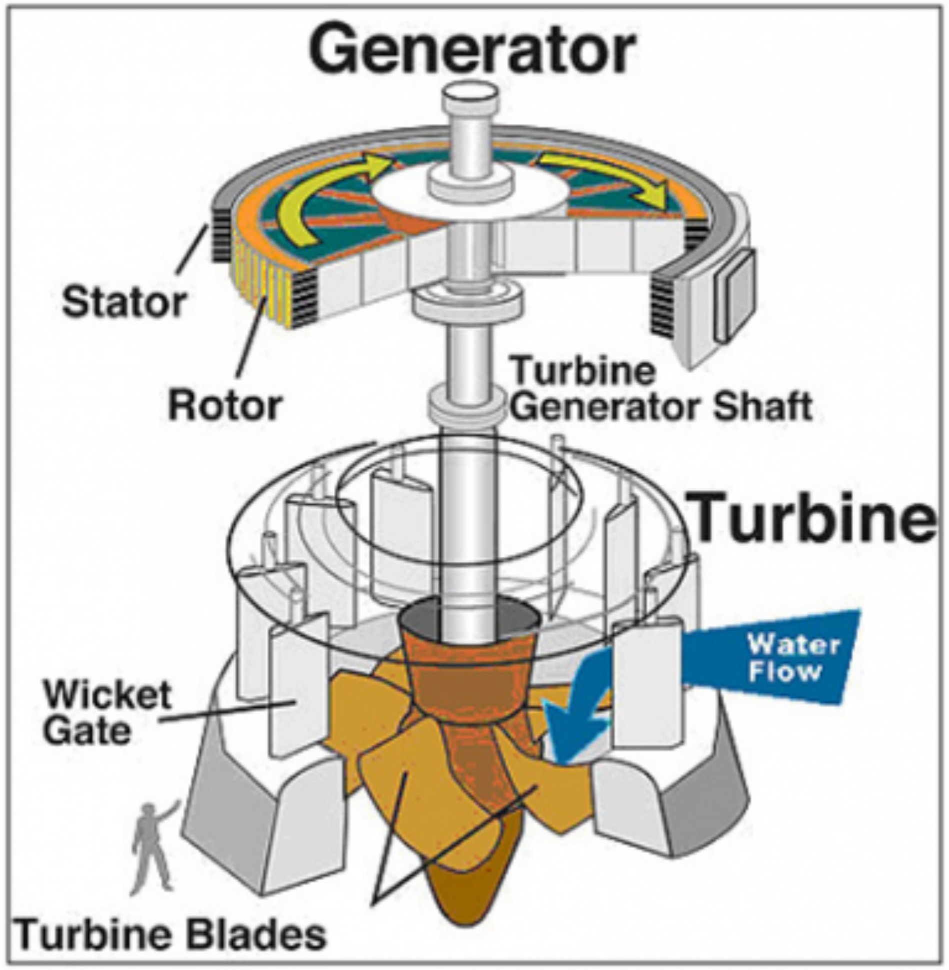
  frequency wave propagation

  optimal placement of inertia+control

Dynamics of AC power grids



- Electricity production with rotating machines
- Potential, chemical, nuclear or thermal energy converted into mechanical energy (rotation)
- Mechanical energy converted into electric energy
- Time-dependence : think power instead of energy
- Balance between power in, power out and energy change in rotator : **SWING EQUATIONS**



Dynamics of AC power grids

Dynamics: Swing Equations.

- from few AC cycles to ~30 secs.
- In rotating frame @ 50/60 Hz

$$I_i\ddot{\theta} + D_i\dot{\theta}_i = P_i - \sum B_{ij}\sin(\theta_i - \theta_j)$$

Bergen and Hill, 1981

- I : inertia ~ rot. kinetic energy
- D : damping from primary control + frequency-dependence of loads

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- A.k.a. second-order Kuramoto model ~model for synchronization

$$\frac{d\theta_i}{dt} = P_i - \sum_j K_{ij}\sin(\theta_j - \theta_i)$$

C Huygens 1629-1695

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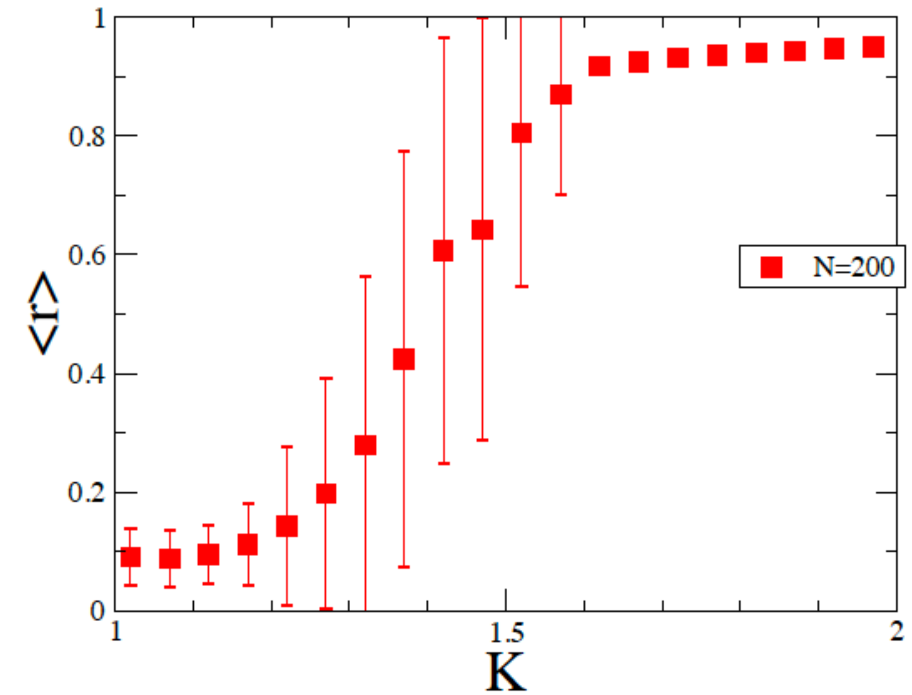
- Winfree '67
- Kuramoto '84 :

  mfa + introduce order parameter

$$r(t) = \left|\frac{1}{N}\sum_j \exp[i\theta_j(t)]\right| = |r(t)|\exp[i\Psi(t)]$$

K>K$_c$=4/π ~stable synchronous fixed point



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- Coupling between power balance and frequency

Change in kinetic energy = balance of power

Dynamics: Swing Equations.

- from few AC cycles to ~30 secs.
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- I : inertia ~ rot. kinetic energy
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Change in kinetic energy = balance of power

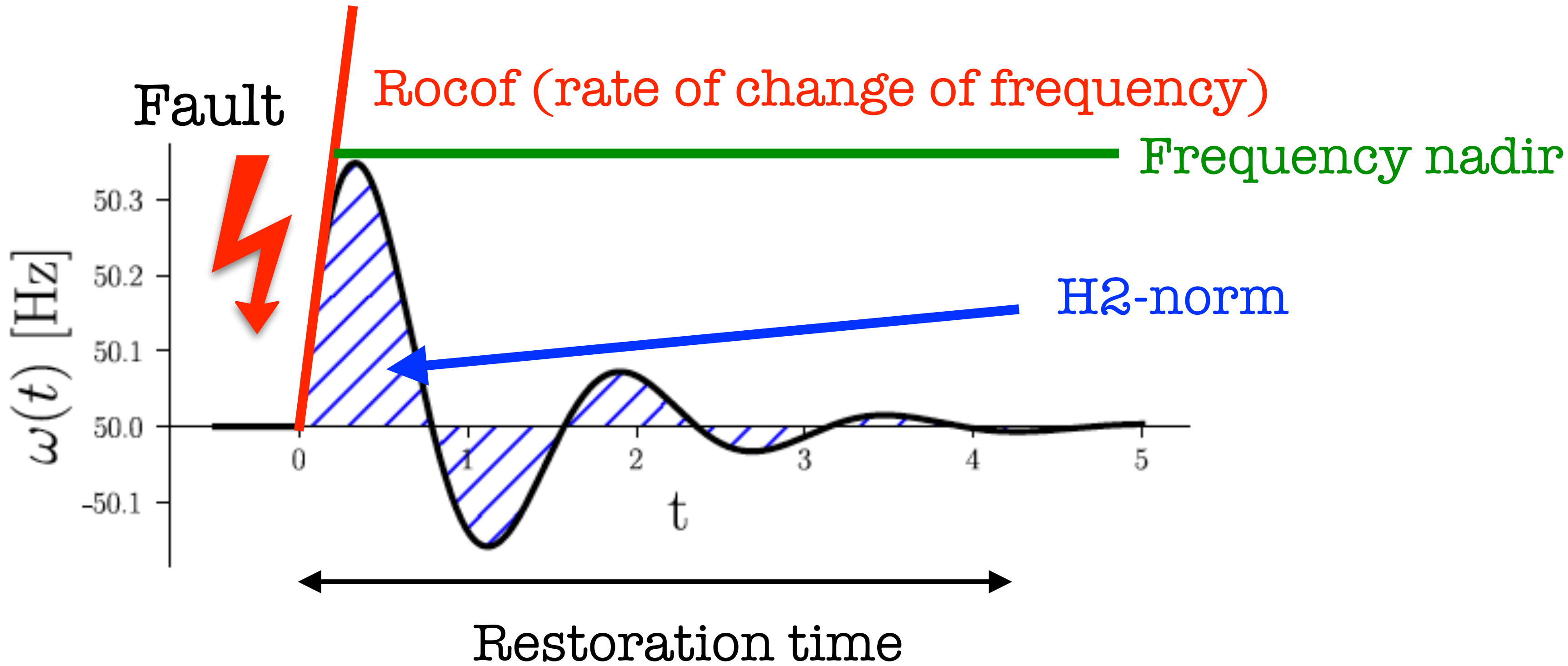
Dynamics of AC power grids

Dynamics: Swing Equations.

- from few AC cycles to ~10-20 secs.
- In rotating frame @ 50/60 Hz

$$I_i\ddot{\theta} + D_i\dot{\theta}_i = P_i - \sum B_{ij}\sin(\theta_i - \theta_j)$$

- I : inertia ~ rot. kinetic energy
- D : damping from primary control



- Frequency transient as indicator of fault magnitude
- Frequency fluctuations need to be minimized… but how ?

The questions of interest - and some answers

1. Is the power grid globally robust against disturbances ?
2. Is the power grid robust against specific, targeted disturbances ?
3. What specific disturbance(s) would lead to the worst response of the grid ?
4. Where should these specific disturbances act to lead to the worst response ?

Global robustness vs. local vulnerabilities

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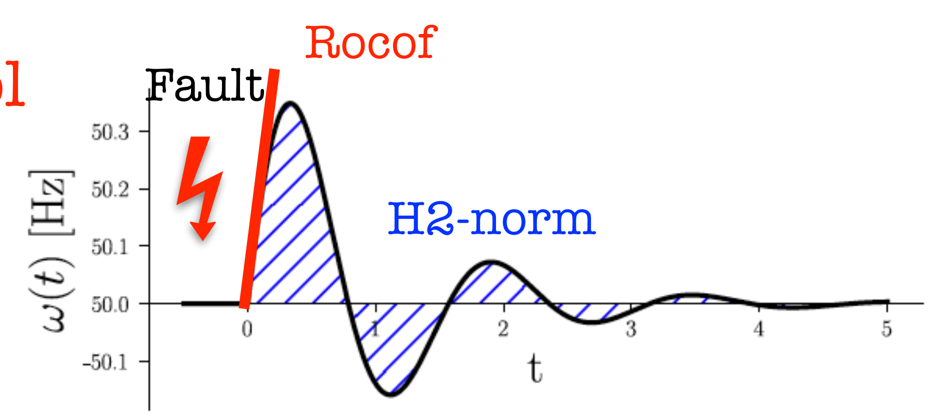
Global robustness vs. local vulnerabilities

1) Global robustness vs. graph topological indices
   Tyloo, Coletta and PJ, PRL ‘18
2) Local vulnerabilities vs. network centralities
   Tyloo, Pagnier and PJ, Science Adv. ’19; Tyloo and PJ, PRE ’19
3) Disturbances vs. line faults
   Coletta and PJ, IEEE TCNS ‘19
4) Disturbance propagation vs. Network eigenmodes
   Pagnier and PJ, PLoS ONE ’19
5) Optimal placement of inertia and primary control
   Pagnier and PJ, IEEE Access ‘19



Outline

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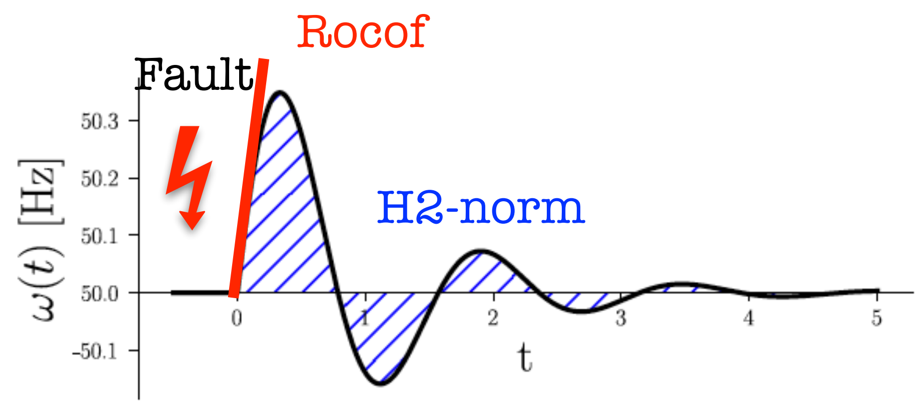
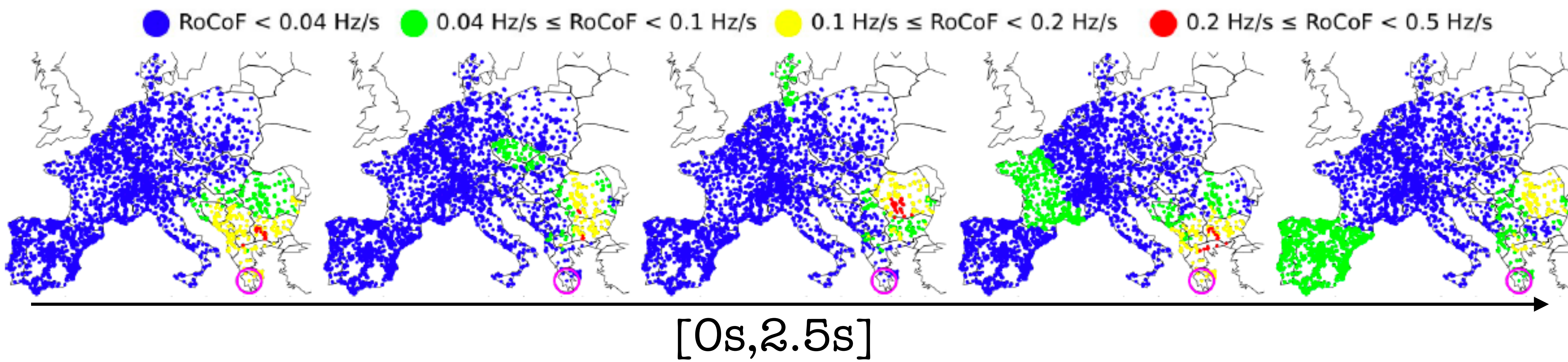
Frequency wave propagation

Fault : sudden power loss

$$P_b = P_b^{(0)} - \Delta P$$





L. Pagnier & PJ, PLoS ONE ‘19

Frequency wave propagation

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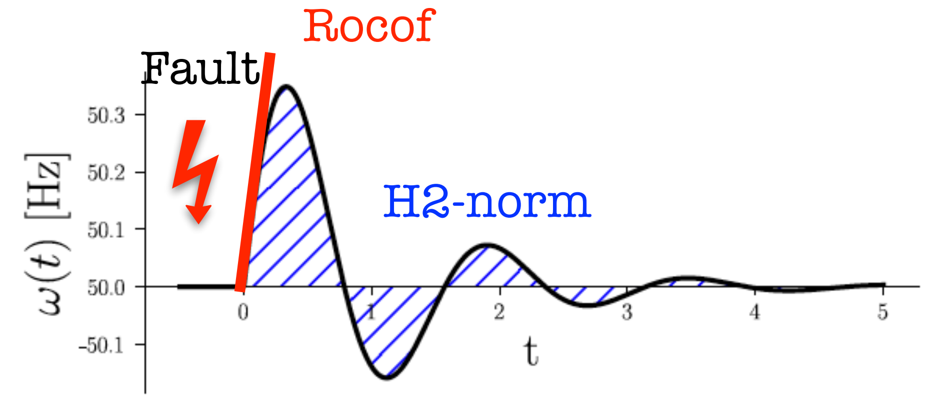

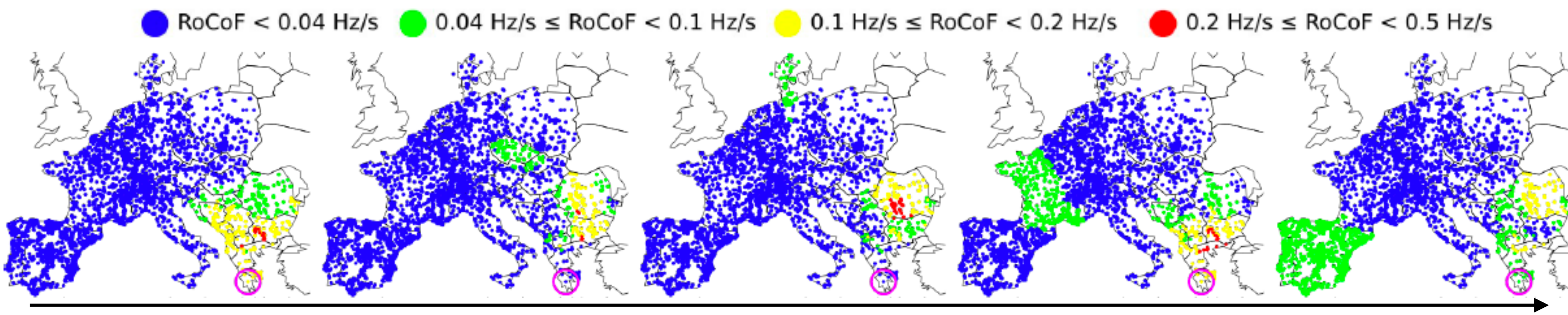

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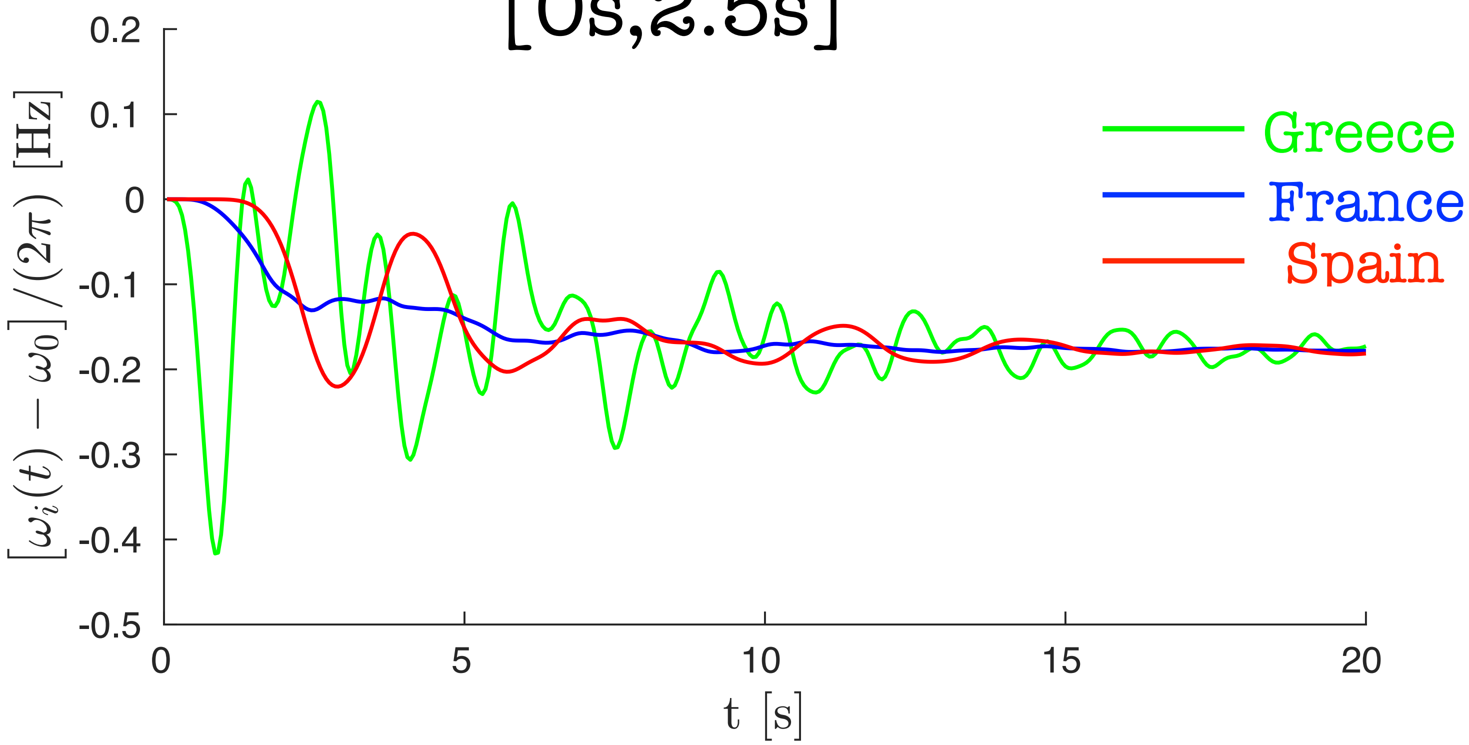

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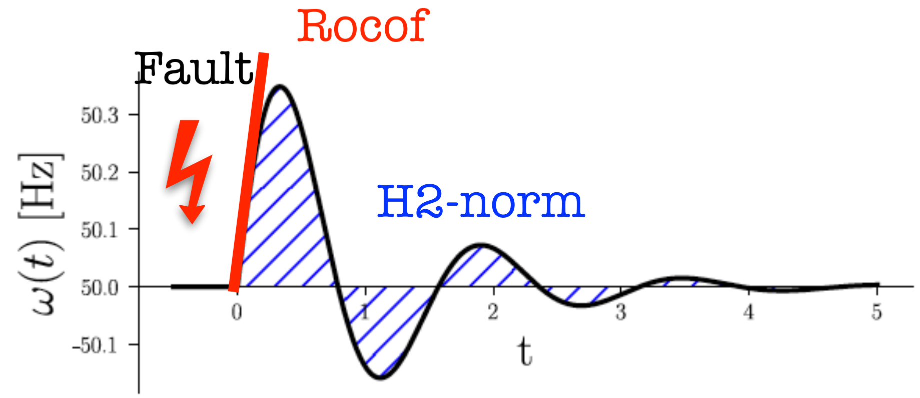
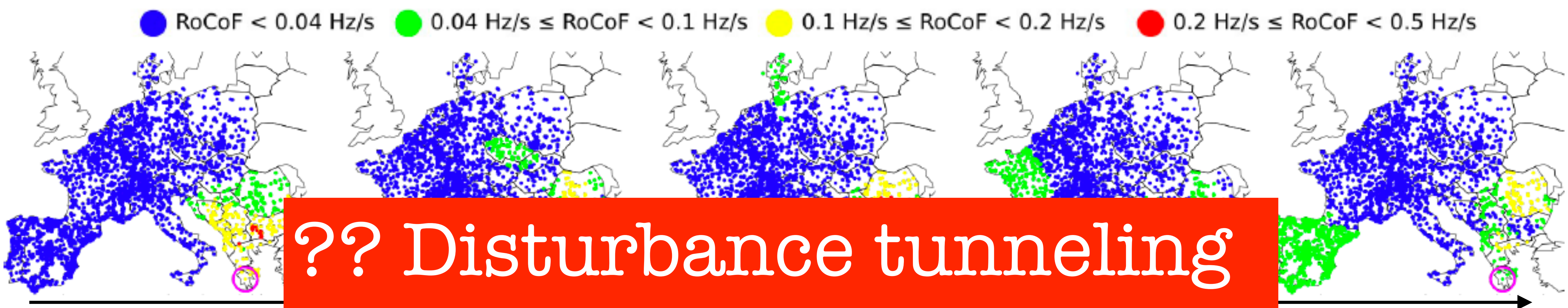
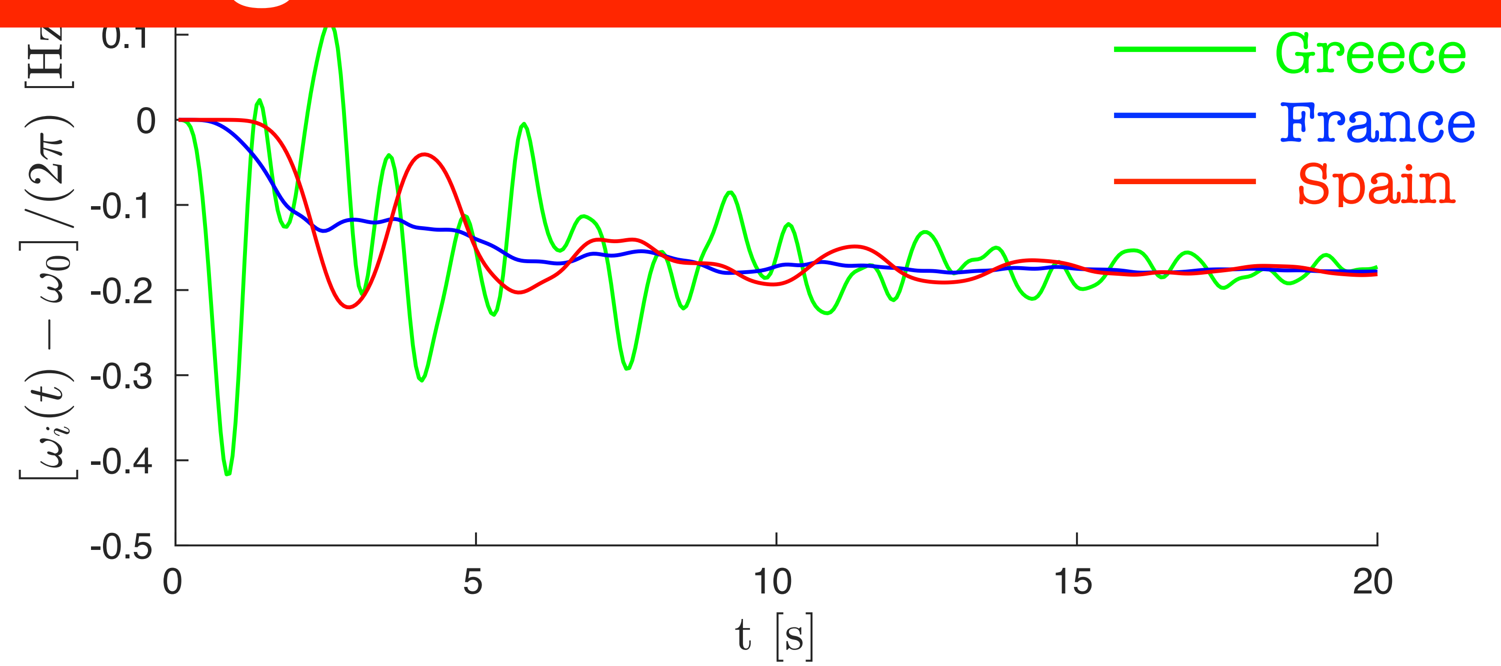




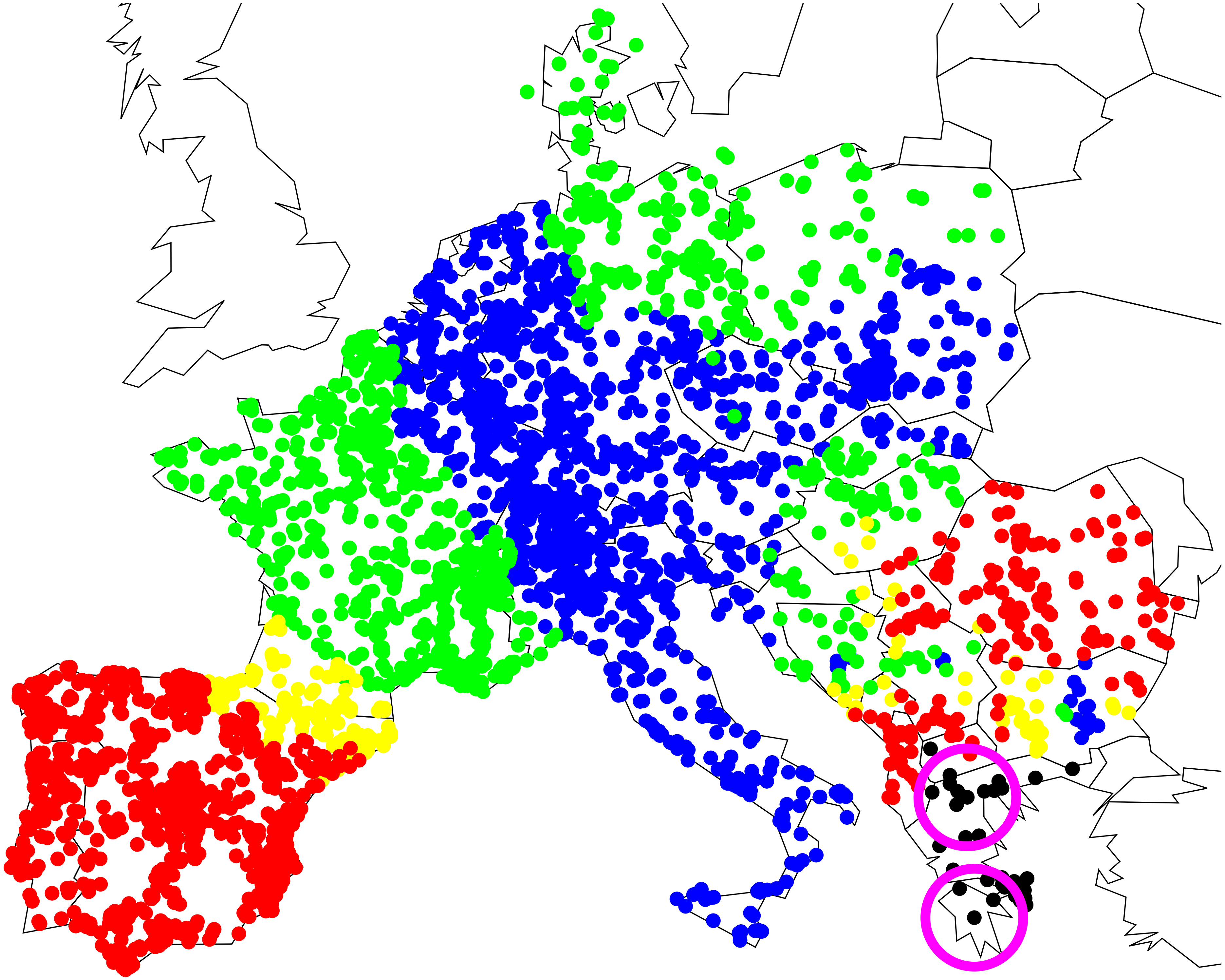
?? Disturbance tunneling through France ??



L. Pagnier & PJ, PLoS ONE '19

Frequency wave propagation

RoCoF < 0.04 Hz/s
0.04 Hz/s ≤ RoCoF < 0.1 Hz/s
0.1 Hz/s ≤ RoCoF < 0.2 Hz/s
0.2 Hz/s ≤ RoCoF < 0.5 Hz/s
0.5 Hz/s ≤ RoCoF < 1 Hz/s



Frequency wave propagation vs. slow modes

Linearization of perturbation next to operating steady-state

$$\boldsymbol{M}\boldsymbol{\delta}\ddot{\boldsymbol{\theta}} + \boldsymbol{D}\boldsymbol{\delta}\dot{\boldsymbol{\theta}} + \boldsymbol{L}\boldsymbol{\delta}\boldsymbol{\theta} = \boldsymbol{\delta}\boldsymbol{P}$$

L. Pagnier & PJ, PLoS ONE '19

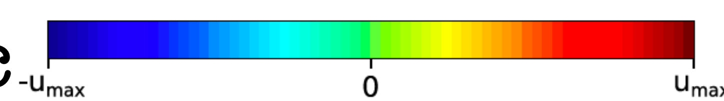
Frequency wave propagation vs. slow modes

Linearization of perturbation next to operating steady-state

$$M\delta\ddot{\theta} + D\delta\dot{\theta} + L\delta\theta = \delta P$$

Two slowest, nonzero modes of the Laplacian matrix

n=2 antisymmetric



n=3 symmetric

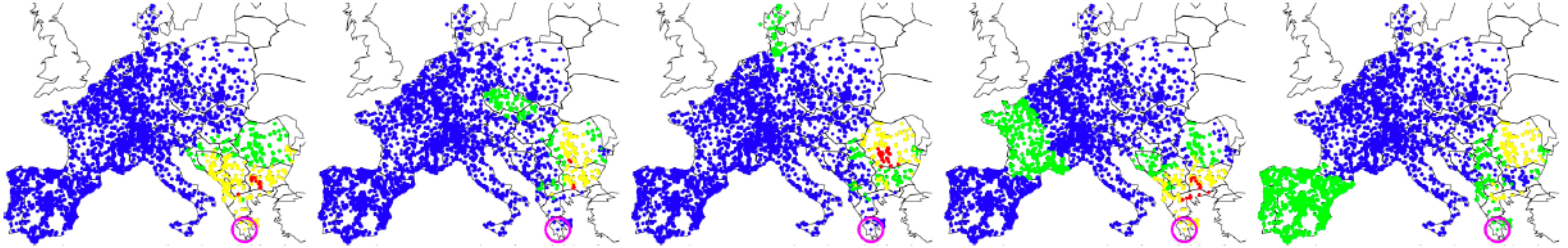
...with the corresponding eigenvalues rather close

~double-well potential vs. inter-area oscillations ?

L. Pagnier & PJ, PLoS ONE '19

Frequency wave propagation vs. inertia

Today's Europe



L. Pagnier & PJ, PLoS ONE '19

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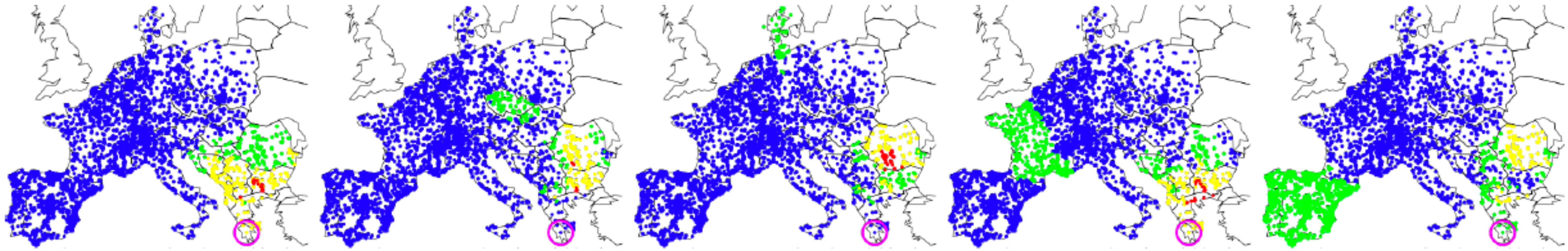
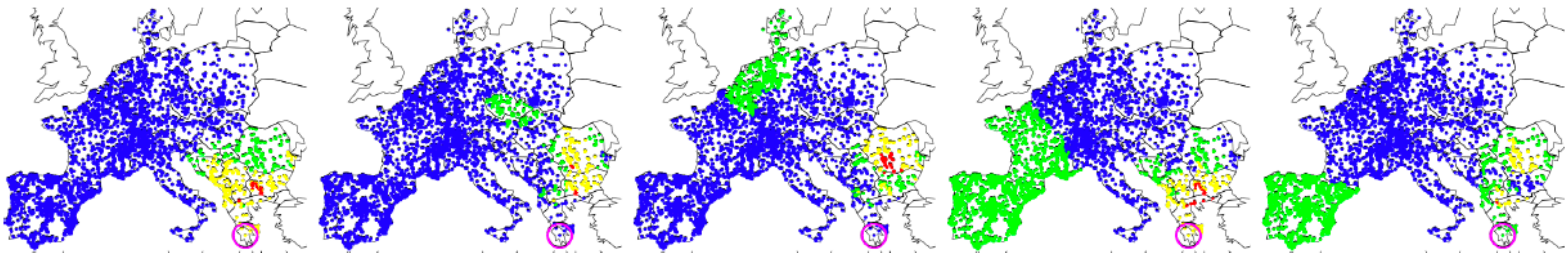


Inertia in France reduced to 50%



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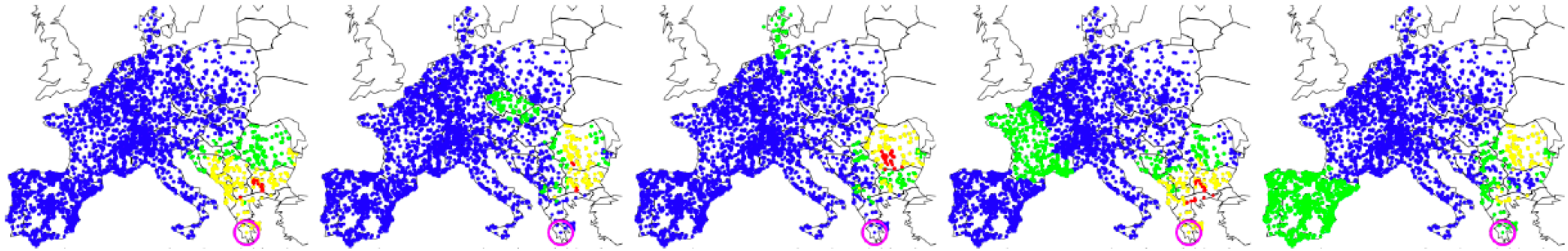

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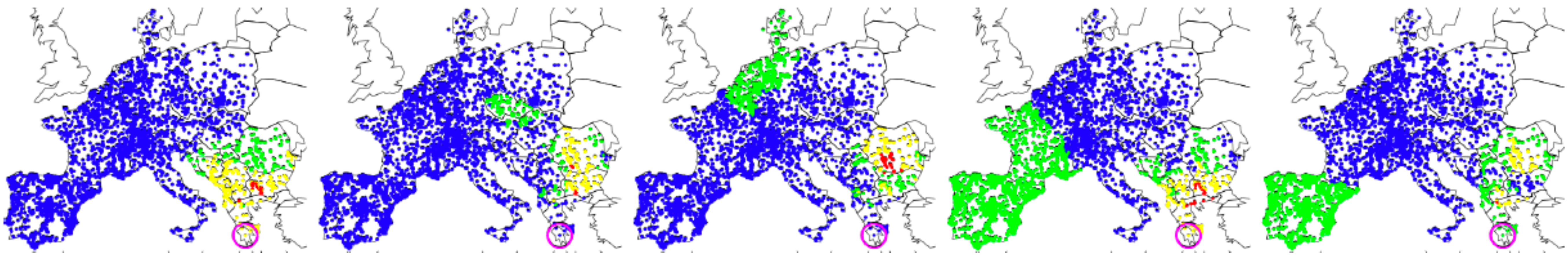
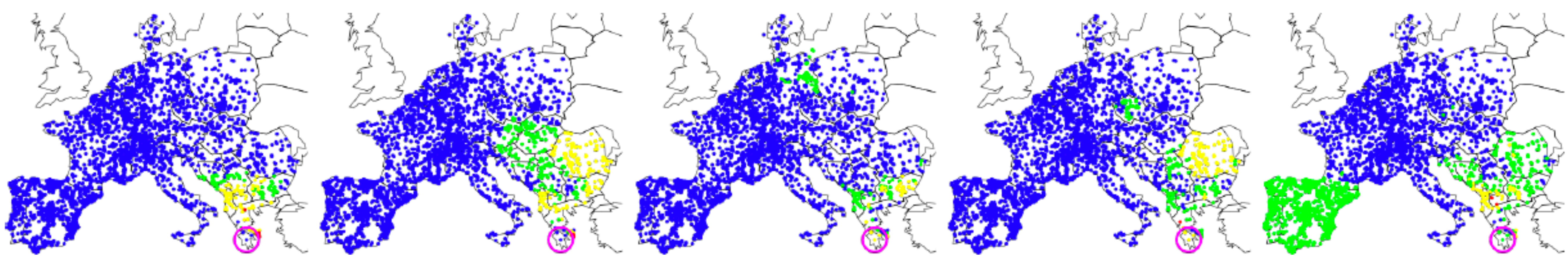


Inertia in Balkans doubled



L. Pagnier & PJ, PLoS ONE '19

Frequency wave propagation vs. inertia

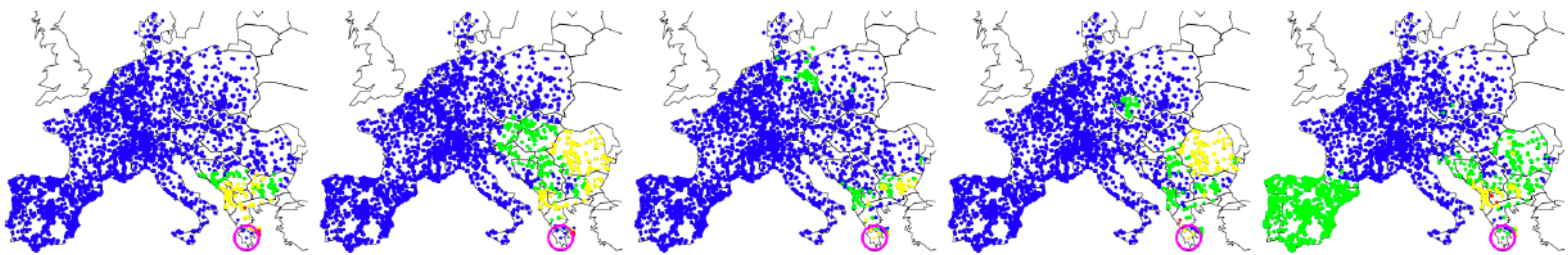
Today’s Europe

Inertia in

Inertia matters mostly :

* locally
* at short times (t<1s)

Inertia in Balkans doubled



L. Pagnier & PJ, PLoS ONE ‘19

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Optimal placement of inertia and primary control

Our approach : cast the problem into a perturbative-minimization problem

Optimal placement of inertia and primary control

Our approach : cast the problem into a perturbative-minimization problem

- Starting point : when can one diagonalize the swing eqs. ? (linearized about steady-state)

(Paganini and Mallada '17)

$$\boxed{\boldsymbol{M}\dot{\boldsymbol{\omega}} + \boldsymbol{D}\boldsymbol{\omega} = \boldsymbol{\delta P} - \boldsymbol{L}\boldsymbol{\delta\theta}}$$

$$\boldsymbol{M} = \mathrm{diag}(\{m_i\})$$
$$\boldsymbol{D} = \mathrm{diag}(\{d_i\})$$

$$\boxed{\boldsymbol{\delta\theta} = \boldsymbol{M}^{-1/2}\boldsymbol{\delta\theta}_M}$$

$$\boxed{\dot{\boldsymbol{\omega}}_M + \underbrace{\boldsymbol{M}^{-1}\boldsymbol{D}}_{\boldsymbol{\Gamma}}\boldsymbol{\omega}_M + \underbrace{\boldsymbol{M}^{-1/2}\boldsymbol{L}\boldsymbol{M}^{-1/2}}_{\boldsymbol{L}_M}\boldsymbol{\delta\theta}_M = \boldsymbol{M}^{-1/2}\boldsymbol{\delta P}}$$

$$\boldsymbol{\Gamma} = \mathrm{diag}(\{d_i/m_i\})$$

Optimal placement of inertia and primary control

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When can this eq. be reduced to a set of scalar diff. eqs. ?

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$$M = \mathrm{diag}(\{m_i\})$$
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$$\boxed{\dot{\omega}_M + \underbrace{M^{-1}D}_{\Gamma}\,\omega_M + \underbrace{M^{-1/2}LM^{-1/2}}_{L_M}\,\delta\theta_M = M^{-1/2}\delta P}$$

$$\Gamma = \mathrm{diag}(\{d_i/m_i\})$$

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A. : when d_i/m_i=constant

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Optimal placement of inertia and primary control

- Deviation from homogeneity

$$m_i = m + \delta m \, r_i \, ,$$

$$d_i = m_i \gamma_i = (m + \delta m \, r_i)(\gamma + \delta\gamma \, a_i)$$

$$-1 \;\leq\; a_i, r_i \;\leq\; 1$$

Do perturbation theory with small parameters

$$\mu \equiv \delta m/m \ll 1$$

$$g \equiv \delta\gamma/\gamma \ll 1$$

Pagnier and PJ, to appear in IEEE Access '19

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Do perturbation theory with small parameters

$$\mu \equiv \delta m / m \ll 1$$
$$g \equiv \delta\gamma / \gamma \ll 1$$

- Perturbative performance measure - to be minimized

$$\mathcal{M}_b = \mathcal{M}_b^{(0)} + r_i \rho_i + a_i \alpha_i + \mathcal{O}(\delta m^2, \delta\gamma^2)$$

Pagnier and PJ, to appear in IEEE Access '19

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$$\mathcal{M}_b = \sum_{k=1}^{N_{\rm sim}} \sum_i \left| r_i(k\Delta t) \right|$$

"for loss of power at b, sum over RoCoF's at all sites and integrate over time"

Pagnier and PJ, to appear in IEEE Access '19

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$$\mathcal{M}_b = \mathcal{M}_b^{(0)} + r_i\rho_i + a_i\alpha_i + \mathcal{O}(\delta m^2, \delta\gamma^2)$$

with susceptibilities (this is what we calculate)

$$\rho_i \equiv \partial\mathcal{M}_b/\partial r_i \quad \alpha_i \equiv \partial\mathcal{M}_b/\partial a_i$$

Pagnier and PJ, to appear in IEEE Access ’19

Optimal placement of inertia and primary control

- Deviation from homogeneity

$$m_i = m + \delta m \, r_i \,,$$
$$d_i = m_i \gamma_i = (m + \delta m \, r_i)(\gamma + \delta\gamma \, a_i)$$
$$-1 \;\leq\; a_i, r_i \;\leq\; 1$$

Do perturbation theory with small parameters

$$\mu \equiv \delta m/m \ll 1$$
$$g \equiv \delta\gamma/\gamma \ll 1$$

- Perturbative performance measure - to be minimized

$$\mathcal{M}_b = \mathcal{M}_b^{(0)} + r_i \rho_i + a_i \alpha_i + \mathcal{O}(\delta m^2, \delta\gamma^2)$$

with susceptibilities (this is what we calculate)

$$\rho_i \equiv \partial \mathcal{M}_b / \partial r_i \quad \alpha_i \equiv \partial \mathcal{M}_b / \partial a_i$$

- Goal : determine optimal distribution of r_i and a_i with constraints

$$-1 \;\leq\; a_i, r_i \;\leq\; 1$$ Local reduction/increase

$$\sum_i r_i \;=\; \sum_i a_i \;=\; 0$$ Total limited resources

Pagnier and PJ, to appear in IEEE Access '19

Optimal placement of inertia and primary control

Inertia. : r_i =0
Wants to keep it homogeneous

$$m_i = m + \delta m \, r_i \, ,$$

$$d_i = m_i \gamma_i = (m + \delta m \, r_i)(\gamma + \delta\gamma \, a_i)$$

Pagnier and PJ, to appear in IEEE Access'19

Optimal placement of inertia and primary control

Inertia. : $r_i = 0$
Wants to keep it homogeneous

Damping/droop : $r_i = 1$ (blue) $r_i = -1$ (red)
Wants to put it at periphery
(vs. resistance distance centrality)

$$m_i = m + \delta m \, r_i \, ,$$

$$d_i = m_i \gamma_i = (m + \delta m \, r_i)(\gamma + \delta\gamma \, a_i)$$

Pagnier and PJ, to appear in IEEE Access'19

Optimal placement of inertia and primary control

The method can be extended :

1) to optimize about another solution
   - current European grid
   - future European grid (less inertia)

Pagnier and PJ, to appear in IEEE Access'19

Optimal placement of inertia and primary control

The method can be extended :

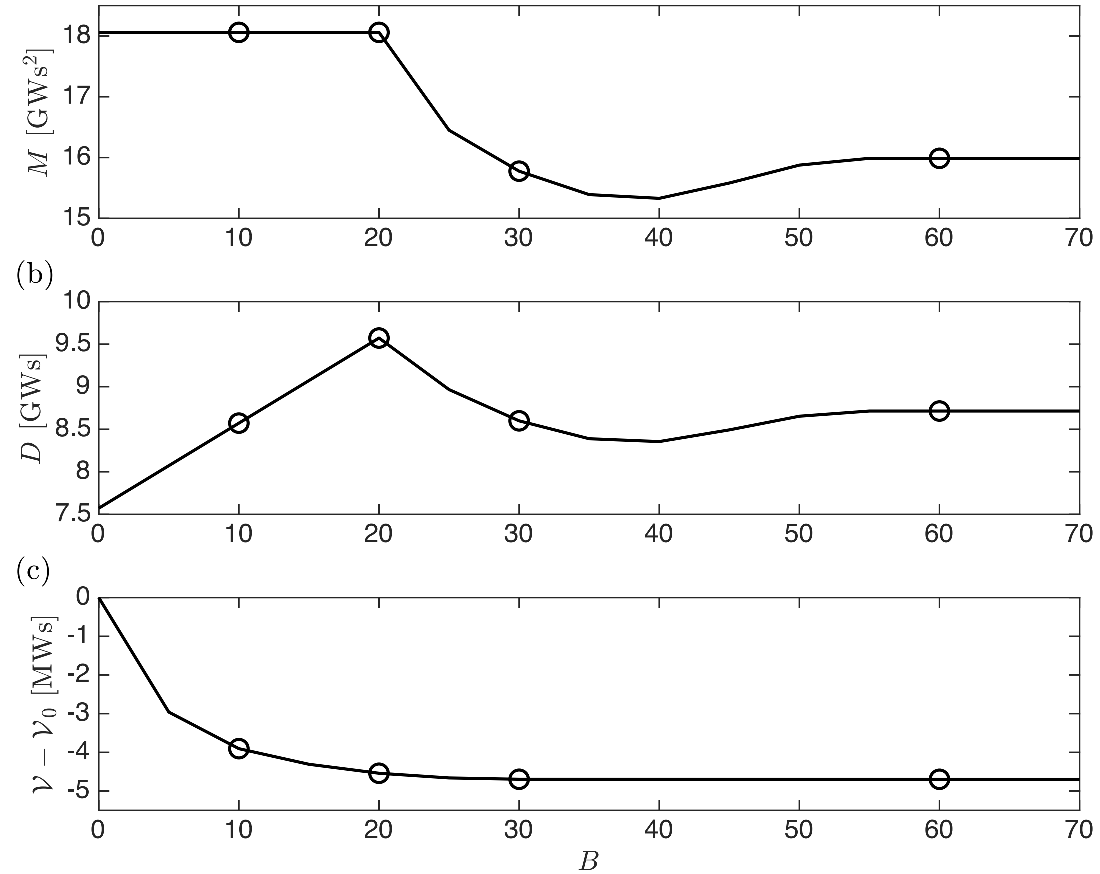
1) to optimize about another solution
   - -current European grid
   - -future European grid (less inertia)

2) to keep cost of upgrade within a given budget B (instead of constraint of constant total resources)

$$\sum_i \Big(c_i^{\mathrm{m}+}\,\delta m_i^+ + c_i^{\mathrm{d}+}\,\delta d_i^+ + c_i^{\mathrm{m}-}\,\delta m_i^- + c_i^{\mathrm{d}-}\,\delta d_i^- \Big) \le B$$

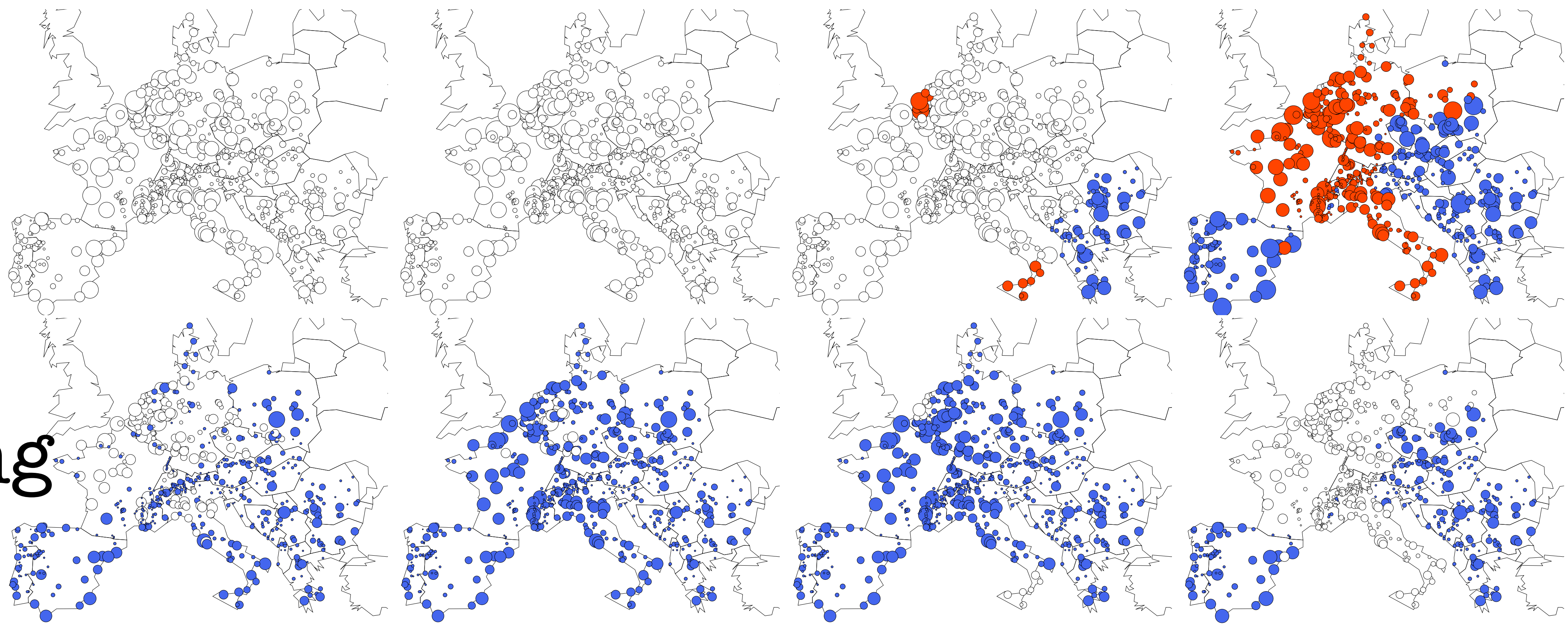
Pagnier and PJ, to appear in IEEE Access'19

Optimal placement of inertia and primary control

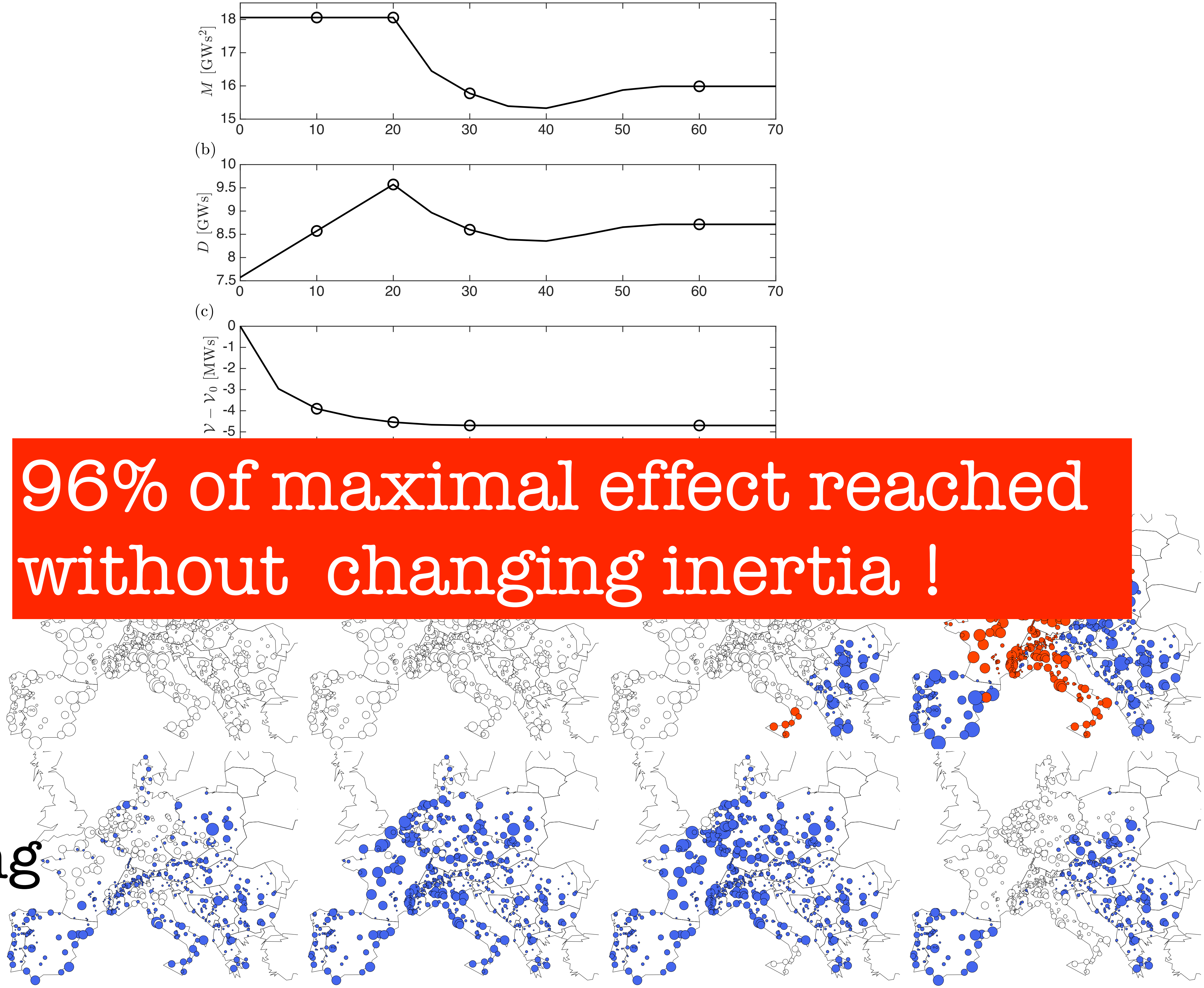


inertia

damping

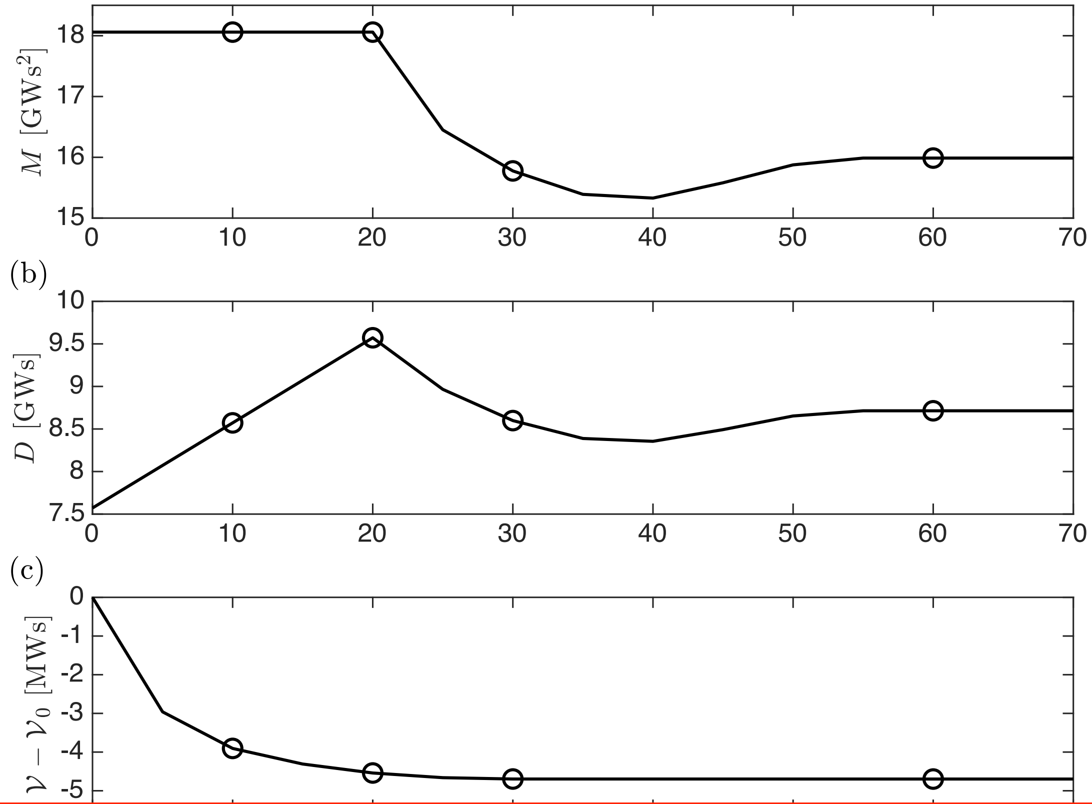


Optimal placement of inertia and primary control



96% of maximal effect reached without changing inertia !

Optimal placement of inertia and primary control



96% of maximal effect reached without changing inertia !

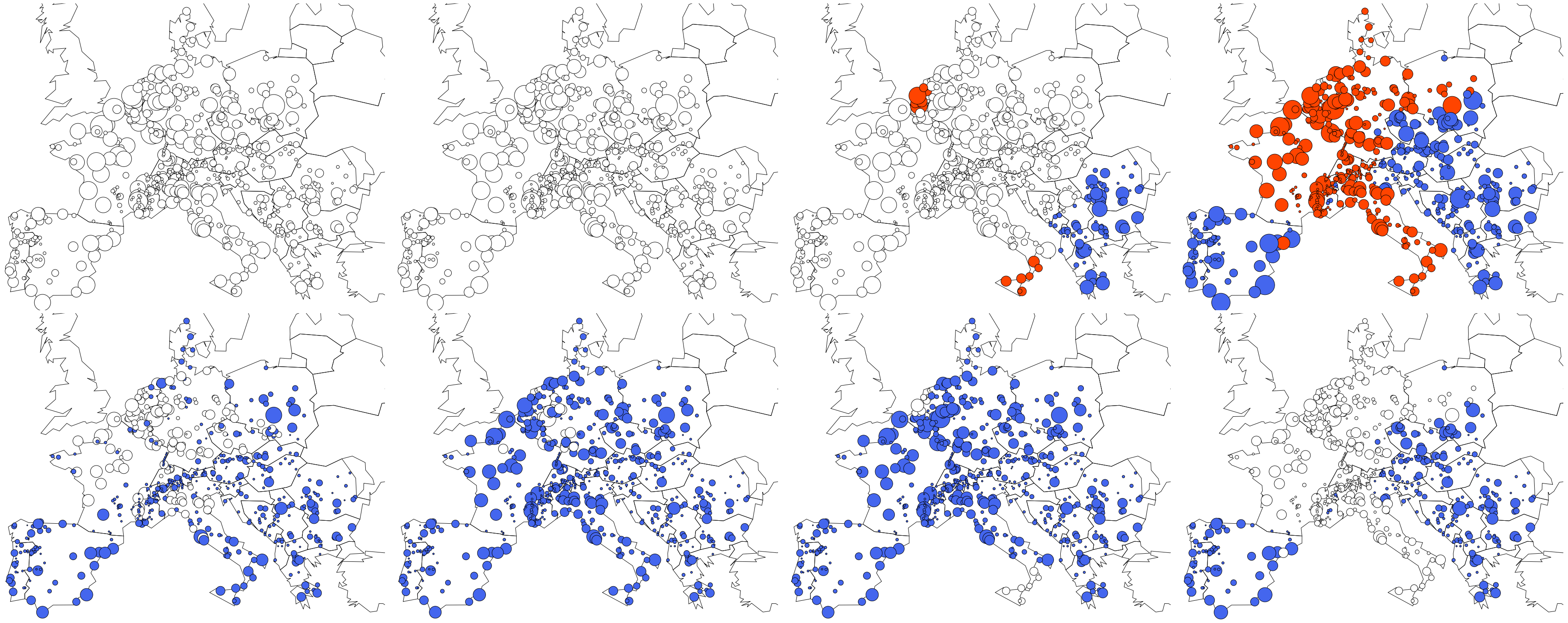
inertia

Add damping on slow modes !

damping

Conclusion

- Power grids are coupled dynamical systems on complex networks
- Analogies with superconductivity / Josephson junction arrays
- They are fast evolving - now is the time for physicists to work on them!
- They will need more primary control in the future, but not necessarily more inertia / inertia substitution



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