The (Quantum ?) Physics of Electric Power Systems

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Stonefest - Yale - 6.26.2019

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Outline

- Electric power systems
- Operating steady-state : power flow equations
- Transient dynamics : swing equations

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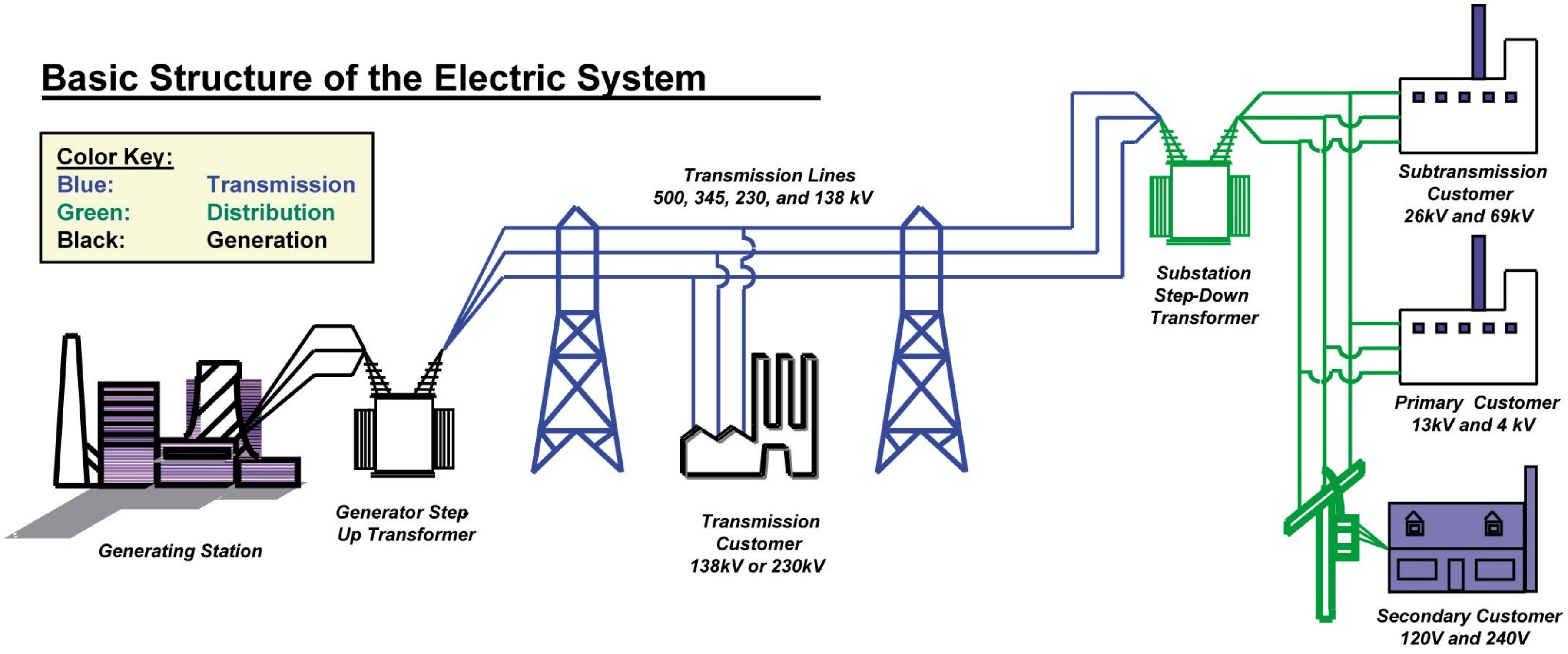
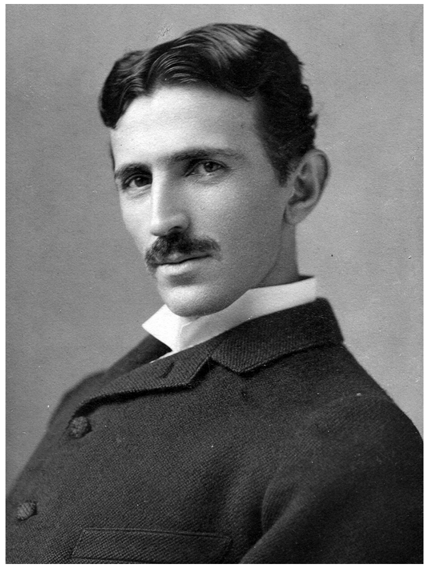
What are electric power systems ?





N Tesla 1856-1943

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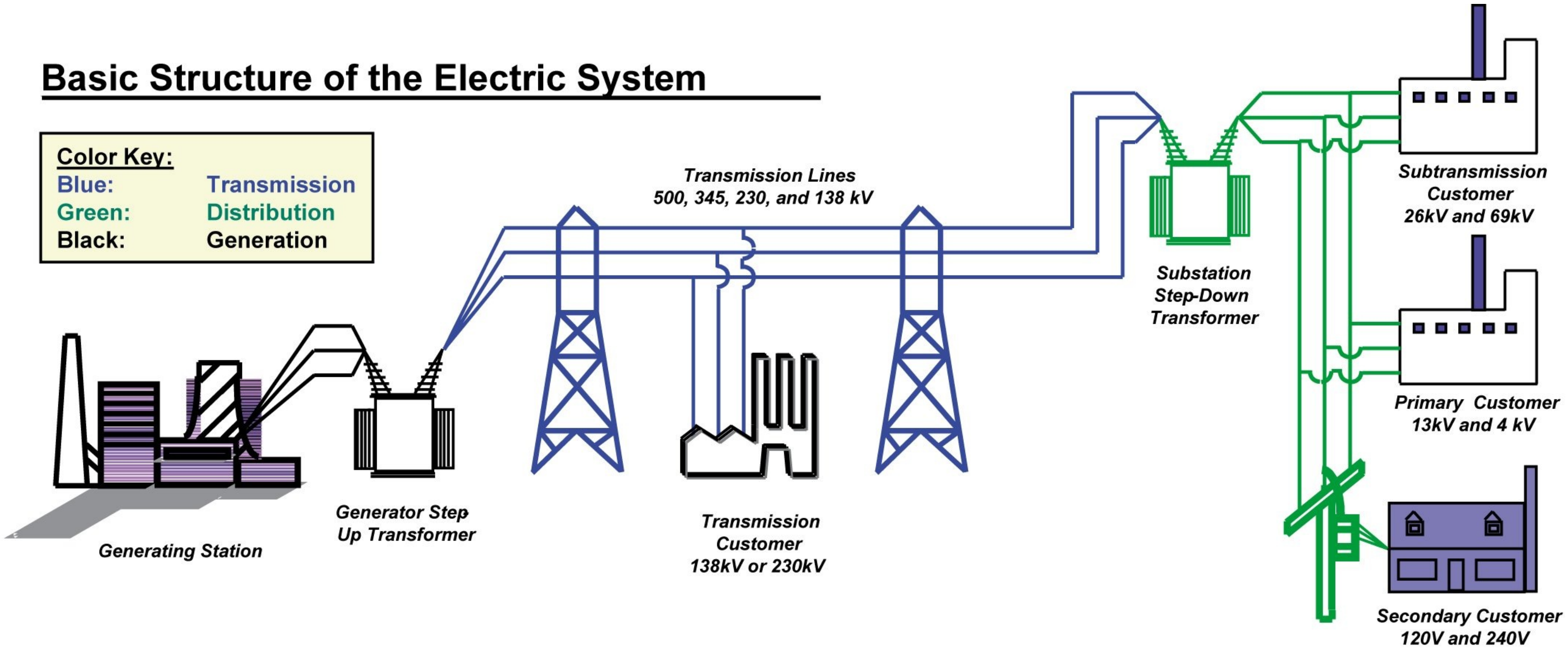

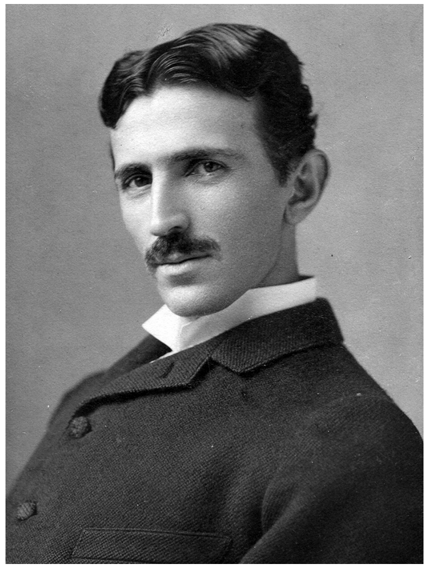

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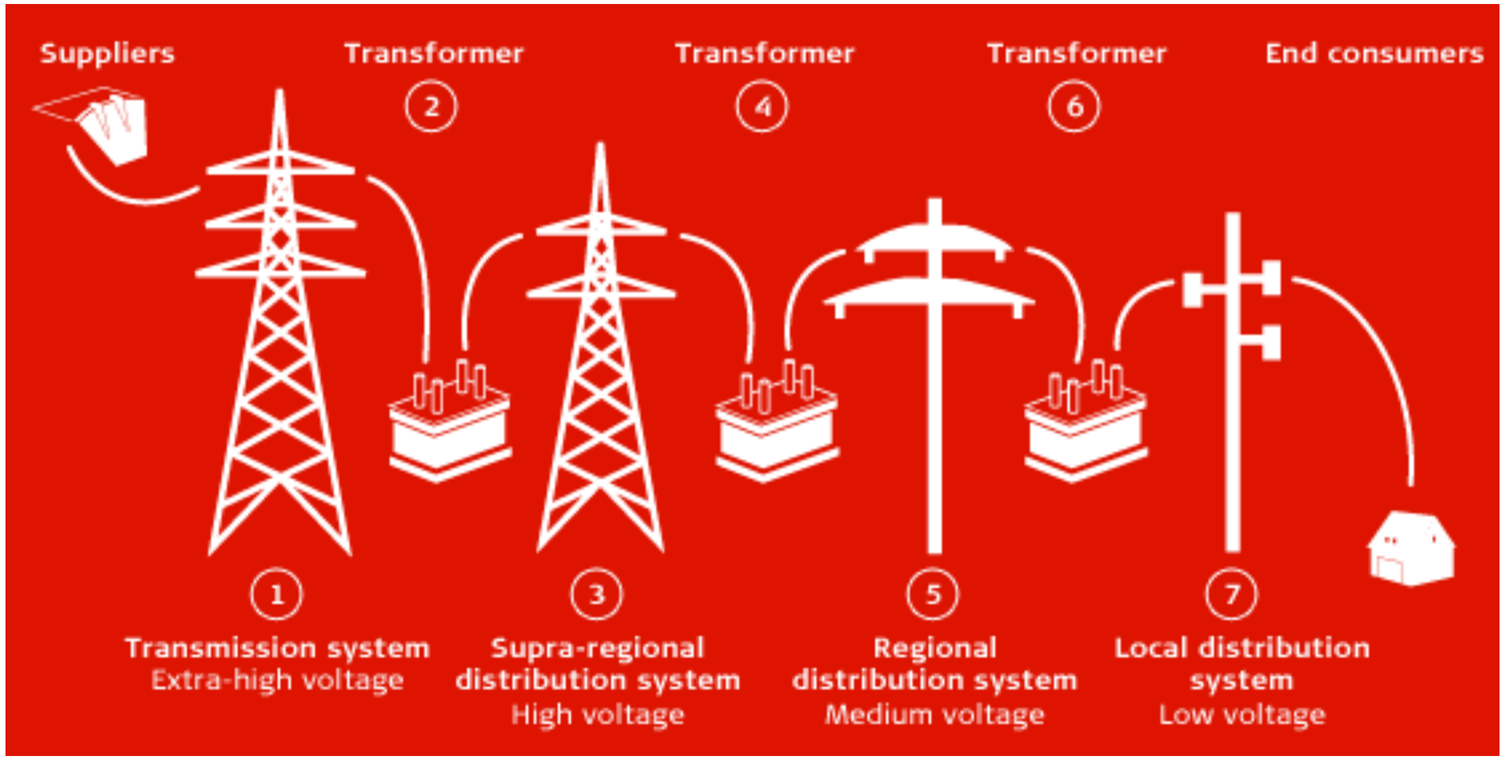
Seven levels of electric power systems



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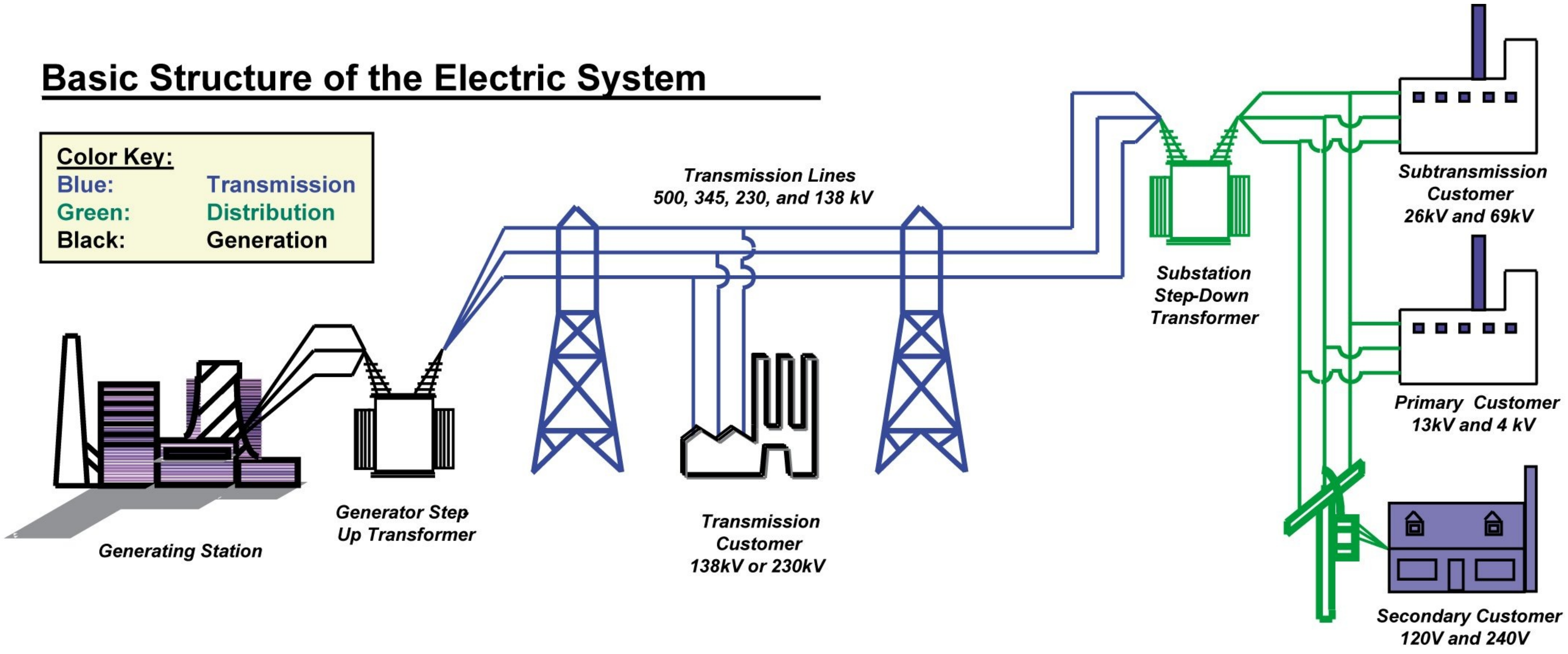

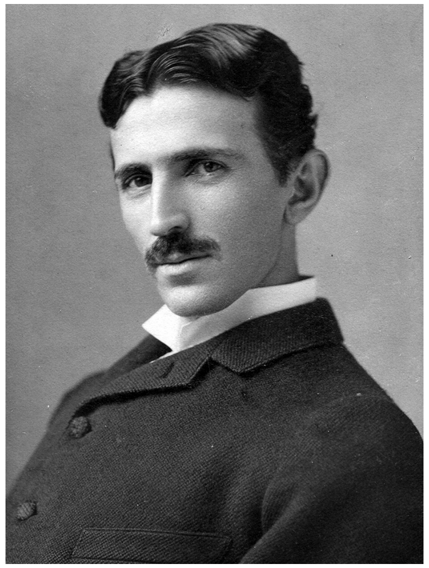

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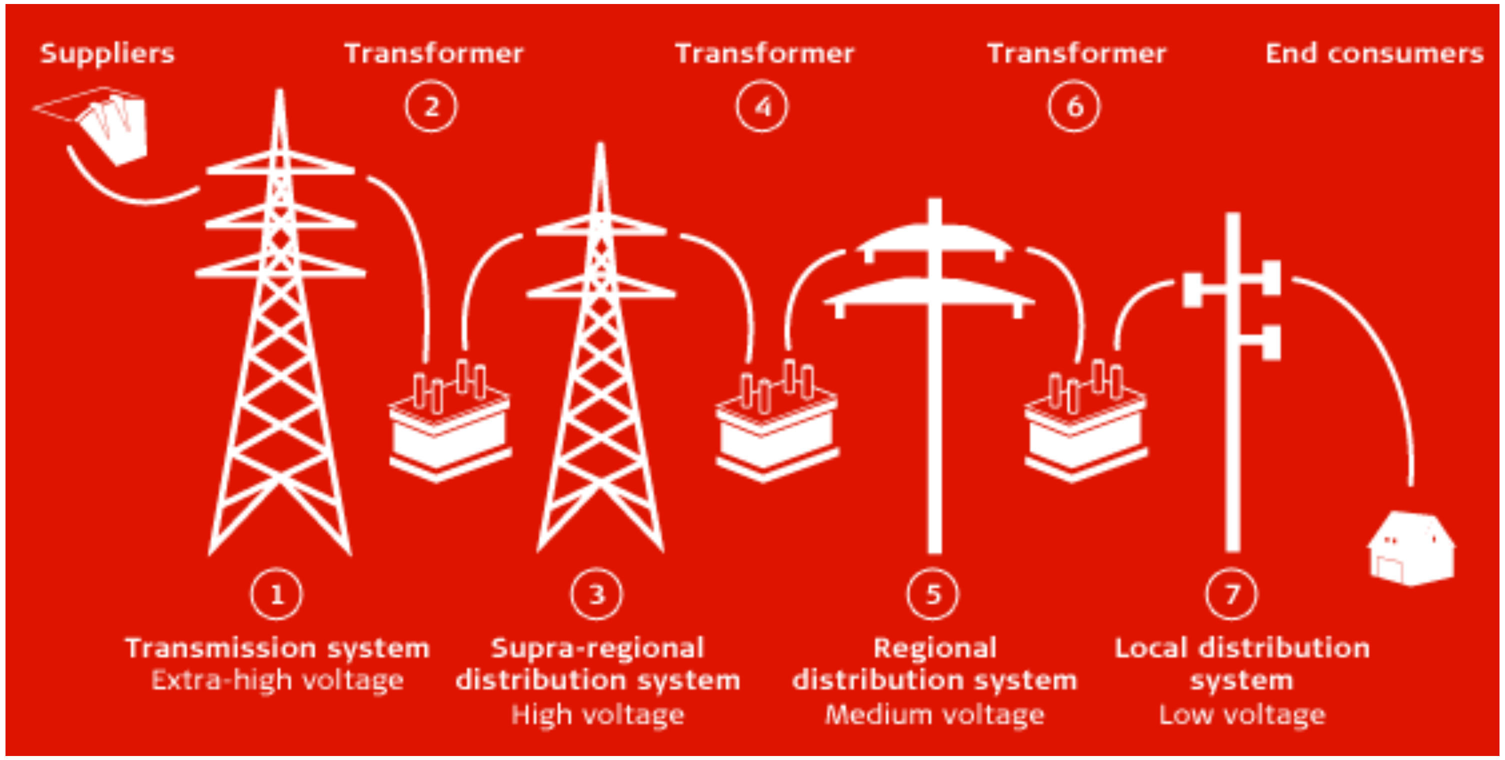
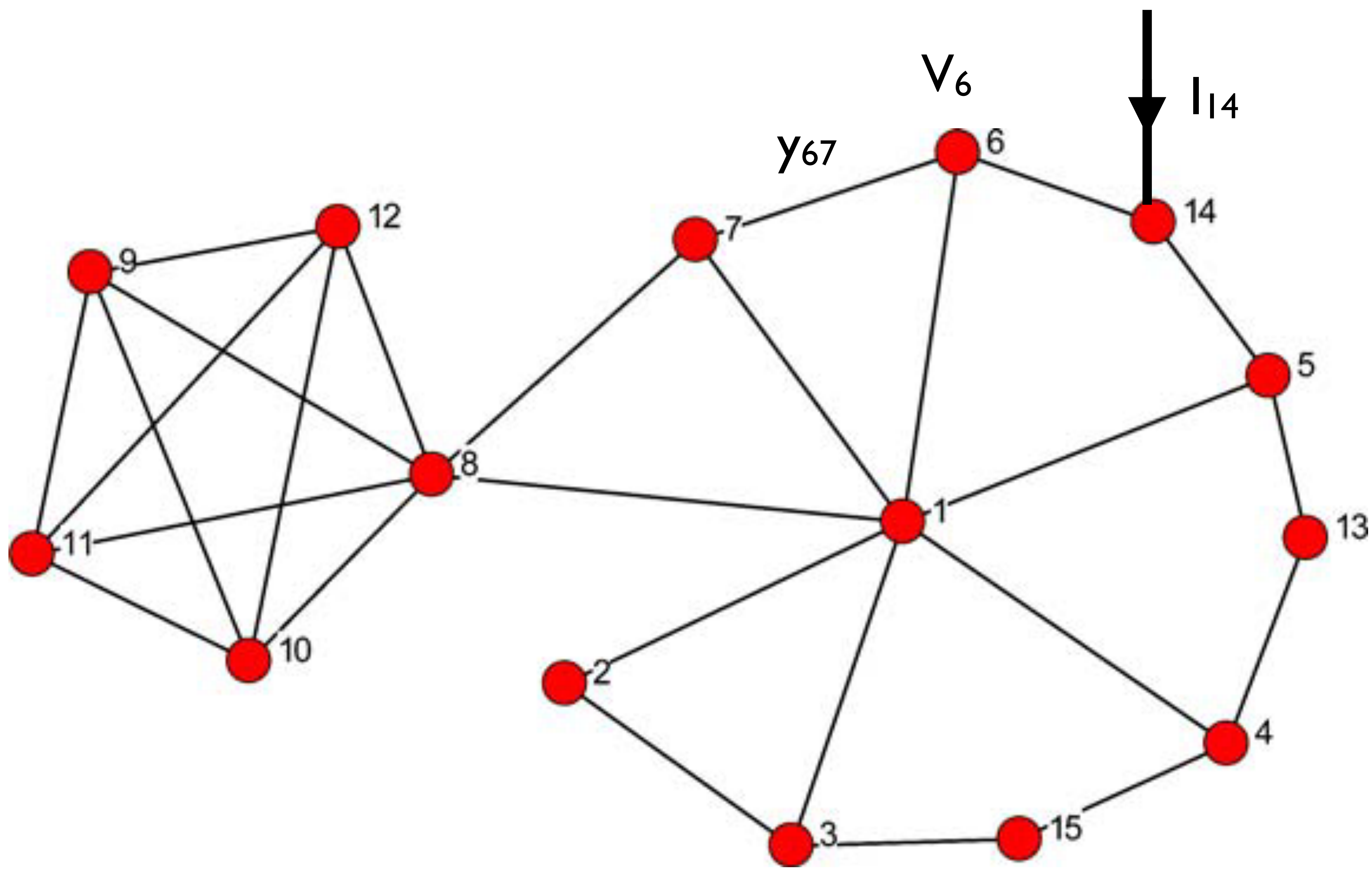


Power :
*conserved (~)
*control parameter
"write Eq. for power"

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
$P=\mathrm{Re}(S)$		$Q=\mathrm{Im}(S)$
finite time-average		zero time-average
"truly transmitted"		"oscillating in the circuit"
(injected and consumed)		

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Power flow equations

$$P_i = \sum_j |V_i V_j| \left[G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right]$$

$$Q_i = \sum_j |V_i V_j| \left[G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right]$$

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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 →

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

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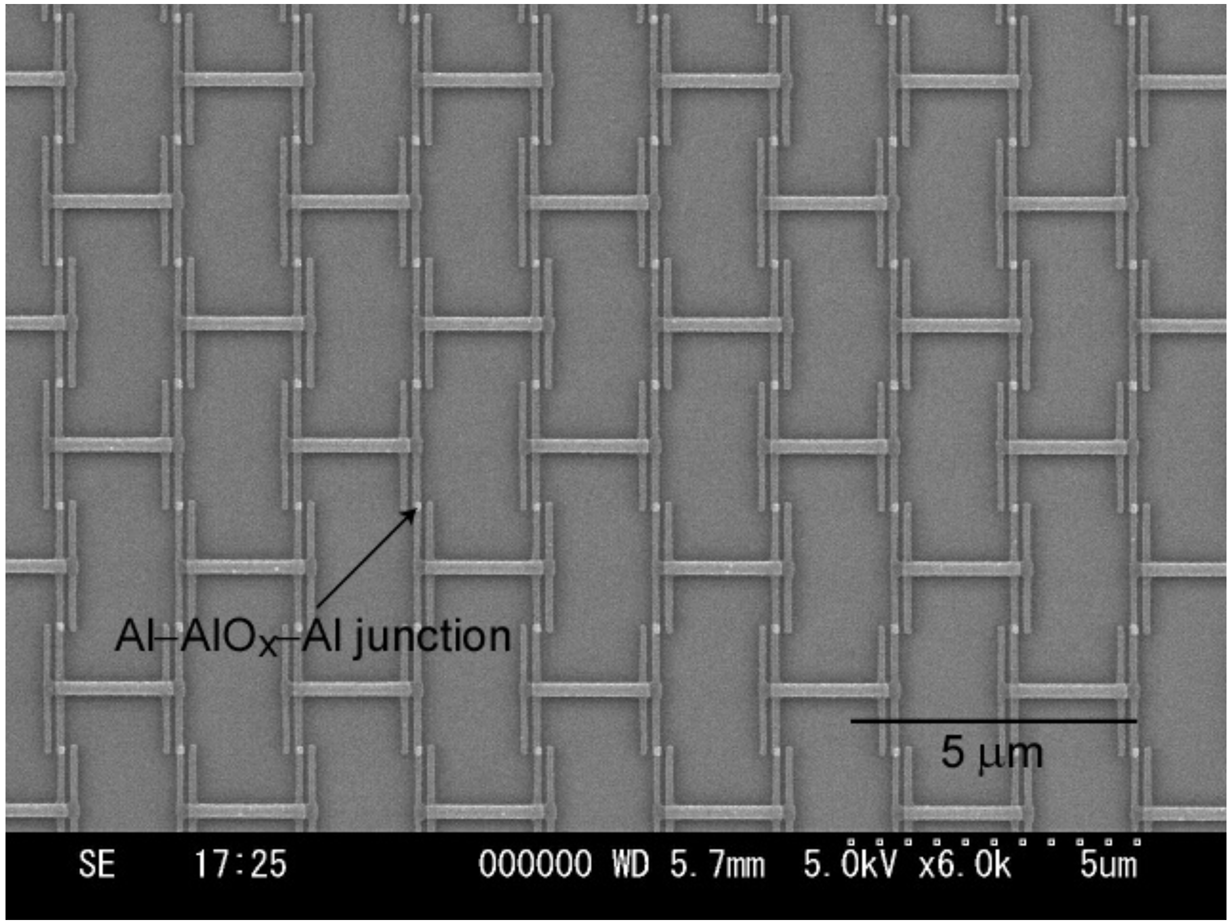
- No conductance ~no voltage drop

consider constant voltage

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

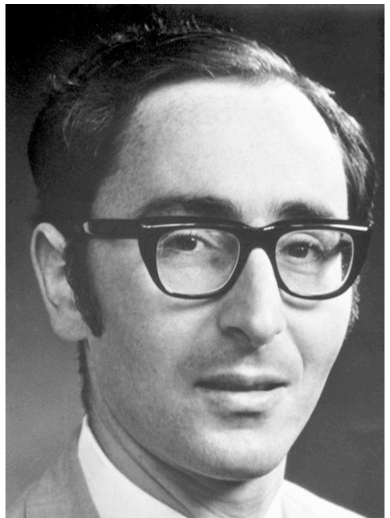
$$P_i = \sum_j B_{ij} \sin(\theta_i - \theta_j)$$

Synchronous fixed points vs. Josephson junctions



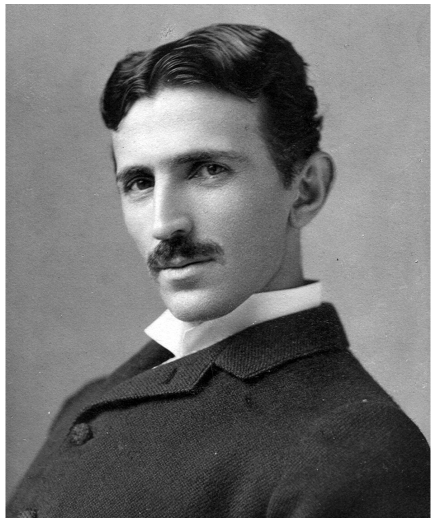
Josephson current

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



High voltage
AC transmitted power

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



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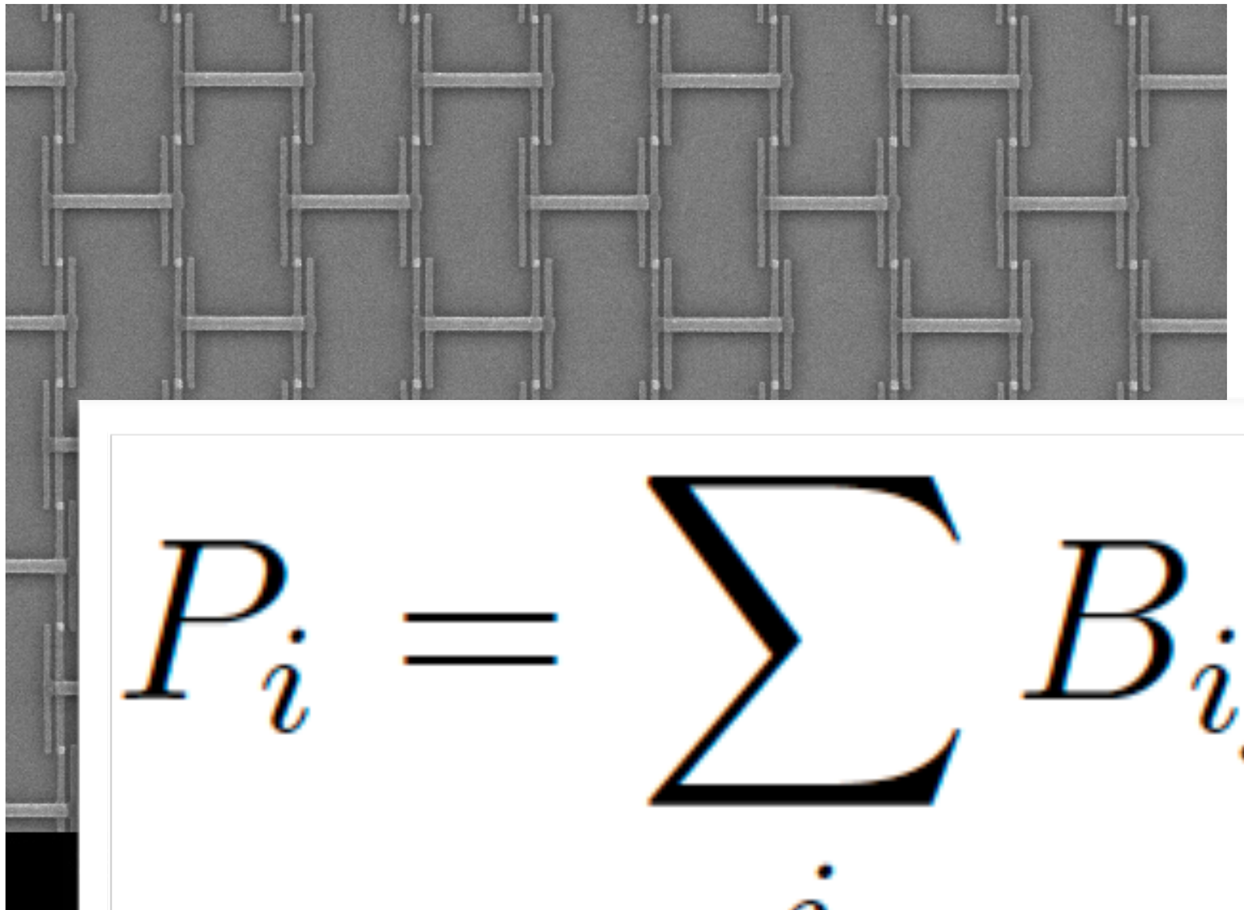

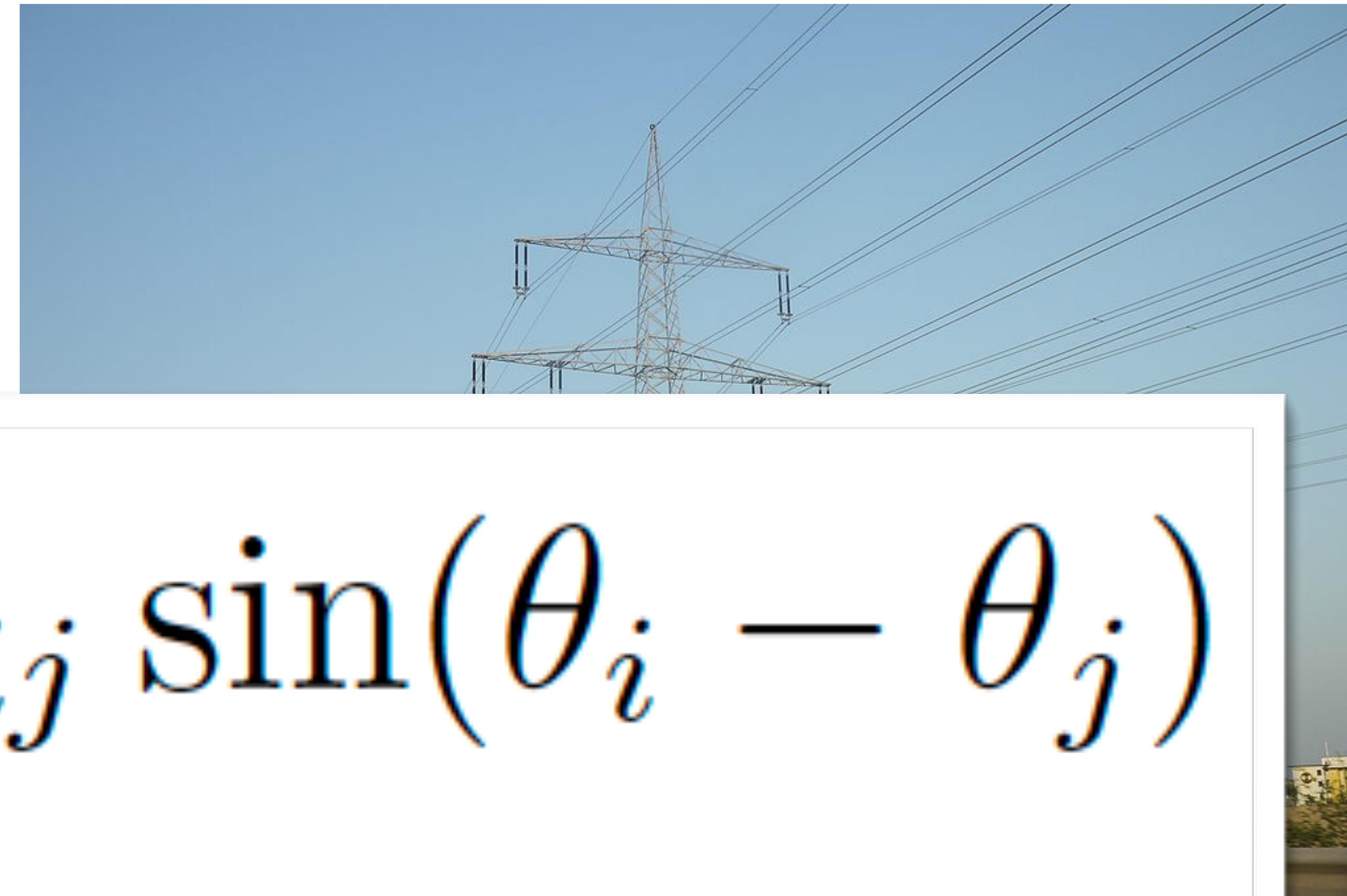

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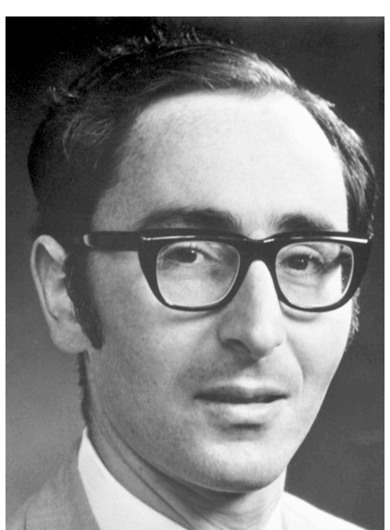

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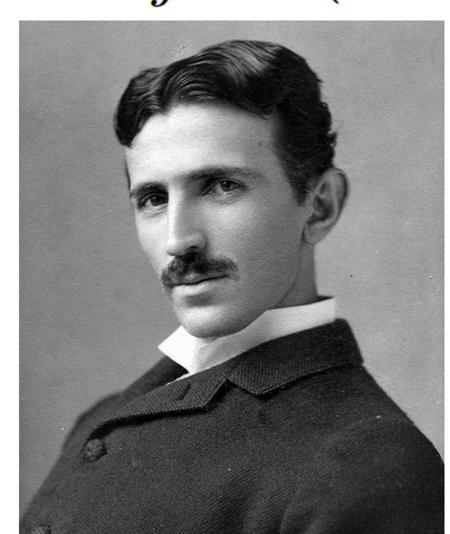

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Circulating loop flows

*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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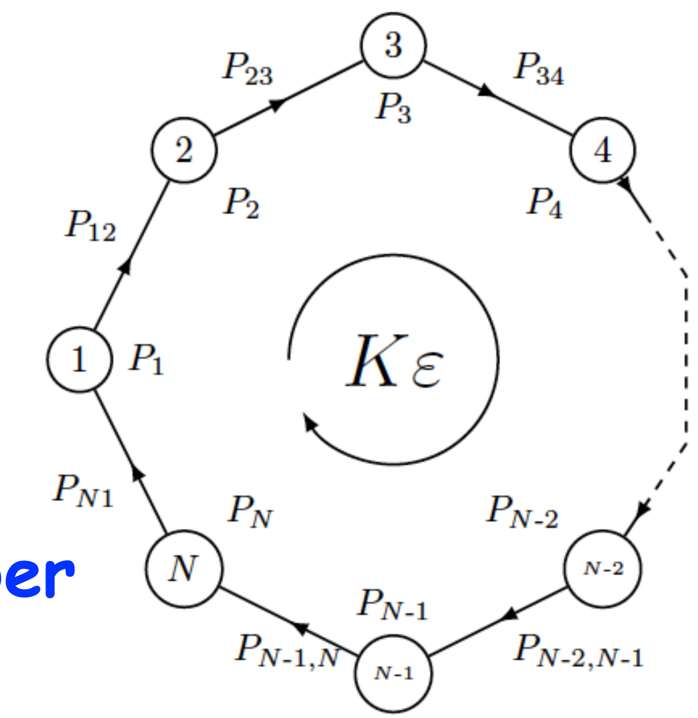

*Voltage angle. $V_i = |V_i| e^{i\theta_i}$ uniquely defined

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

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

Janssens and Kamagate '03; Delabays, Coletta and PJ, JMP '16; JMP '17

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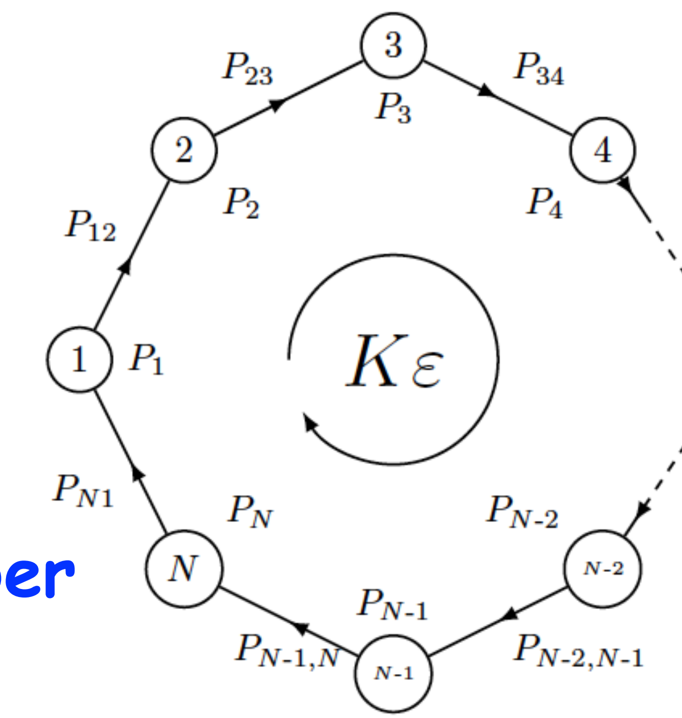

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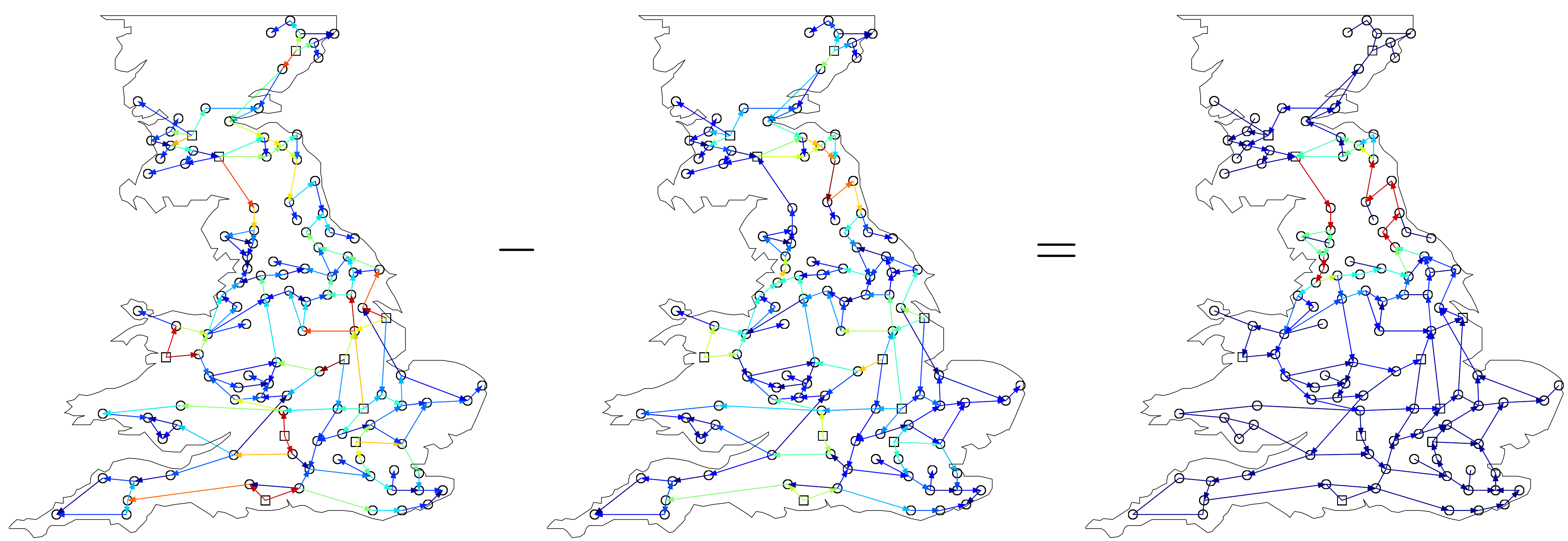

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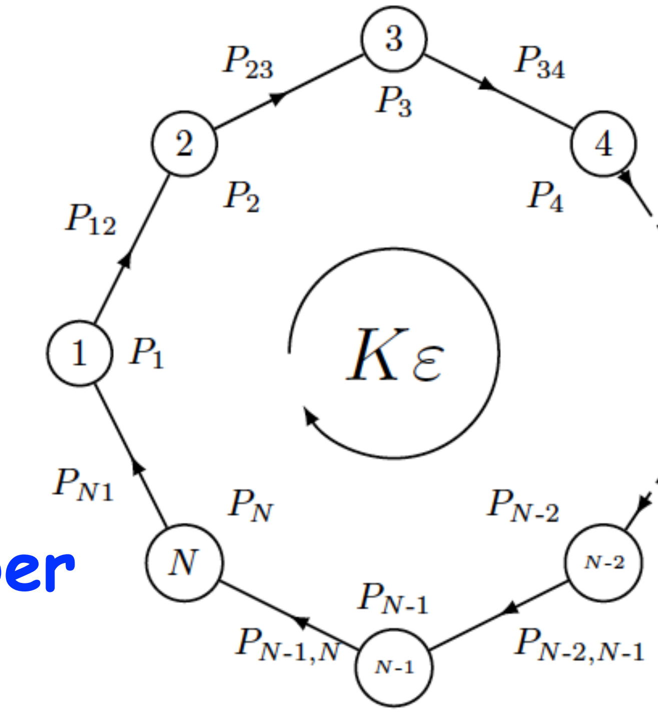

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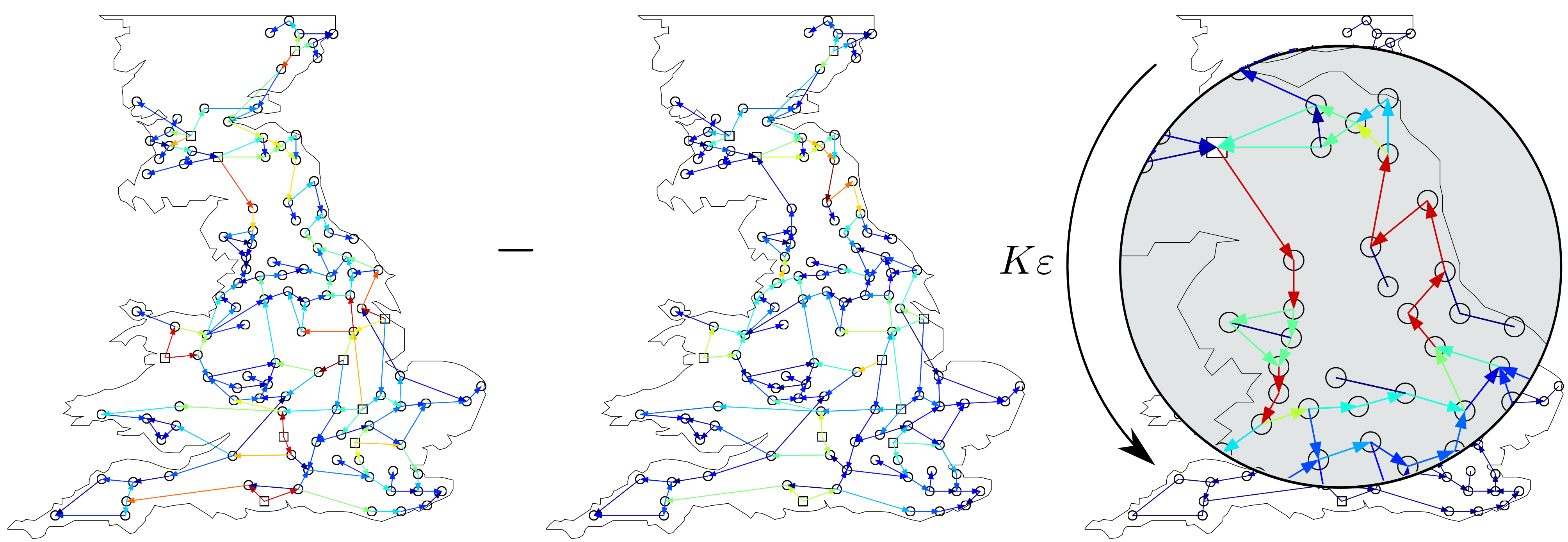
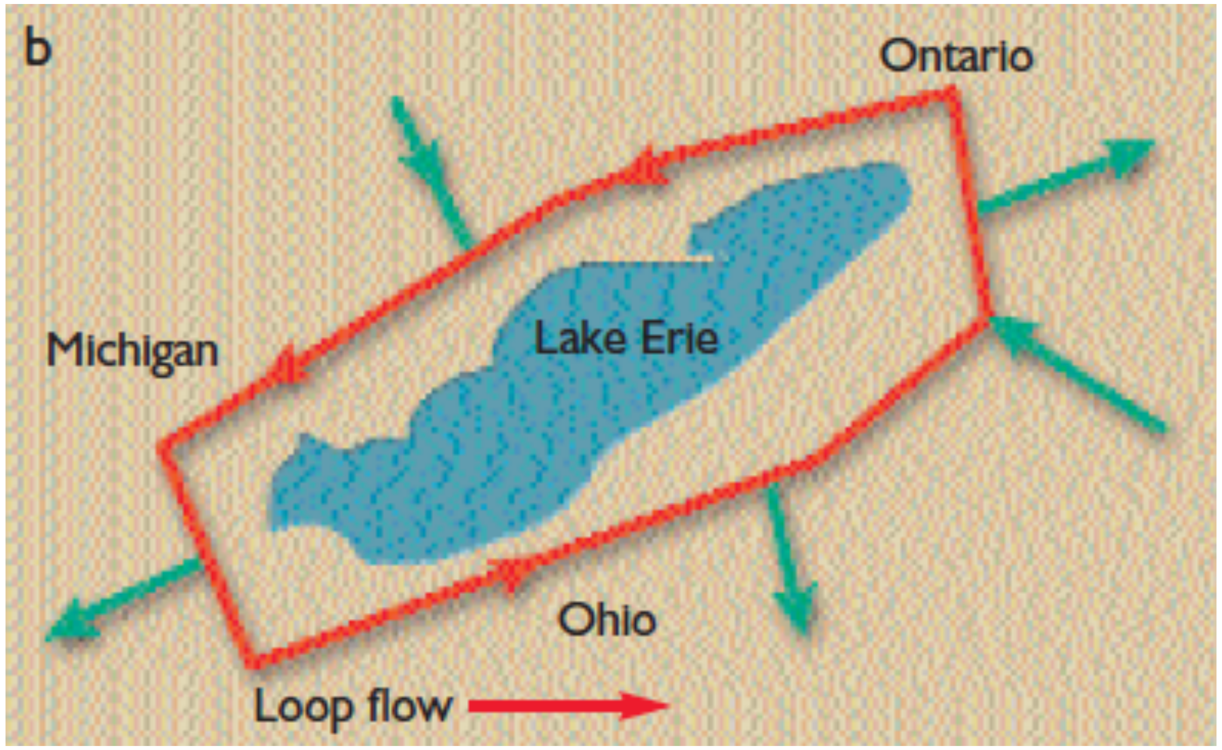


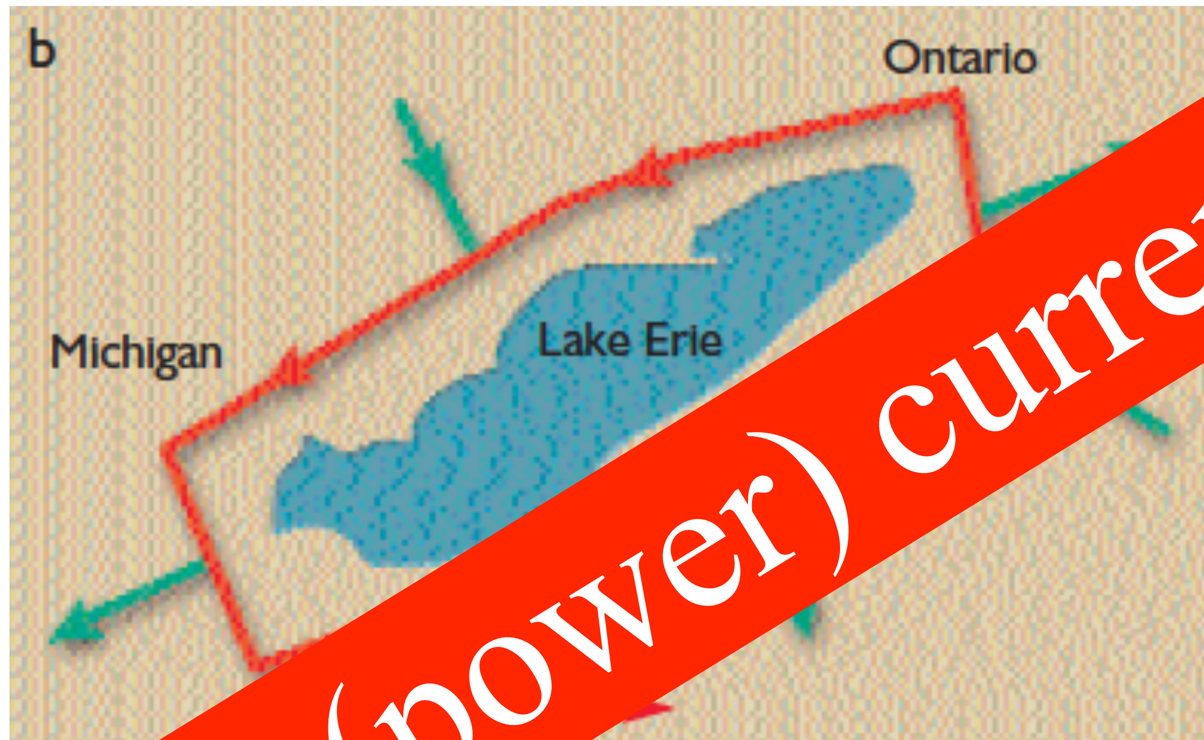
Circulating loop flows



"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)

Circulating loop flows



Persistent (power) current !

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Circulating loop flows

Different power flow solutions
with different loop flows exist, but…

How do they appear ? how are they generated ?

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with different loop flows exist, but…

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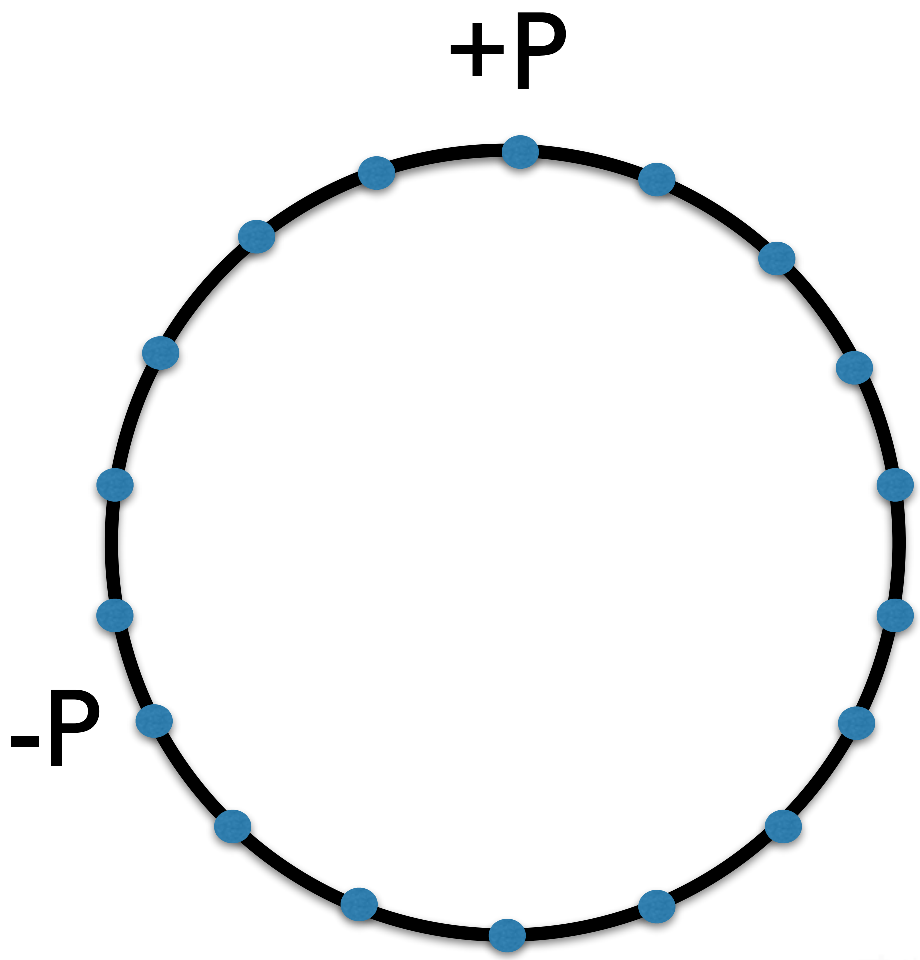
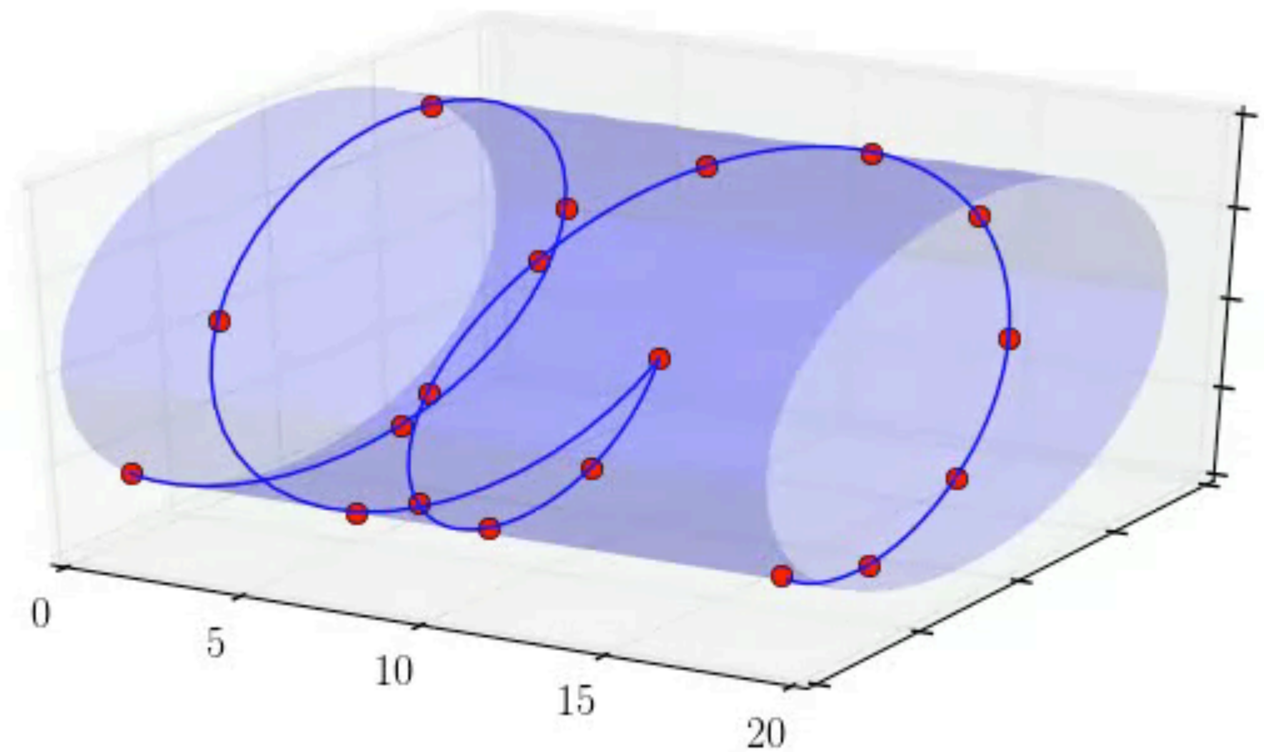
Solution :

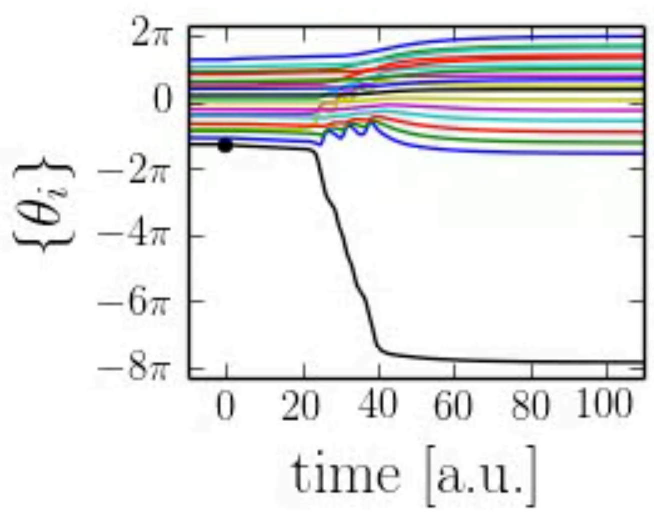
(i) line tripping
(ii) line tripping and reclosing
(iii) dynamical phase slip
(iv) fluctuating power injections

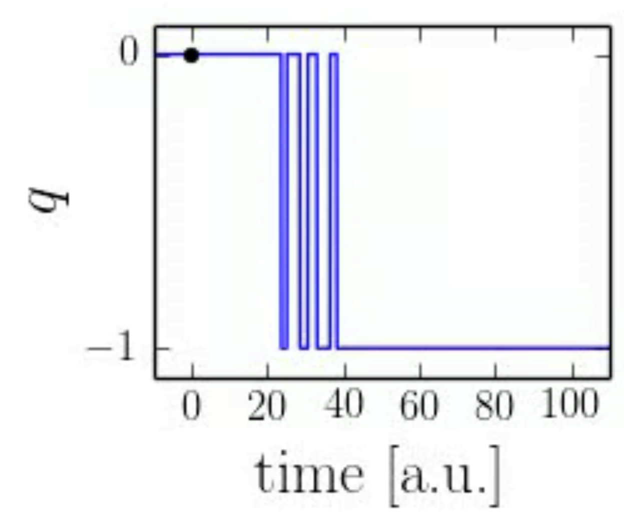
Coletta, Delabays, Adagideli and PJ, New J Phys. '16
Tyloo, Delabays and PJ, PRE '19
Hindes, PJ and Schwartz, arXiv:1904.12174

Dynamical generation of vortex flows









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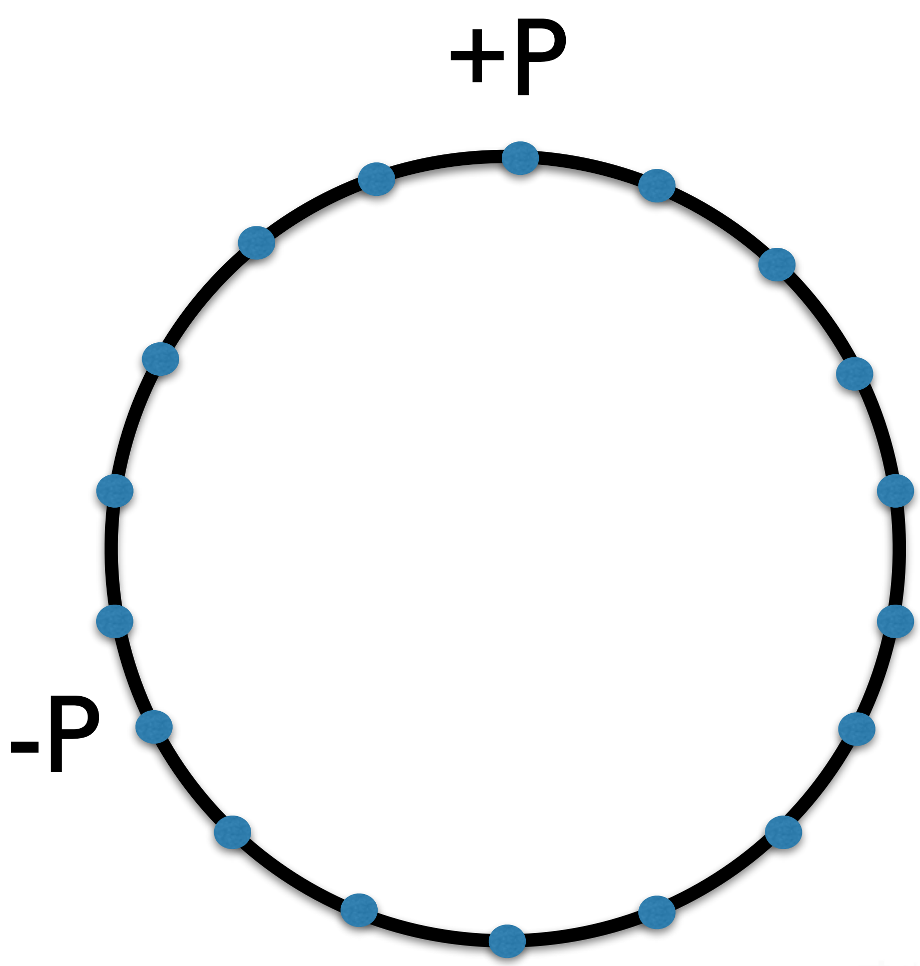

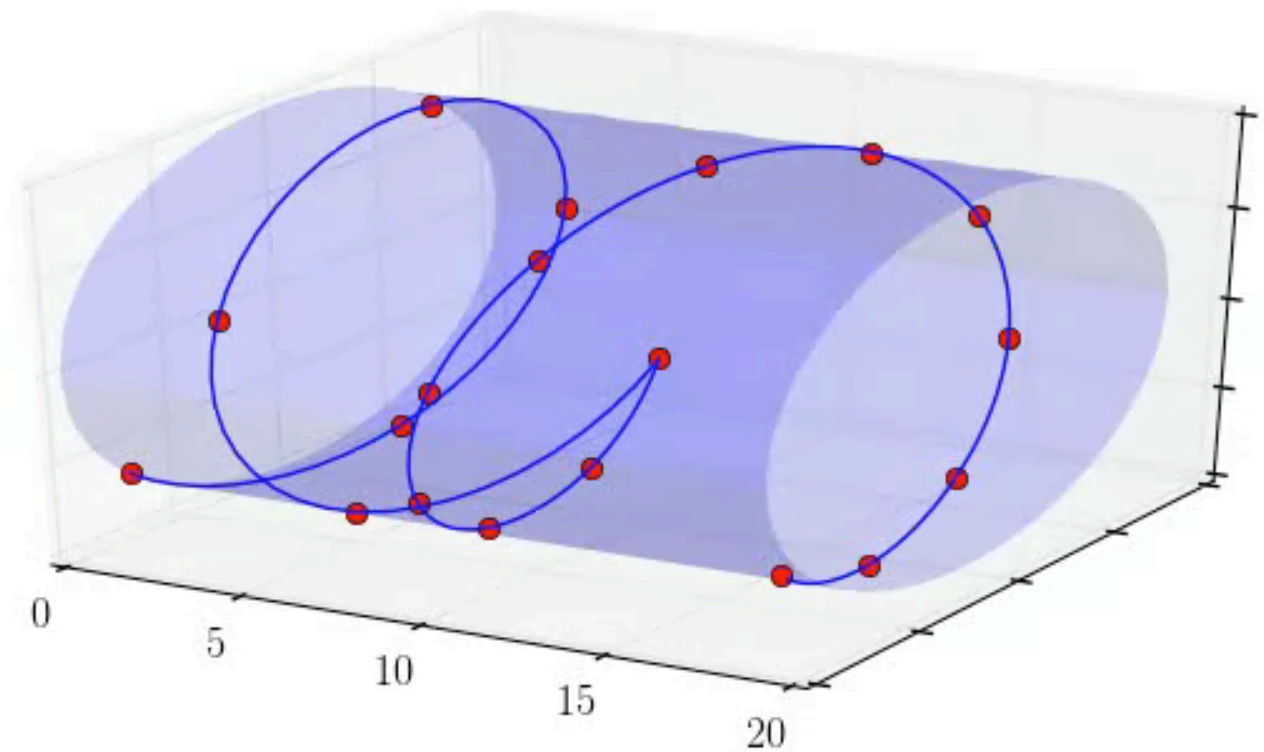

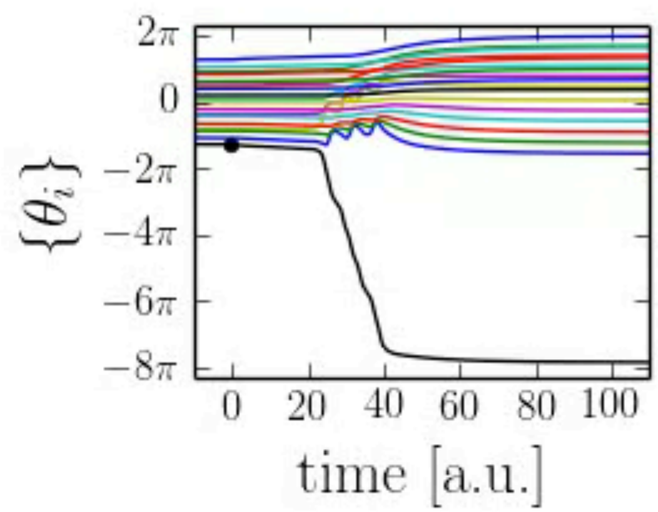

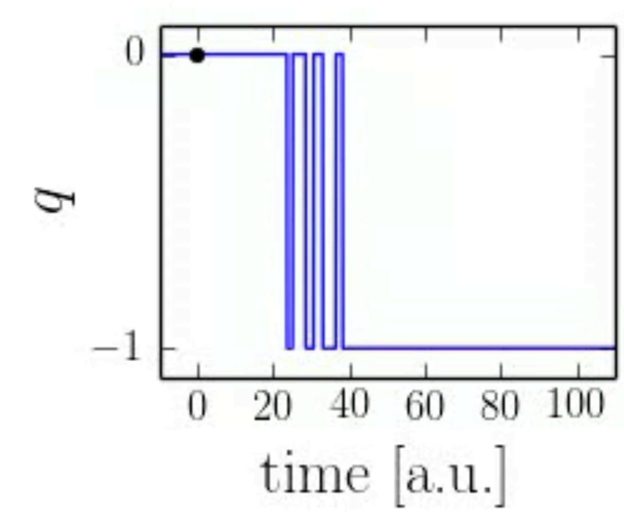

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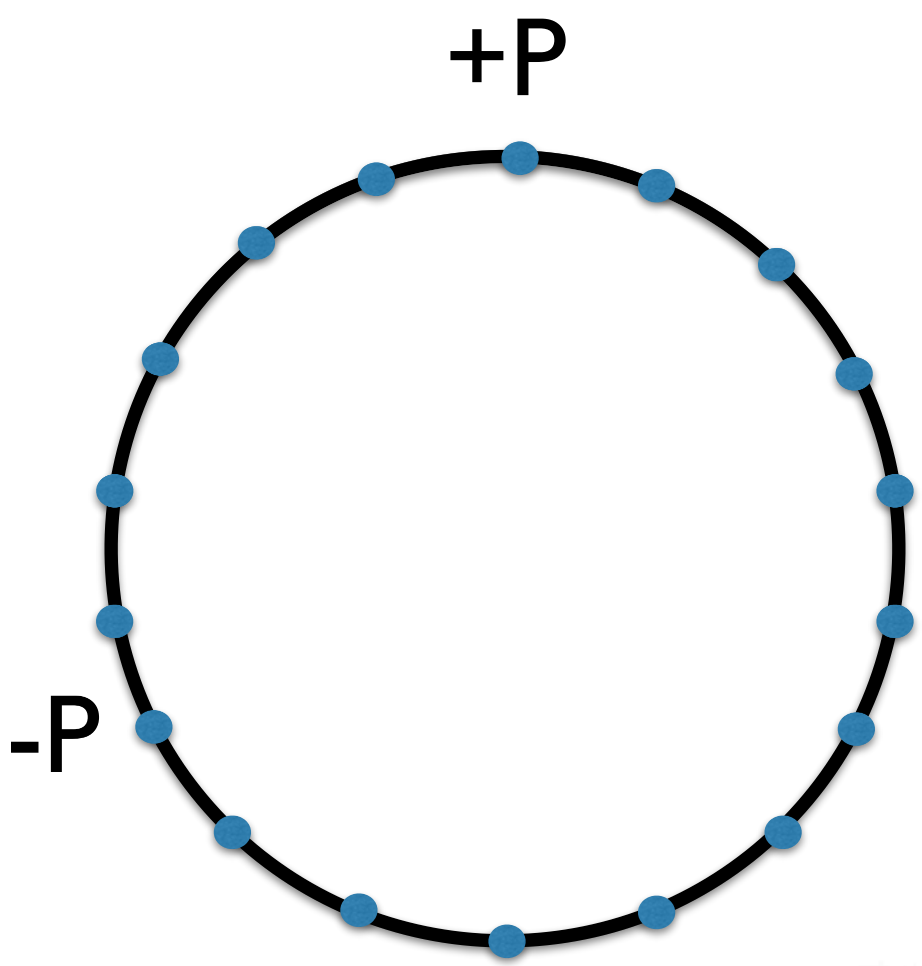

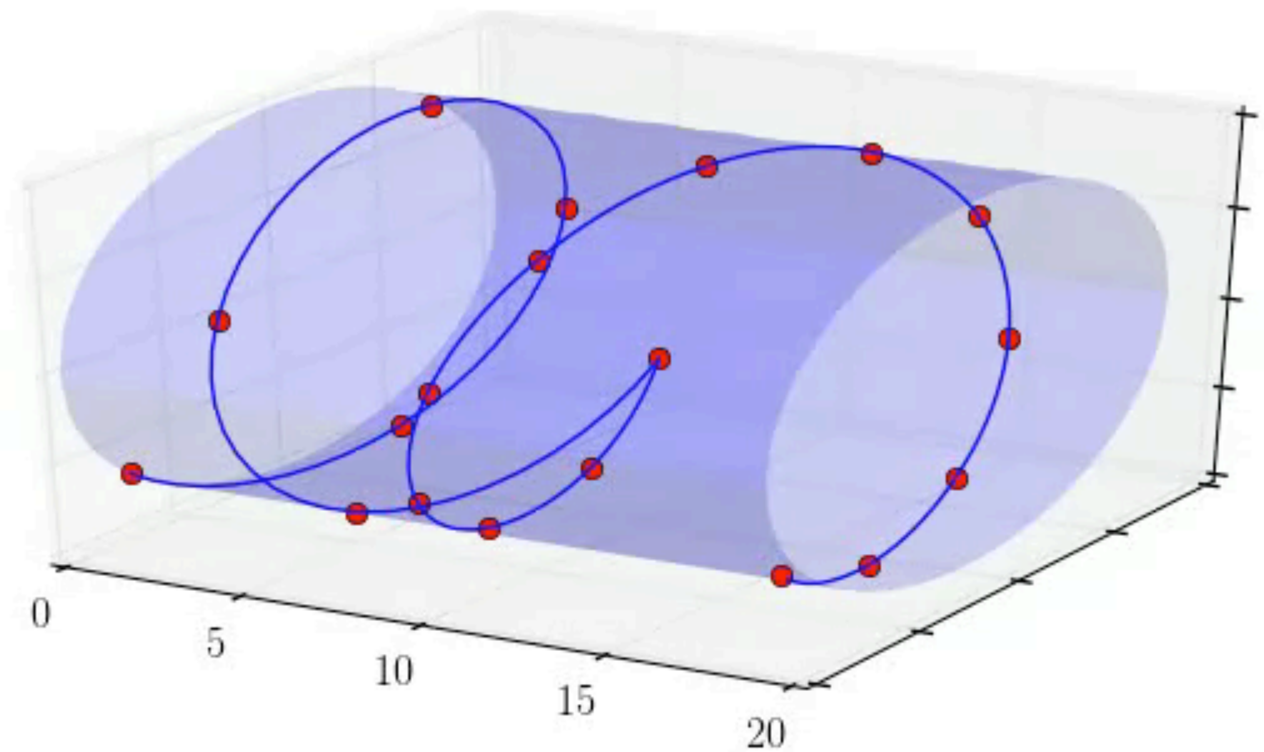

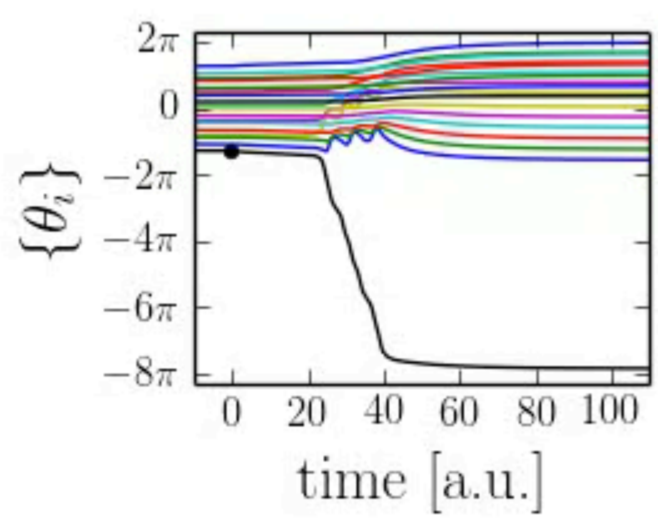

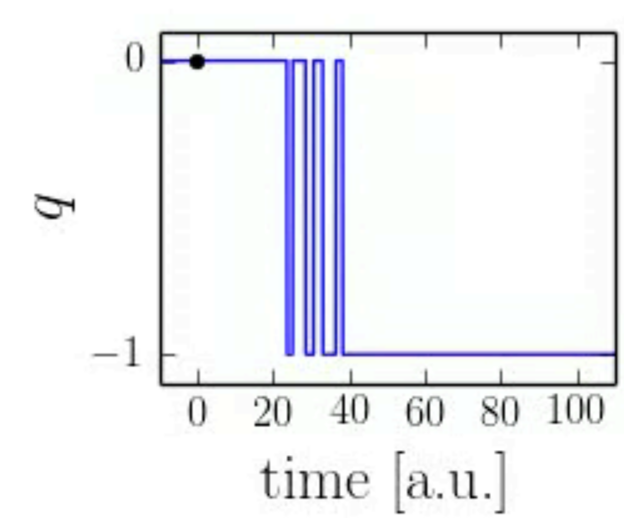

Coletta, Delabays, Adagideli and PJ, New J Phys. '16

Similarity with quantum phase slips in small SC and JJ arrays
D. S. Golubev and A. D. Zaikin, '01
Lau, Markovic, Bockrath, Bezryadin and Tinkham '01
Matveev, Larkin and Glazman '02

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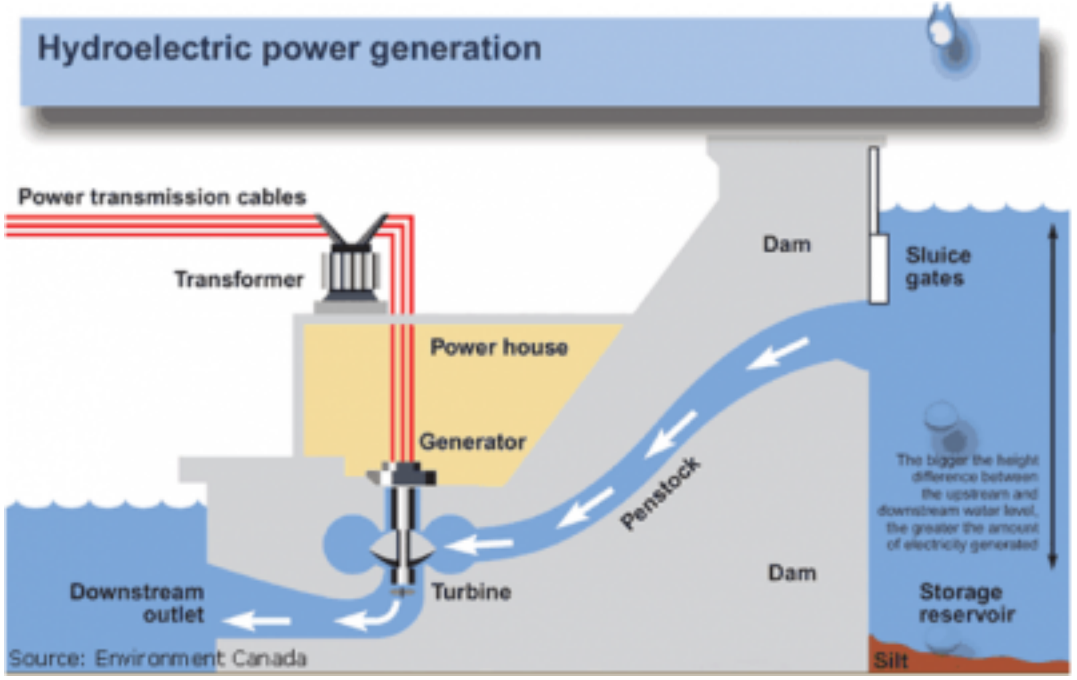
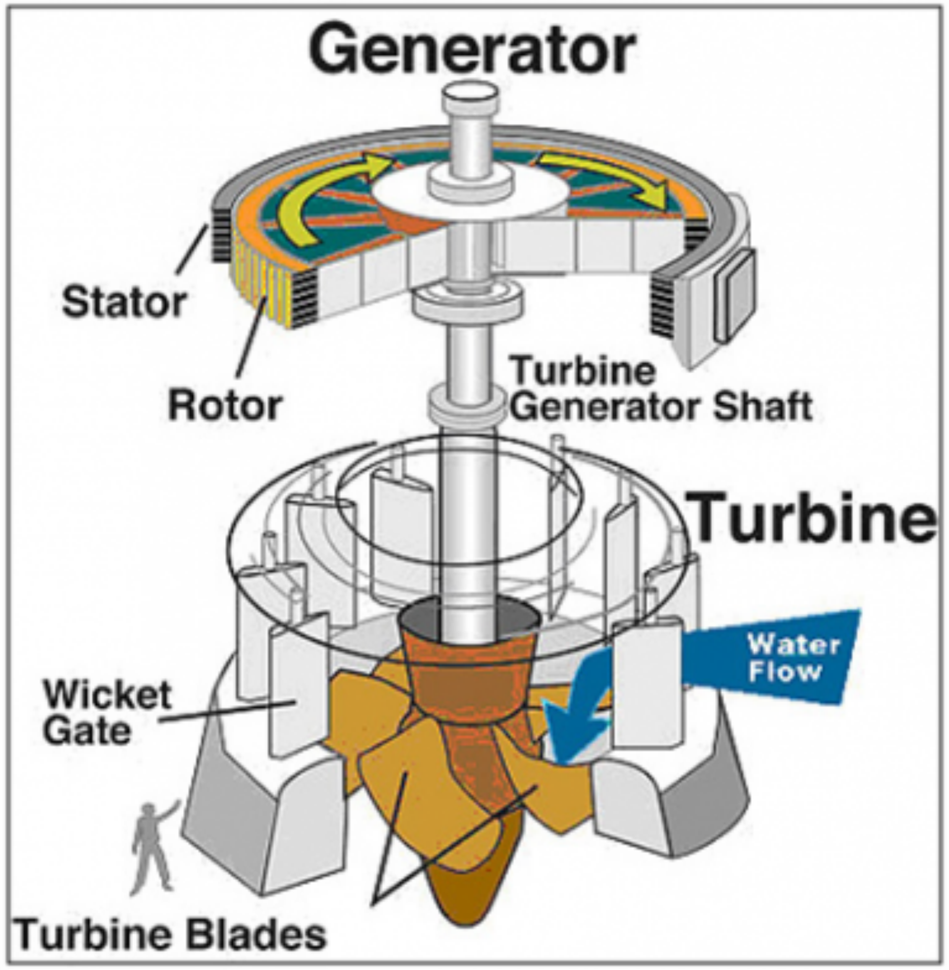
Dynamics of AC power grids

- 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**





Today's (and yesterday's) 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

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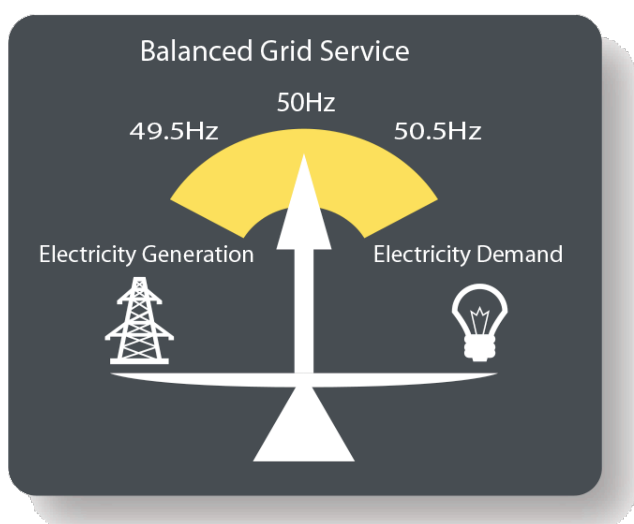
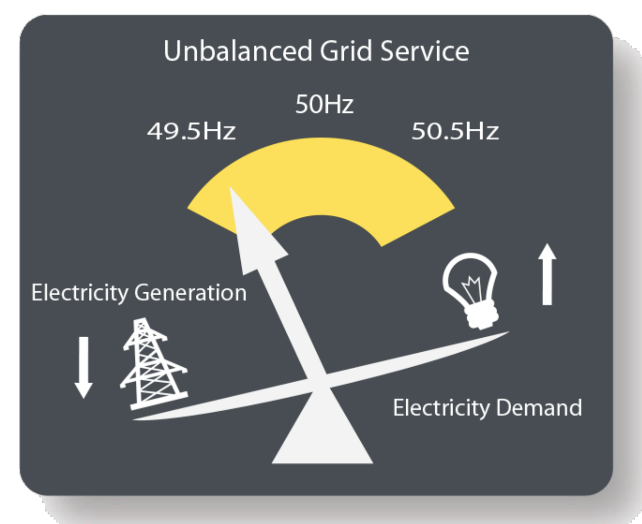
- Coupling between power balance and frequency





figs.Taken from http://northernutilities.co.uk

Change in kinetic energy = balance of power

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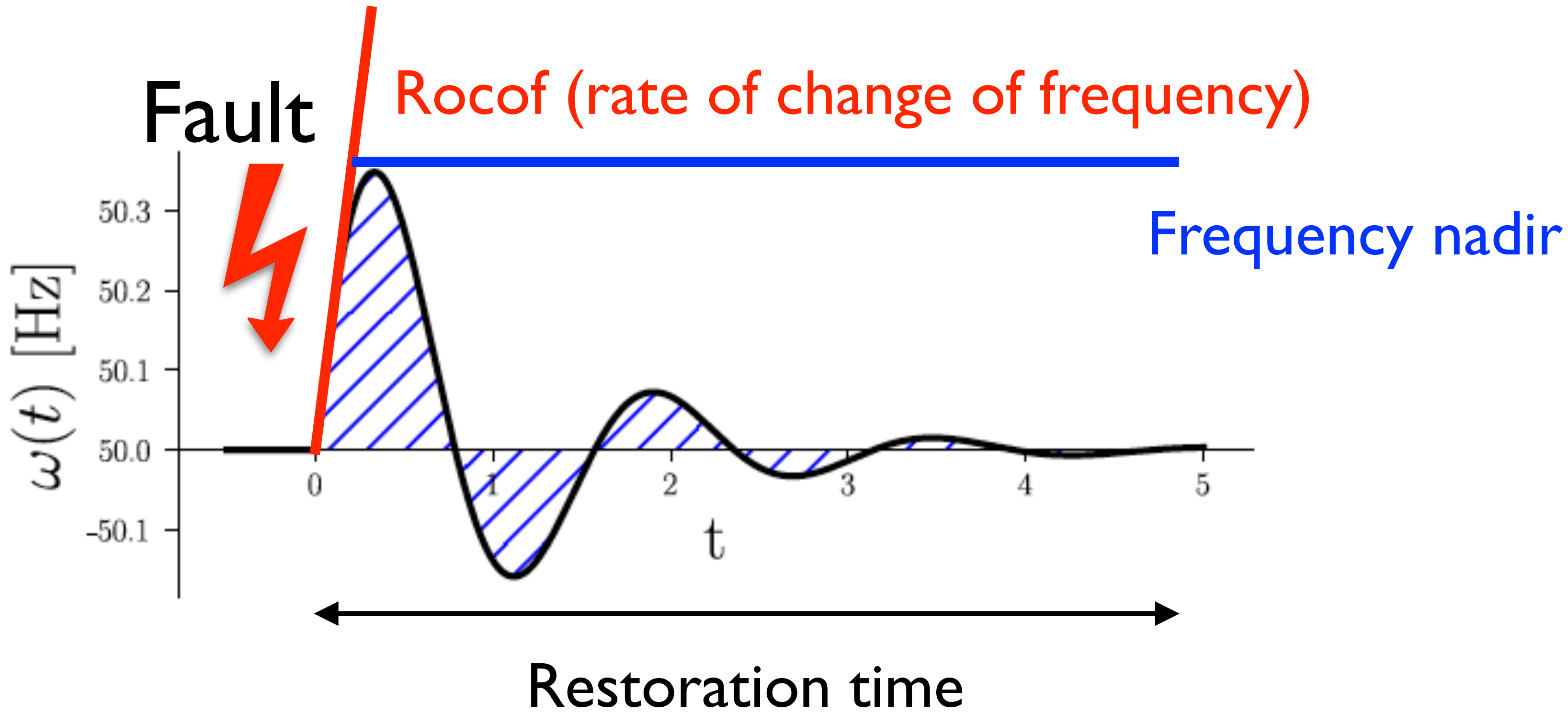
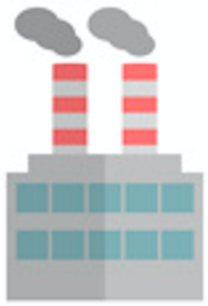
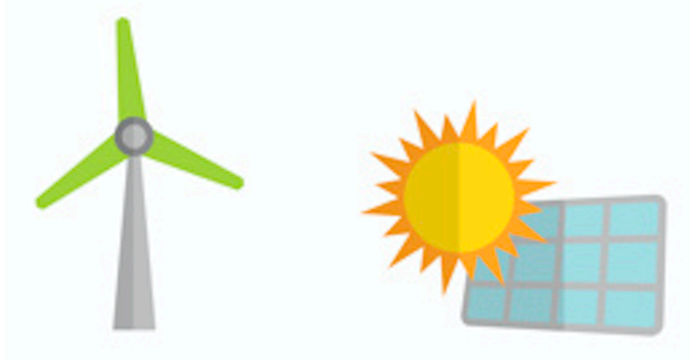


- Frequency transient as indicator of fault magnitude
- Frequency fluctuations need to be minimized… but how ?

Tomorrow's power grids





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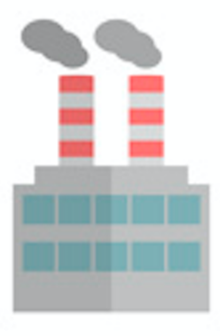
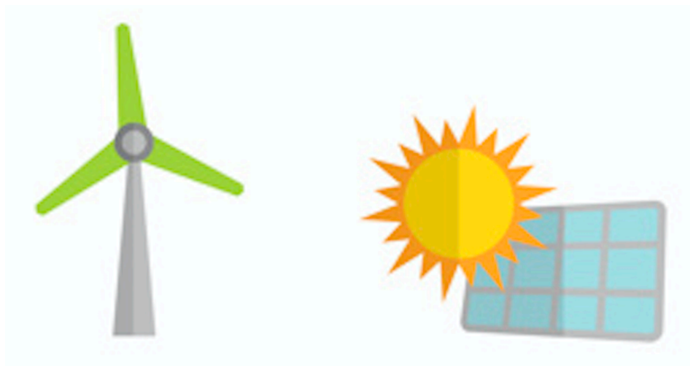
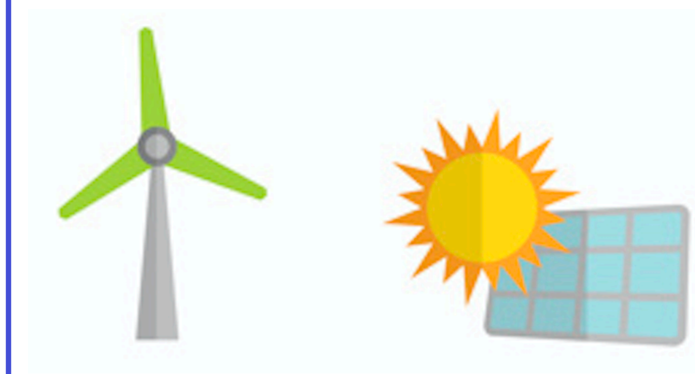


- Centralized



- Decentralized
  - -issues at distribution level
  - -easier at transmission level (=reduction in load) up to some level…

Tomorrow's power grids



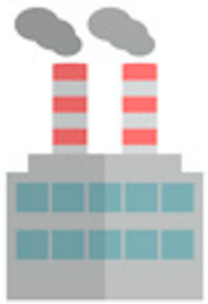
- Centralized

- Dispatchable/predictable

- Decentralized
  -issues at distribution level
  -easier at transmission level (=reduction in load) up to some level…

- Uncertain
  -power / energy reserve

Tomorro



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

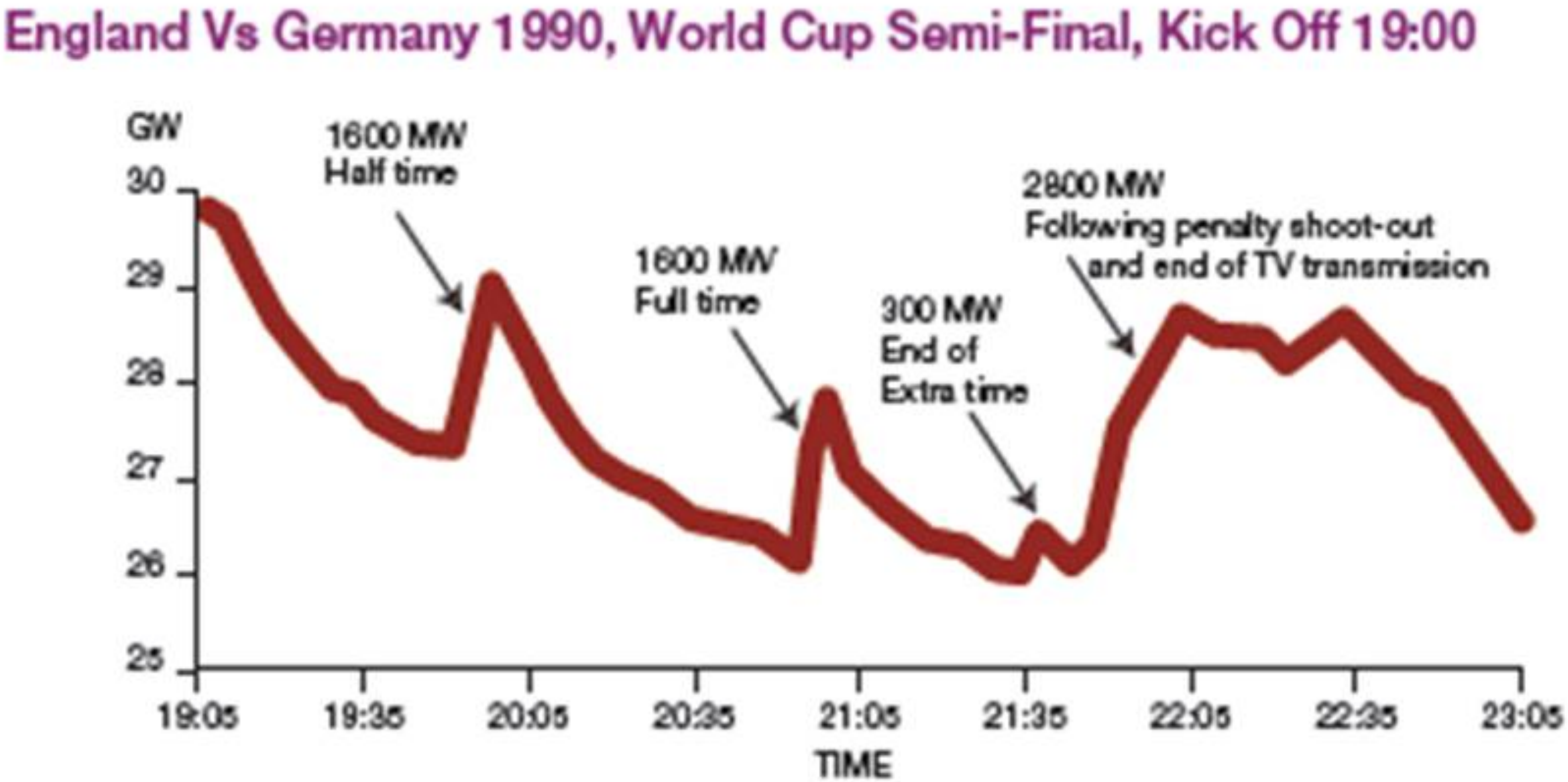
- Centra

level
level
ıp to

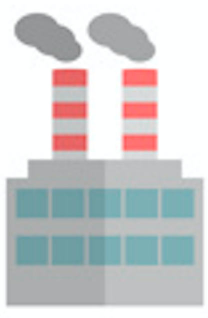
- Dispat

ve

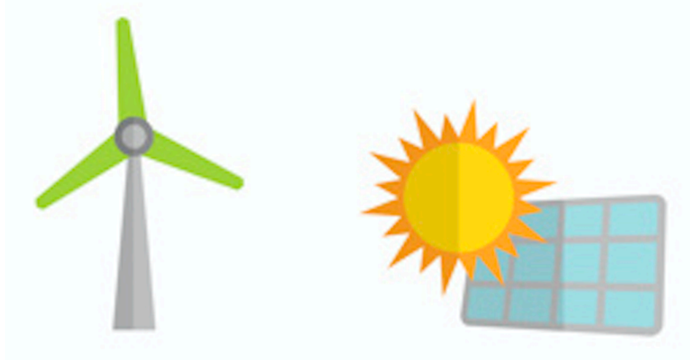
Variability and uncertainty are nothing new for grid operators



Old vs. new productions

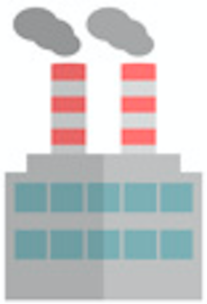


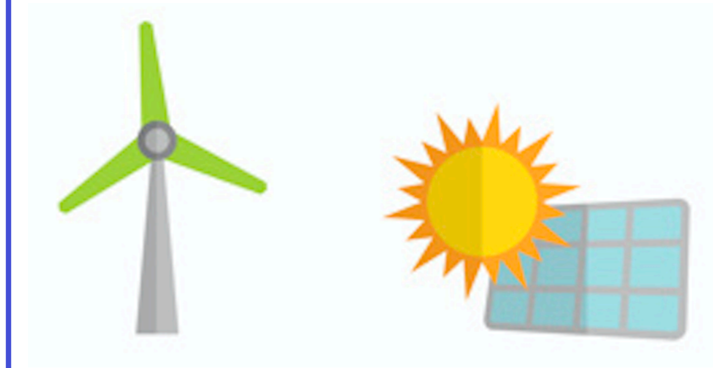
- Rotating machine with inertia
  - -frequency definition
  - -grid stability :
    - *energy reserve
    - *droop control



- No inertia

Old vs. new productions

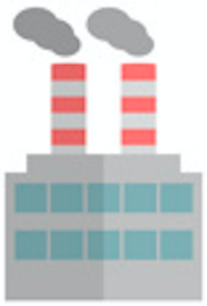


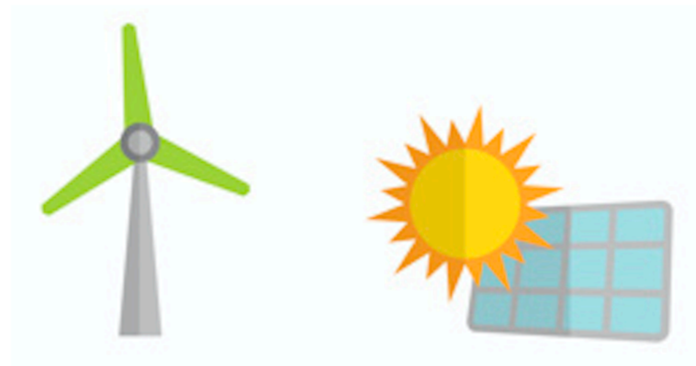


?? Where is it problematic to substitute old productions with new renewables ??

- Ro
  inertia
  - -frequency definition
  - -grid stability :
    - *energy reserve
    - *droop control

Old vs. new productions





- Ro
  inertia
  - -frequency definition
  - -grid stability
    - *energy re
    - *droop control

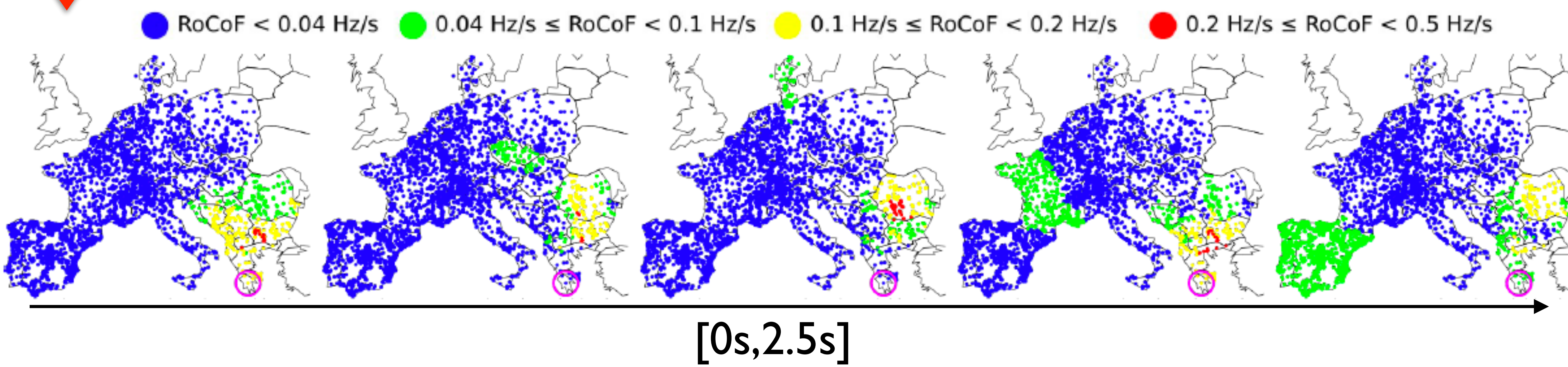
?? Where is it problematic to substitute old productions with new renewables ??

?? Where is it not ??

Disturbance propagation

Fault : sudden power loss

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

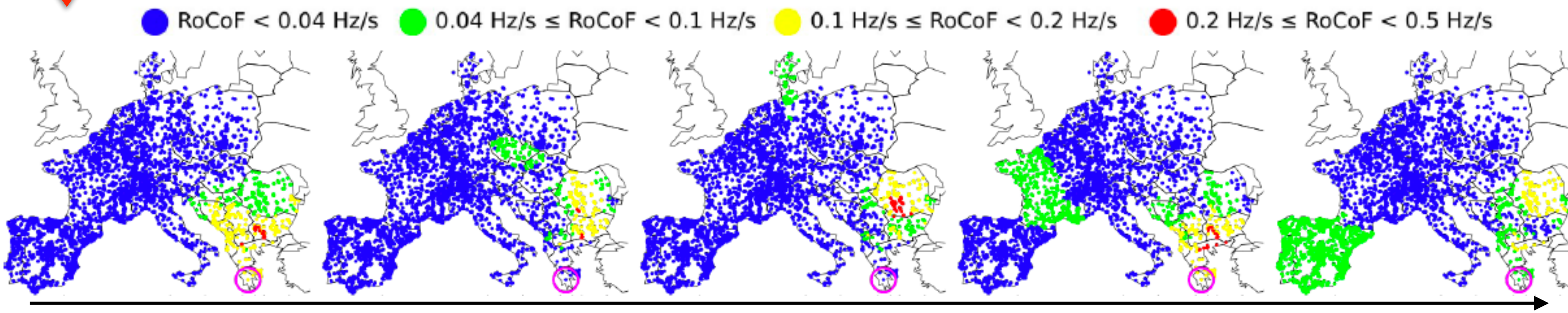


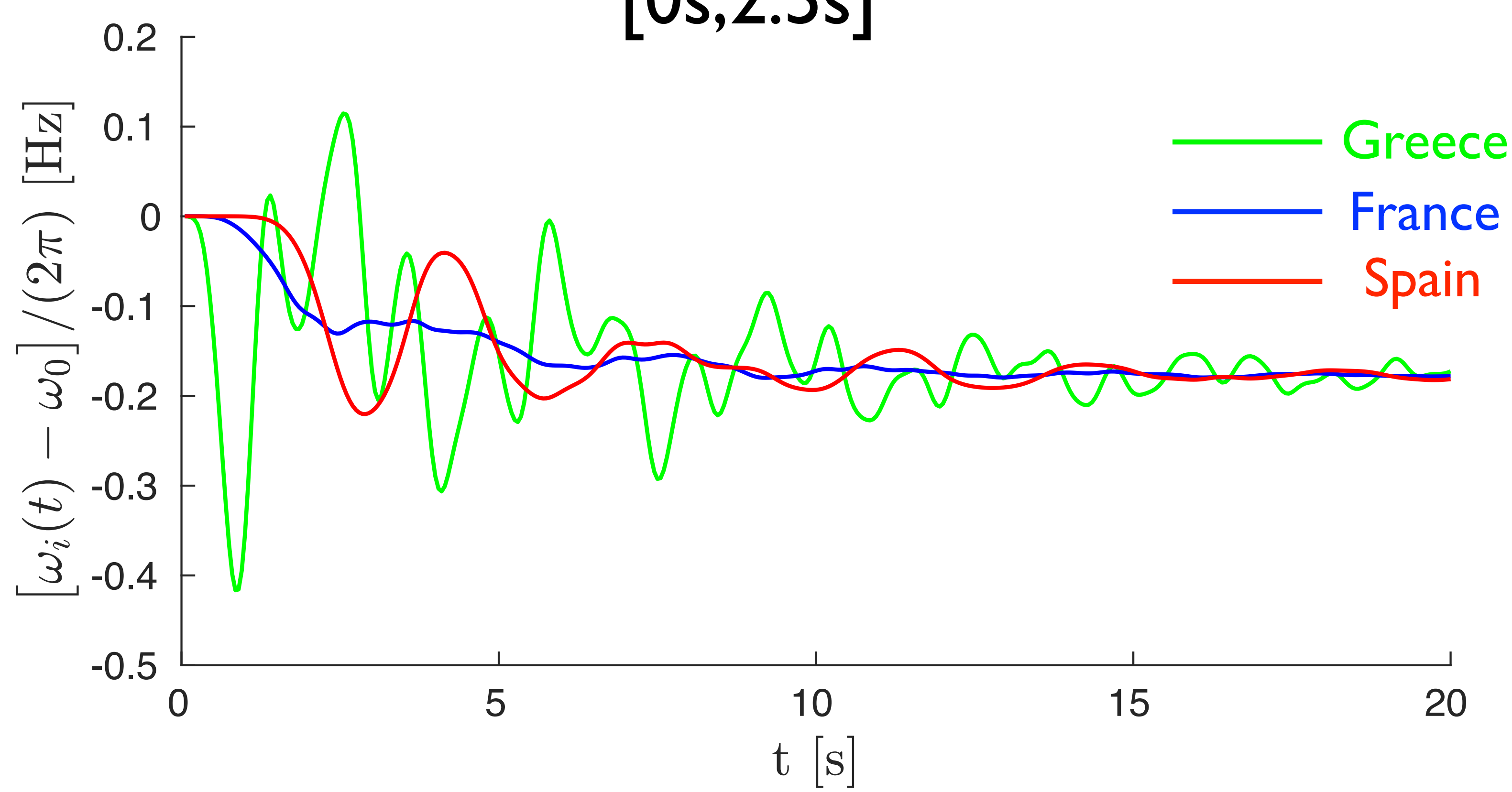
L. Pagnier & PJ, PLoS ONE '19

Disturbance propagation

Fault : sudden power loss

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





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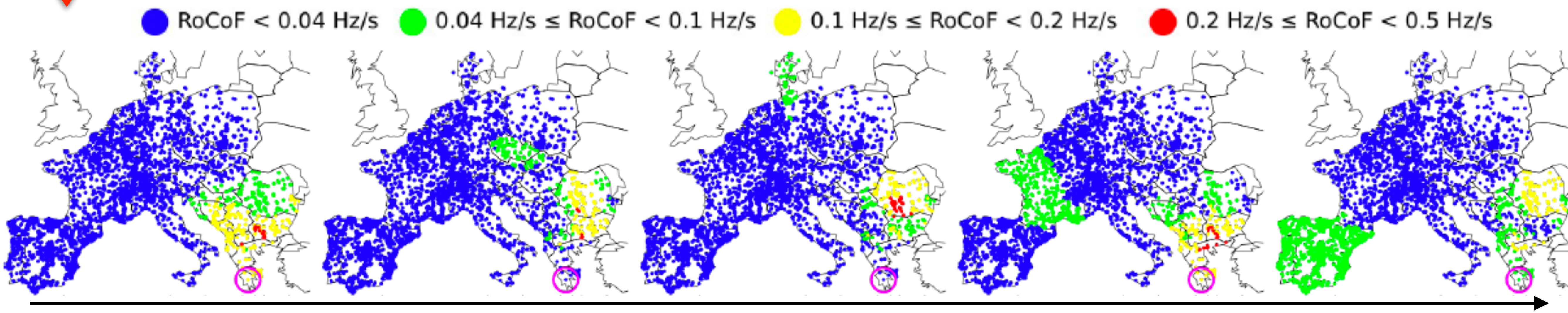
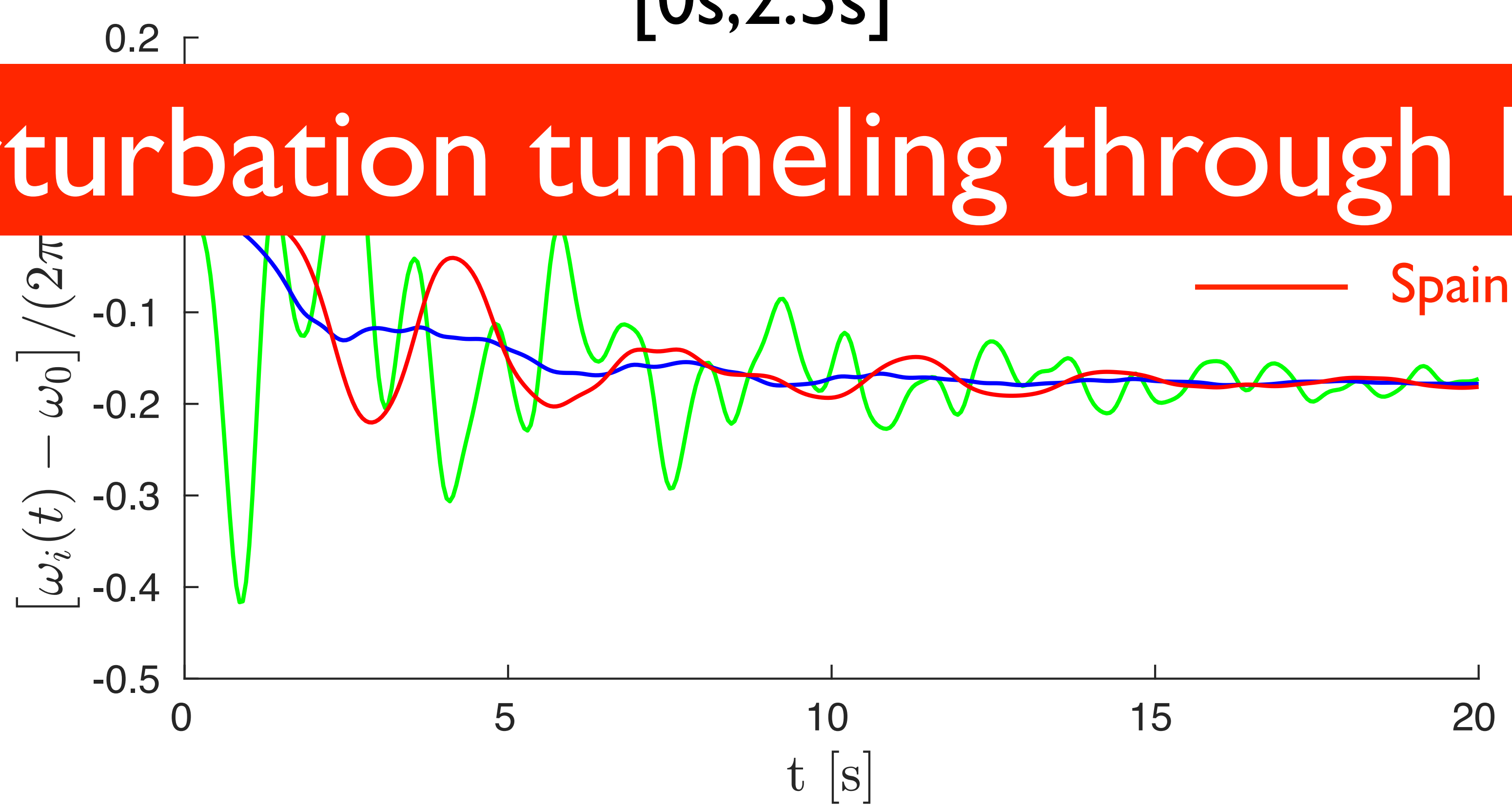
Disturbance propagation

Fault : sudden power loss

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





?? Perturbation tunneling through France ??

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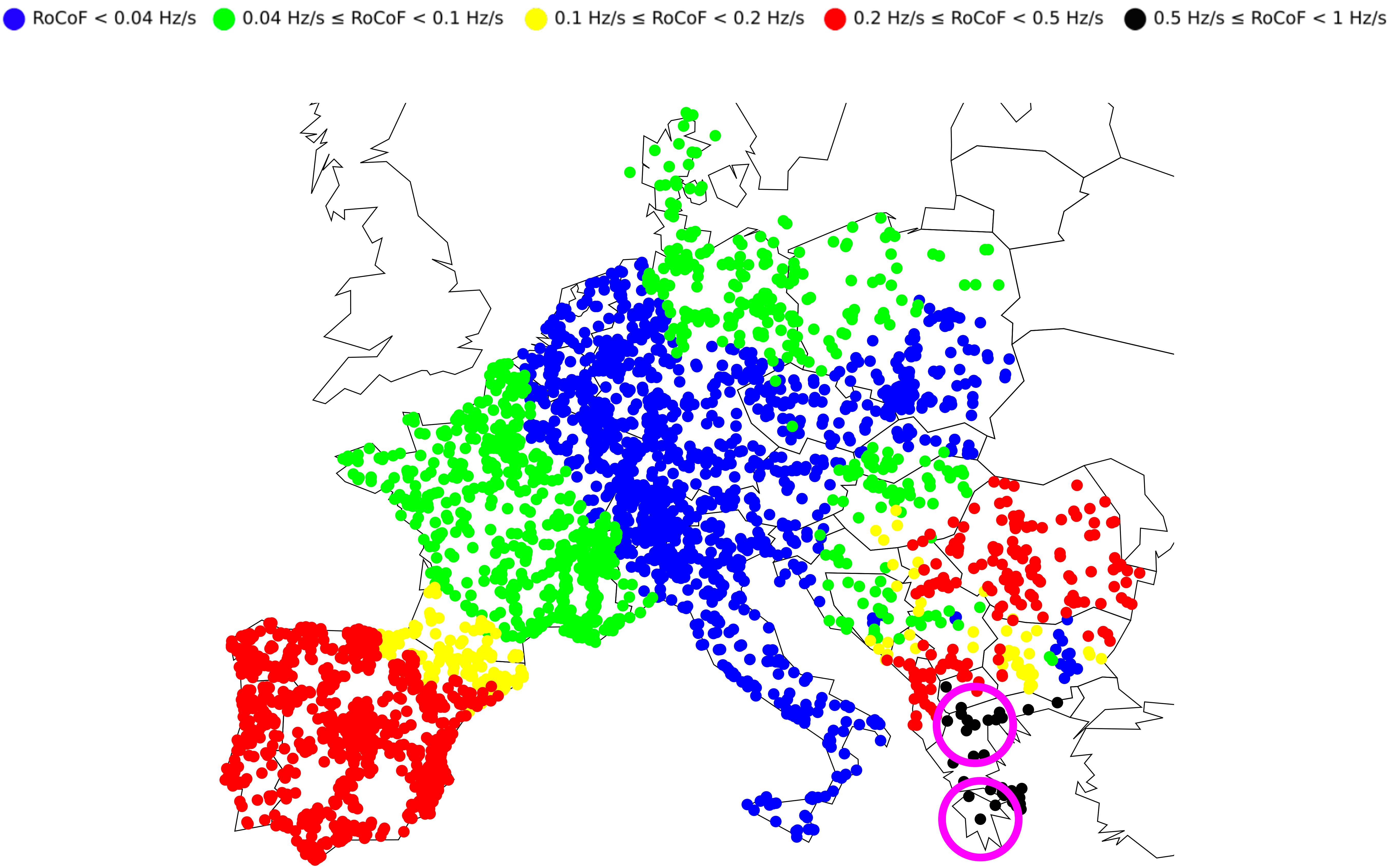
Disturbance propagation



Disturbance propagation vs. slow modes

Linearization of perturbation next to operating steady-state

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

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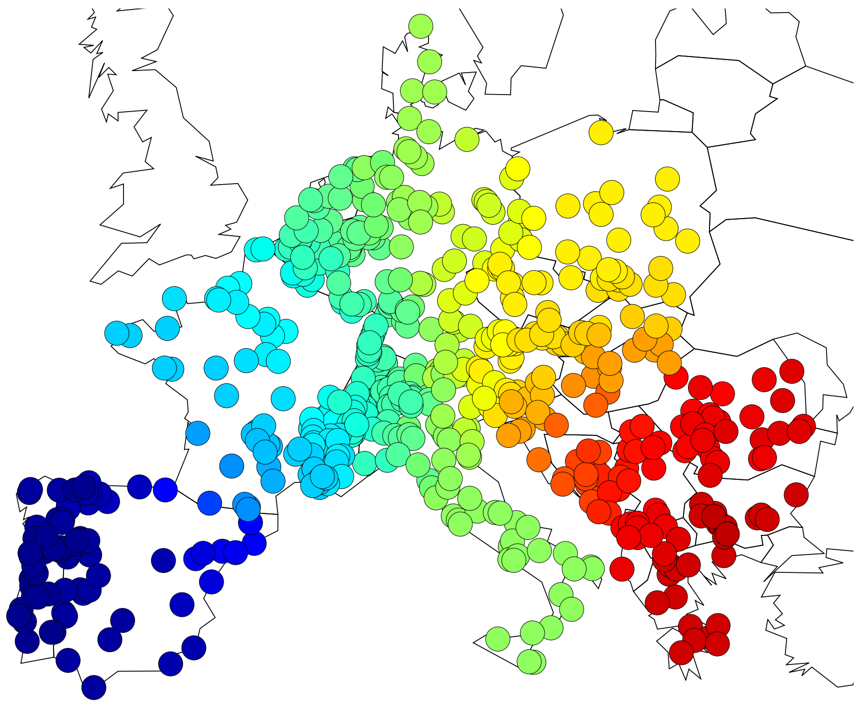
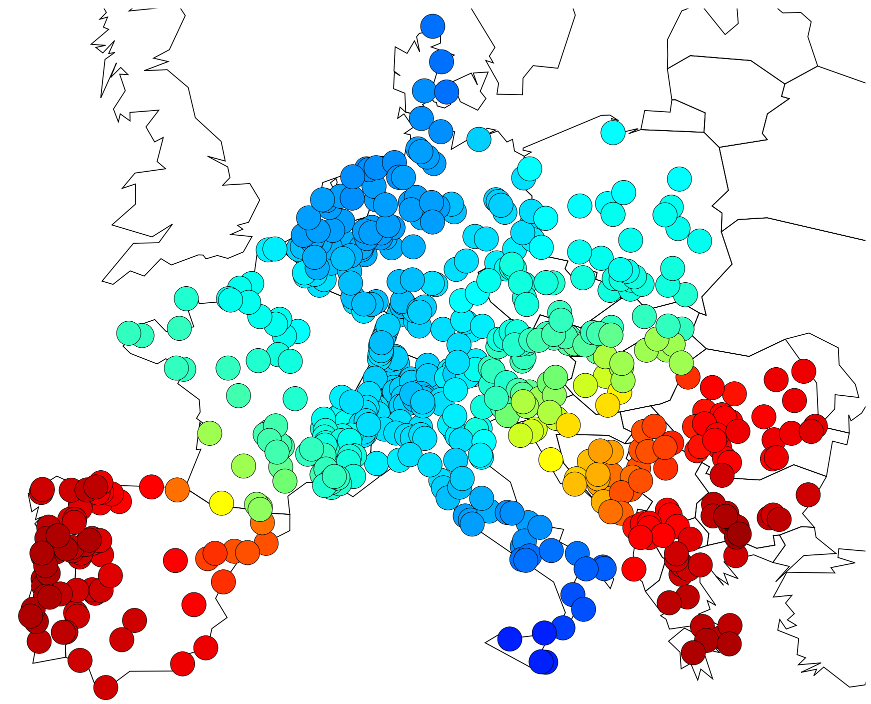
Disturbance propagation vs. slow modes

Linearization of perturbation next to operating steady-state

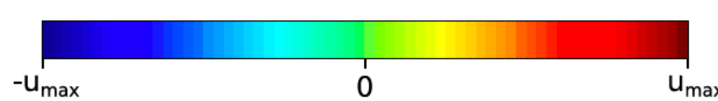
$$M\delta\ddot{\theta} + D\delta\dot{\theta} + L\delta\theta = \delta P$$

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 ?

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Disturbance propagation vs. inertia

Today's Europe

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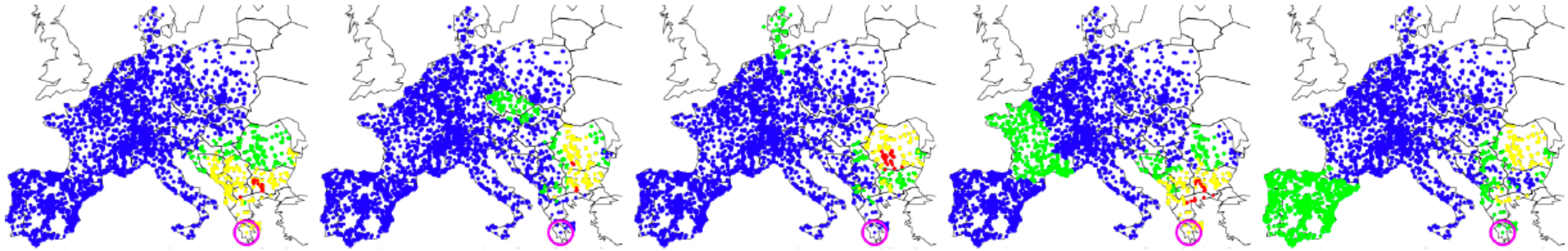
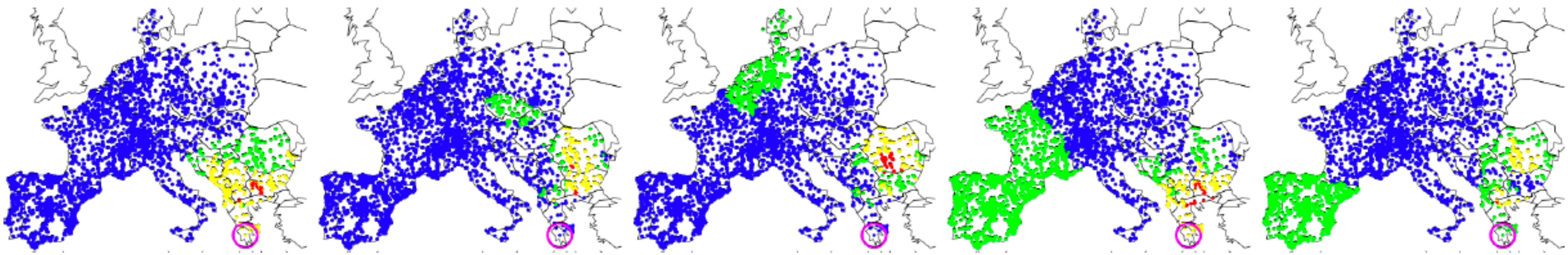
Disturbance propagation vs. inertia

Today's Europe



Inertia in France reduced to 50%



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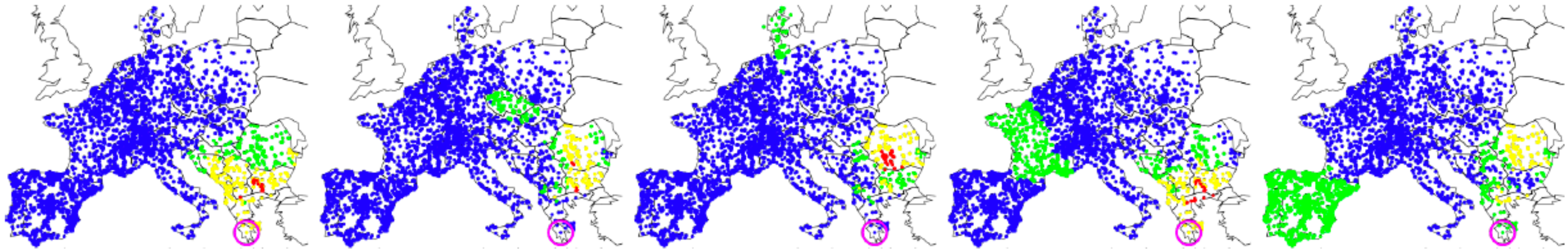
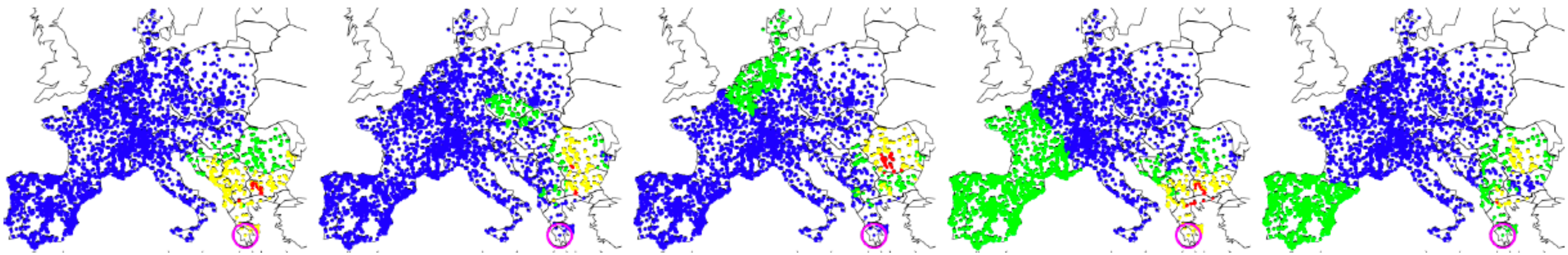
Disturbance propagation vs. inertia

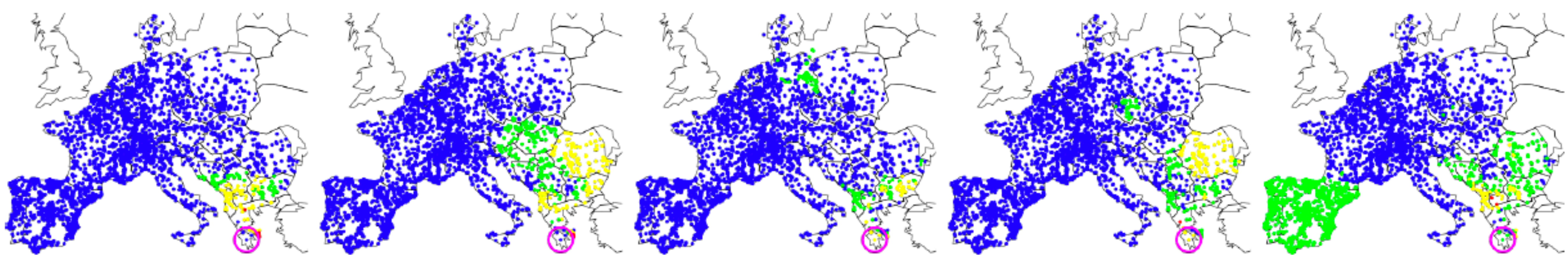
Today's Europe



Inertia in France reduced to 50%



Inertia in Balkans doubled



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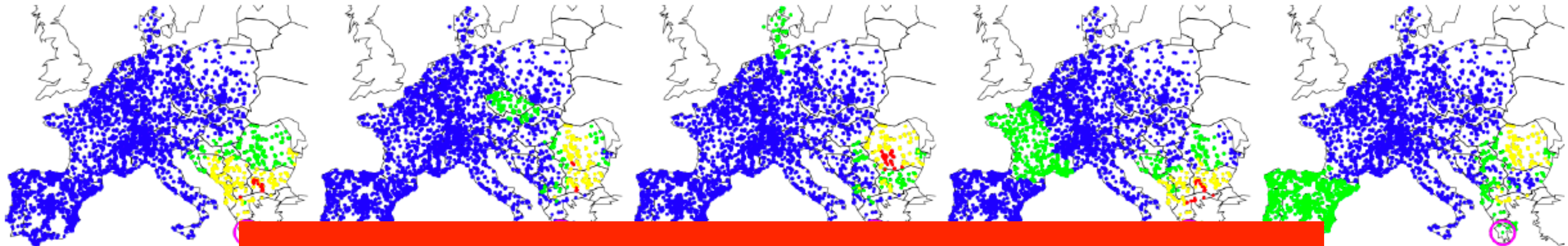
Disturbance propagation vs. inertia

Today's Europe



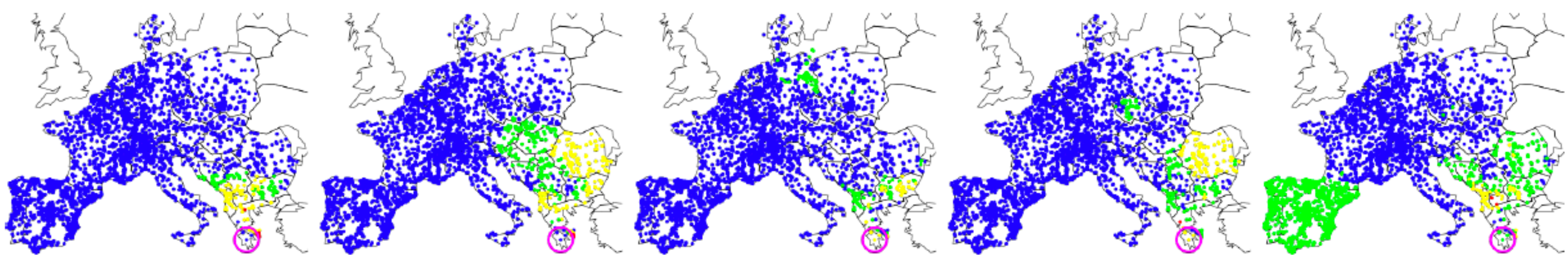
Inertia in Fr

Inertia matters mostly :

*locally

*at short times (t<1s)

Inertia in Balkans doubled



L. Pagnier & PJ, PLoS ONE '19

Disturbance propagation vs. inertia

Optimal placement of inertia and primary control : a matrix perturbation theory approach

L. Pagnier & PJ, arXiv:1906.06922

Disturbance propagation vs. inertia

Optimal placement of inertia and primary control : a matrix perturbation theory approach

Matrix perturbation theory gives approximate expressions for the eigenvectors $\boldsymbol{u}_\alpha$ and eigenvalues λ_α of $\boldsymbol{L}_M$ in terms of those ($\boldsymbol{u}_\alpha^{(0)}$ and $\lambda_\alpha^{(0)}$) of $\boldsymbol{L}$ [10]. To leading order in μ one has

$$\lambda_\alpha = m^{-1}\big[\lambda_\alpha^{(0)} + \mu\lambda_\alpha^{(1)} + \mathcal{O}(\mu^2)\big]\,, \tag{27}$$

$$\boldsymbol{u}_\alpha = \boldsymbol{u}_\alpha^{(0)} + \mu\boldsymbol{u}_\alpha^{(1)} + \mathcal{O}(\mu^2)\,, \tag{28}$$

with

$$\lambda_\alpha^{(1)} = \boldsymbol{u}_\alpha^{(0)\top}\boldsymbol{V}_1\boldsymbol{u}_\alpha^{(0)}\,, \tag{29}$$

$$\boldsymbol{u}_\alpha^{(1)} = \sum_{\beta\neq\alpha}\frac{\boldsymbol{u}_\beta^{(0)\top}\boldsymbol{V}_1\boldsymbol{u}_\alpha^{(0)}}{\lambda_\alpha^{(0)} - \lambda_\beta^{(0)}}\boldsymbol{u}_\beta^{(0)}\,. \tag{30}$$

L. Pagnier & PJ, arXiv:1906.06922

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*Optimization of a cost function ~magnitude of faults
*1st order perturbation theory about homogeneity

L. Pagnier & PJ, arXiv:1906.06922

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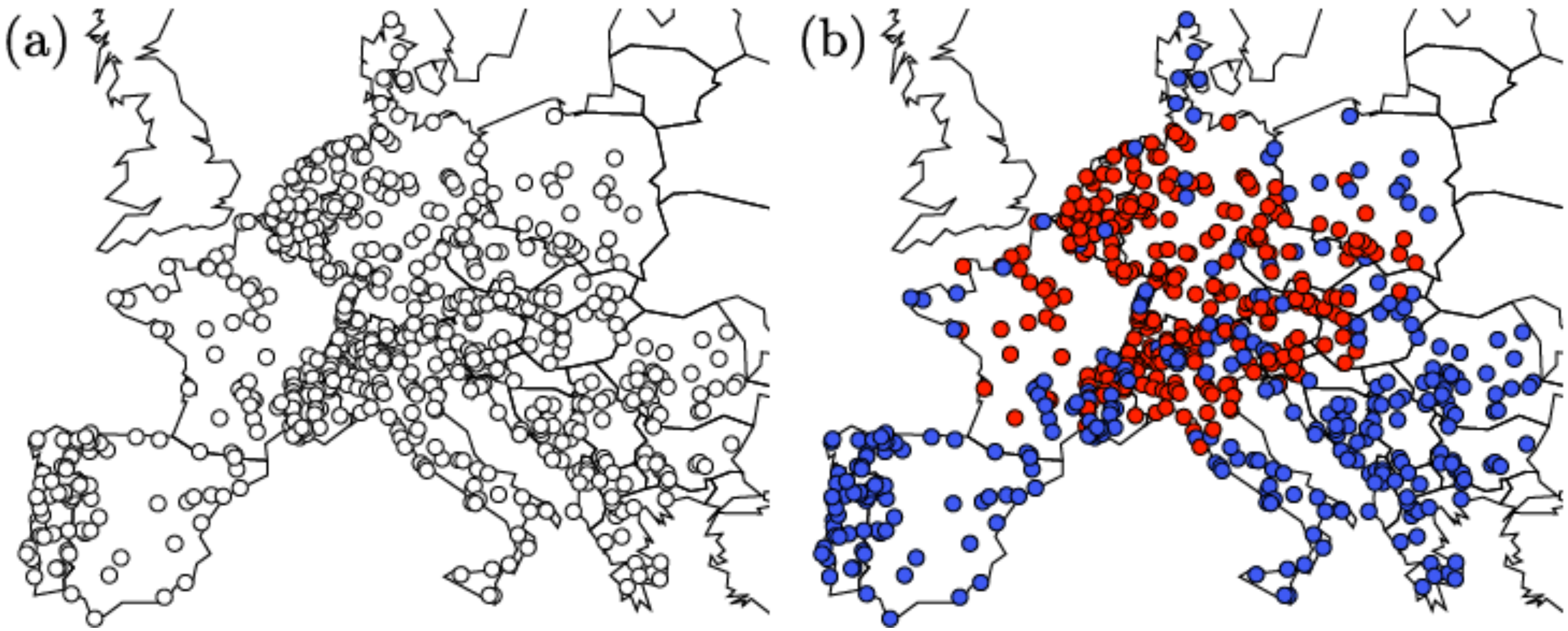

Inertia
Optimal when homogeneous

Primary control (a.k.a. damping)
Optimal when on slow modes

L. Pagnier & PJ, arXiv:1906.06922

The team

Philippe

Robin,
Melvyn
André

Laurent

Glory
(still has to discover alpine activities)

Tommaso
(now with Sophia genetics)

swissgrid FNSNF