Reconciling reliability and sustainability:
Some thermodynamic insights dedicated to the integration of renewables in the Power System
Motivation

- Drastically reduce DoF to manage macroscopic and relevant information on a system

- Provide rich- and simple-enough lumped insights on operation to long term technico-economic planning exercise
  - Space: from µm to grid scale
  - Time: from ms to 50-100 years

- Existence of "constant(s) of motion" for any steady-state dynamic system
  - Energy-based theoretically expected from time-uniformity
    ➔ 2nd principle of thermodynamics
    ➔ Space aggregation and time reconciliation

- Power system is Schneider Electric’ playground:
  - Intimacy of control and power flow
  - Indiscernability of mechanical and electromagnetic powers
    ➔ Two energy-based constants of motion
Electromagnetism: from steady-state to transient regimes

Couplings:
- magnetic free currents $I$
- Electric earth potential $V$
- heat tank Joule losses

The utility acts on:
- the mechanical power $P_m$
- the excitation of the rotor $I$

Modeling issue:

$\Rightarrow$ Decouple control and power flow

Relevant perimeter for energy assessment (1st principle): $G(T,I,V,X)$

2nd principle of thermodynamics:

$P_m - \frac{dG}{dt} \geq 0$


Electromagnetism: A natural trend towards reversibility

Weak reversibility:

\[ P_m - \frac{dG}{dt} = \min (P_m - \frac{dG}{dt}) \geq 0 \]

2nd principle of thermodynamics:

\[ P_m - \frac{dG}{dt} \geq 0 \]
Energy conservation:

\[ P_m - \frac{dG}{dt} = \min \left( P_m - \frac{dG}{dt} \right) \geq 0 \]

Weak reversibility:

\[ P_m - \frac{dG}{dt} = \min \left( P_{Joule} + \frac{d(\varphi I + QV)}{dt} \right) \geq 0 \]
Energy conservation:

\[ P_{\text{m,ext}} - \frac{dE_{\text{kin}}}{dt} - \frac{dG}{dt} = \min \left(P_{\text{joule}} + \frac{d(\varphi I + QV)}{dt}\right) \geq 0 \]

Lenz law

Faraday's law is restored by assuming a reversible evolution:
- All the energy losses (conversion, distribution, end-use) are attainable
- Multi-scale framework with successful issues (material law,…, CAD tools,…)

Energy-based «constants of motion»:
- existence justified by time-uniformity:
  - Electromagnetic energy w/ coupling \( G \)
  - Kinetic energy \( E_{\text{kin}} \)
- Conversely, provide insights for:
  - time-reconciliation, and
  - space-analysis
Power management: Basics
Focus at the higher aggregated scale

- Heat transfer
- Work flow

Poynting equation:

\[ P_{elec} + P_{m,ext} = P_{joule} + \frac{dE_{kin}}{dt} + \frac{dF}{dt} \]

- System adequacy
- Transient stability (ancillary services)
Power management: Leverage the highest kinetic energy

Before adequacy (primary/secondary/tertiary reserve)

\[ E_{\text{kin}}(\Omega) \leq E_{\text{kin}} \leq \sum_\Omega E_{\text{kin}}(\Omega) \ ? \]

Capture the critical behavior thanks to a dedicated lattice model:

- Coherence of fully-correlated oscillator population:
- Synchronism is ensured for tight enough binding (admittance matrix):

\[ \dot{\theta}_i + d_i \dot{\theta}_i = \omega_i - \sum_{\langle i,j \rangle} \frac{K_{ij}}{N} \sin(\theta_i - \theta_j) \]

\[ \lambda_2(G) \geq \| B^T P_{\text{mech}} \|_{\infty} = \max_{\{i,j\} \in G} | P_{\text{mech},i} - P_{\text{mech},j} | \]


Disordering factors:
- \( N \to \infty \) (long range disordering modes)
- Intensive use of transmission lines
- High frequency

Ordering factors:
- Lattice interaction and admittance
- Locally balanced connection point
- Low frequency

Synchronization is not inconditionnallly stable!

Power management: Decoupling control and power flow

Synchronism:

- Voltage plan conditions Reactive Power and
- Gibbs free-energy $G$ induces electrodynamic resistant torque
- "Rigidity"-induced synchronism:
  - Decrease congestion rate
  - Improve grid connectivity
  - Decrease frequency

$$H_{syn} = \frac{\lambda(G)}{\max_{ij}(P_i - P_j)}$$
Power management: Decoupling control and power flow

Transient stability:
- Frequency
- Kinetic energy $E_{\text{kin}}$
- Transient stability provides time-reconciliation:
  - Extend «copper plate» for aggregation
  - Favour huge moving mass
  - Increase the frequency

$$H_{\text{kin}} = \frac{\sum_{\Omega} E_{\text{kin}}(\Omega)}{S}$$
Active power flow exchanged throughout the grid

Synchronism:
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## Power management: Forthcoming competitions

Naturally expressed within the second principle:

\[
P_{\text{elec}} + P_{m,\text{ext}} - \frac{dE_{\text{kin}}}{dt} - \frac{dG}{dt} = \min\left(P_{\text{joule}} + \frac{d(\phi I + QV)}{dt}\right) \geq 0
\]

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Energy-based «constants of motion»:

➔ Existence justified by time-uniformity:
  – Electromagnetic energy w/ coupling $G$
  – Kinetic energy $E_{\text{kin}}$

➔ Field-type energies dedicated to stability

Dedicating flexibilities to adequacy is limited by:

➔ IT energy footprint to manage:
  • Space complexity
  • Time agility

➔ Stability issue (« real-time » never exists!)

CMA (MINES ParisTech) partnership:
- G. Seck
- R. Cluet
- and many others before

Long term planning exercise:
- Technical linear optimization model, demand-driven, achieving a technico-economic optimum
- TIMES-FR

Reduction of the transmission grid:
- Over the 13 administrative regions
- Keeping the synchronism indicator constant

Cost-effectiveness fulfillment of generation potentials
Yearly generation under reliability constraint

Regional mix under reliability constraints


Transient stability vs. synchronism

French mix fiability and network stability for various TIMES scenarios

From “country” to “local” Renewable empowerment

Realistic for balancing active energy (adequacy) for all regions except IdF (25 to 46%)

Low autonomy for ancillary services:
- Except RAA, HdF and Normandy
- High contribution of Biomass, Hydro and geothermy
- Implementation of 4GW storage (current STEP capacity)

Overgeneration of 124TWh
Grid synchronism is a **critical** issue to correctly aggregate kinetic energy and face to fluctuations:

- Centralized systems favors transient stability **but needs grid reinforcement** for the aggregation of kinetic energy; while
- Decentralized system favors synchronism **but jeopardize transient stability** by an intrinsic lack of kinetic energy. However, the constraint on synchronism is rejected on the distribution network (with lower voltage and extra losses) inducing investment at this scale;

➔ **On-grid µ-grid concept** consists in the first step of the grid transformation to host high share of renewables;
➔ **Change the grid topology (“Russian dolls”)** to remain below the Kosterlitz transition... and achieve the power system decarbonation!

High variable renewable energy penetration seems technically feasible without jeopardizing the reliability, **BUT**:

- The necessity to use conventional flexible plants (**biomass**) which are functioning in extreme peak;
- The importance of **power exchanges** with neighboring countries;
- More implications of three options for flexibility to satisfy the reliability constraint: the Demand-Response, the storage technologies and the new interconnections (copper plate);

for which the **environmental issue** should be assessed!

Design should be performed at the **largest scale**:

- to ensure **Cost-effectiveness**;
- to size **system adequacy AND ancillary services**!
- To take **externalities** into account (**scarcity of functional material and IT energy footprint**)