Minimising Electrical Losses in Long Term Power Planning

Mathilde Drouineau[1] Vincent Mazauric[2,1] Nadia Maïzi[1]

[1]Center for Applied Mathematics
Mines Paristech (France)

[2]Corporate Research Division
Schneider Electric (France)

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Electrical Losses: Observation & Trend

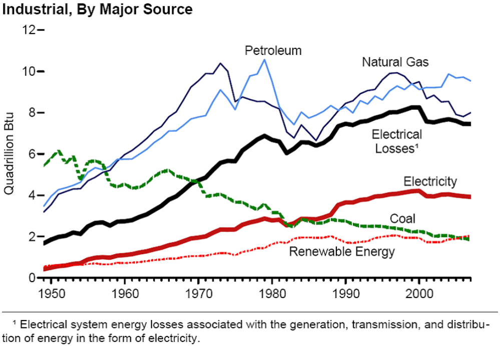

Figure: Energy consumption in the industrial sector in the US, 1949-2007.

Source: US Depatment of Energy.

- Since 1949, electrical losses are twice the electricity consumption.
- Electricity consumption will significantly increase in the next decades [IEA].
- Therefore minimising losses is a major issue.

Electrical Losses: Description

We can define two kinds of Electrical Losses :

The conveyance losses

- Occuring during power transmission;
- Depending on:
  - the **spatial distribution** of power plants and loads,
  - the network architecture,
  - the load profile;
- Can be assessed from a steady-state analysis.

The reliability-induced losses

- Required to handle the dynamic management (frequency and voltage controls);
- Depending on:
  - the level of reliability,
  - the **dynamic properties** of capacities,
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Electrical Losses: Duality

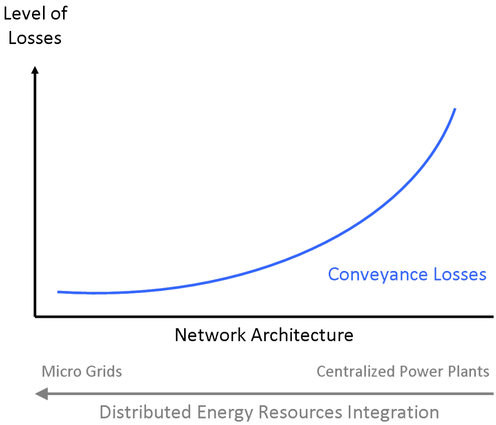

Figure: Qualitative level of losses versus network architecture.

- **Conveyance** losses decrease when capacities are close to the loads, encouraging the development of distributed units.
- Conversely, **reliability-induced** losses decrease with centralized units.
- **Our Goal**: minimising at the same time the two kinds of losses.

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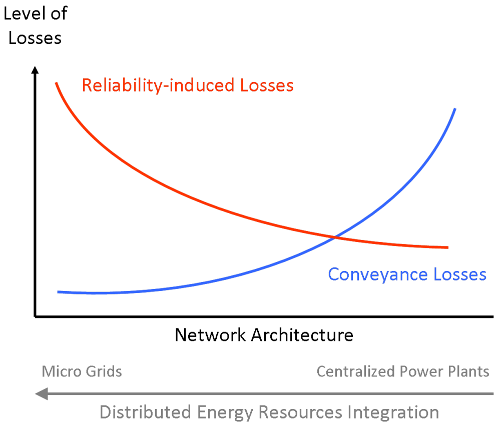

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Using a Thermodynamic Framework

Motivations:

1. We seek for a global approach to describe power systems:
    - to exhibit the main drivers of losses,
    - to avoid *time-consuming* methods relying on Kirchhoff laws.
2. This approach provides reliable results, to describe electromagnestism, especially finding the Faraday's law.
3. It shows that electricity can achieve the best power transactions.

Basic principles: 1 - Thermodynamic System

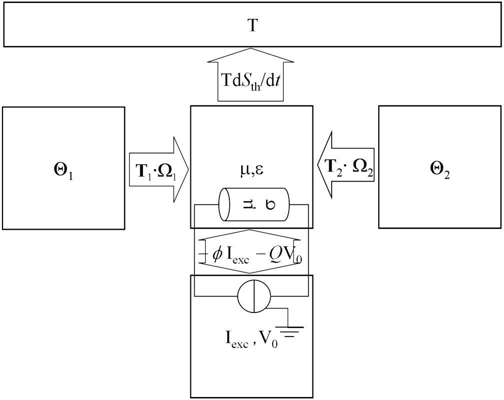

Figure: Chart of the energy exchanges between the subsystems involved in the Thermodynamic Framework.

- The electromagnetic field is the studied system. It is seen as a power conveyor.
- Generators Θ_1 exchange work with motors Θ_2 through the field.
- T is the thermostat.
- I_{exc} is the current exciting the field and V_0 the earth voltage.
- $(\Phi I_{exc} - QV_0)$ is the coupling energy between the field and the machines.

Basic principles: 2 - Variational Formulation I

Maximum-entropy Principle

- The entropy S measures the missing information describing the system.
- Equilibrium conditions are obtained from the maximum-entropy principle, while keeping the macroscopic information, namely:
  - the positions of the moving parts (Θ for the machines),
  - the internal energy $\mathcal{U}$,
  - the magnetic flux Φ and the electric charge Q squeezed from the earth.
- The system can also be described with its state variables: $\{T, I_{exc}, V_0\}$.

Basic principles: 2 - Variational Formulation II

Non-equilibrium Evolution

- For non-equilibrium conditions, considering an isothermal evolution, the entropy of the isolated[a] system can only increase.
- Then, the evolution is said **reversible** when the entropy is not modified.
- Otherwise, the evolution is said **irreversible** and the more reversible evolution is reached when the variation of entropy is minimised.

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[a] The system is isolated thanks to the couplings exhibited in the last picture.

Basic principles: 3 - Condition of Reversibility I

1. The **First Principle** conveys the Energy Conservation:

$$\frac{dU}{dt} = P_{\text{mech}} - T\frac{dS_{\text{th}}}{dt} \tag{1}$$

   - U is the internal energy of the isolated system,
   - $P_{\text{mech}} = \sum \mathbf{T} \cdot \mathbf{\Omega}$ is the mechanical power,
   - S_{th} is the entropy of the thermostat, and $T\frac{dS_{\text{th}}}{dt}$ is the heat exchanged with the thermostat.

2. For an isothermal evolution, we introduce the Helmoltz free-energy, $F = U - TS$, to take into account the coupling with the thermostat T:

$$P_{\text{mech}} - \frac{dF}{dt} = T\left(\frac{dS}{dt} + \frac{dS_{\text{th}}}{dt}\right) \tag{2}$$

The RHS stands for the Joule losses, the heat dissipated by the whole system.

Basic principles: 3 - Condition of Reversibility II

- According to the **Second Principle**, Joule losses are always $\geqslant 0$.
- When minimised, the evolution is the more reversible.

3. To take into account the electromagnetic coupling, we introduce the Gibbs free-energy, $G = F - \Phi I_{exc} - QV_0$.
   A **condition of reversibility** for power systems is then expressed:

$$P_{mech} - \frac{dG}{dt} = \min\left(P_{Joule} + \frac{d(\Phi I_{exc})}{dt} + \frac{d(QV_0)}{dt}\right) \tag{3}$$

Main Remarks

The condition of reversibility:

$$\min \left(P_{\text{Joule}} + \frac{d(\Phi I_{\text{exc}})}{dt} + \frac{d(QV_0)}{dt} \right) \qquad (4)$$

1. We use a **global approach** which enables to use a multi-scale description of power systems.
2. The reversibility condition suggests drivers to approach the minimum of losses:
   - the Joule losses, related to the spatial distribution,
   - the electromagnetic coupling, related to the dynamic management.

One-Loop Grid: *power systems with a global description*

Using the Thermodynamic Framework, the description of a power system is reduced to its upper scale. It comes down to a One-loop Equivalent Circuit:

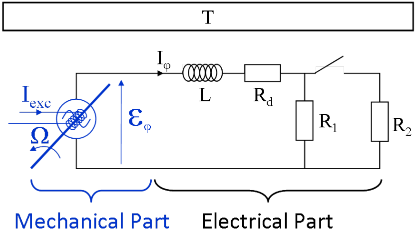


Figure: The One-loop Grid, a circuit equivalent for power systems. One-phase φ representation.

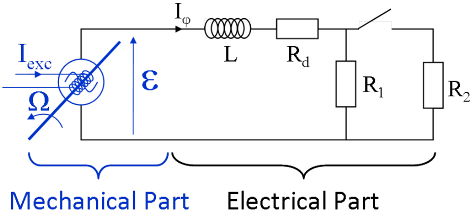
Mechanical equation:

$$\frac{d}{dt}\left(\frac{J\Omega(t)^2}{2}\right) = P_{Gene} - \sum_{\varphi} \varepsilon_\varphi(t) I_\varphi(t) \tag{5}$$

Electrical equation:

$$\varepsilon_\varphi(t) = L\frac{dI_\varphi(t)}{dt} + (R_d + R_1) I_\varphi(t) \tag{6}$$

Power Conservation in the One-loop Grid



$$P_{Gene} - P_{Load} = \sum_{\varphi} R_d I_\varphi^2(t) + \frac{d}{dt}\left(\sum_{\varphi} \frac{L I_\varphi^2(t)}{2} + \frac{J\Omega(t)^2}{2}\right) \tag{7}$$

- $P_{Load} = R_1 I_\varphi^2(t)$,
- $P_{Joule} = \sum_{\varphi} R_d I_\varphi^2(t)$.

Formulation of the Optimisation Problem

- We state the **Optimisation Problem** as follow:

Objective Function:

The best power transaction is achieved for:

$$\min \left(\underbrace{R_d I_\varphi^2(t)}_{\text{Power Transmission}} + \underbrace{\frac{d}{dt}\left(\frac{L I_\varphi^2(t)}{2} + \frac{J\Omega(t)^2}{2} \right)}_{\text{Dynamic Management}} \right) \tag{8}$$

which is related to the conveyance losses (power transmission) and the reliability-induced losses (dynamic management).

- **Next Step**: finding the **Constraints** binding our problem.

Technical Constraints

Figure: Europe from orbit during the Italian blackout (Sept. 28th, 2003).
Source: French TSO.

Constraints binding the Optimisation Problem are related to:

- the given spatial distribution of loads and capacities;
- the expected level of reliability to prevent from power outages.

Recent issue related to the level of reliability.

Using **Transient Stability Studies**:

- load fluctuations management;
- based on Power System Analysis.

Transient Stability

Definition: Ability of a Power System after a Transient Period to lock back into Steady-State conditions, maintaining Synchronism.

During the Transient Period:

- Frequency and voltages change;
- The operator can't modify the production plan;
- The system relies on the inertia (kinetic and magnetic) of its transmission and production capacities;
- The power system must remain stable.

Transient Stability Studies assess the level of Reliability of power systems.

3-bus Power System

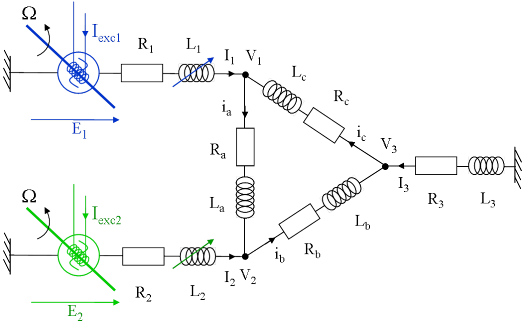


Figure: 3-bus Power System on which we carry out Transient Stability Studies.

Stability Limits

Frequency Variations:

- Related to kinetic power (J)
- Stability: ±0.5 Hz

Load Voltage Variations:

- Related to reactive power (L)
- Stability: ±5%

Power Angle δ (generator):

- Between the open-circuit voltage ε and the terminal voltage V
- $P_{\text{Gene}} = \dfrac{\varepsilon V}{X_{\text{Gene}}} \sin\delta$
- Stability: $-90^\circ \leqslant \delta \leqslant +90^\circ$

Decision Variables & Feasible Space

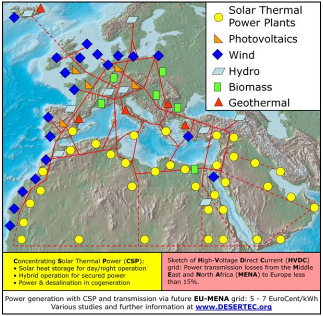
- **Decision Variables** of the Optimisation Problem may be as follow:

Decision Variables:

- R, related to the Spatial Distribution
- J, L, δ, P_{mech} related to Transient Stability Studies

- **Feasible Space** from the 3-bus Power System:
  - **expected results**
  - Frequency variations with the One-loop Grid. ▸ Jump to Frequency

Main Conclusions



Concentrating **S**olar Thermal **P**ower (**CSP**):
- Solar heat storage for day/night operation
- Hybrid operation for secured power
- Power & desalination in cogeneration

Sketch of **H**igh-**V**oltage **D**irect **C**urrent (**HVDC**) grid: Power transmission losses from the **M**iddle **E**ast and **N**orth **A**frica (**MENA**) to Europe less than 15%.

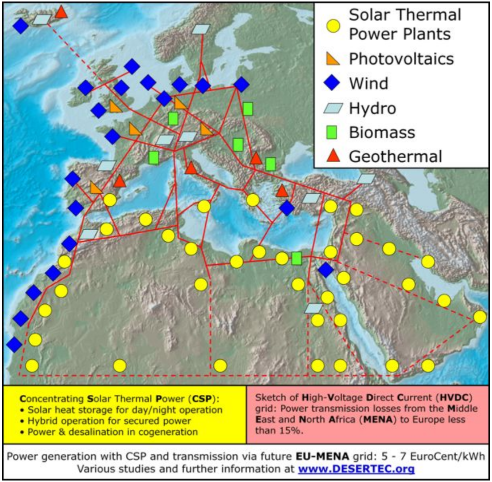
Power generation with CSP and transmission via future **EU-MENA** grid: 5 - 7 EuroCent/kWh
Various studies and further information at www.DESERTEC.org

Figure: All-Renewable Electricity Generation in 2050.

Source: DESERTEC.

Conclusive Remarks

1. **Contributions**:
   - A global description of Electrical Losses;
   - Formulation of an Optimisation Problem.
2. **Main stakes**:
   - Finding best power systems in terms of power transactions;
   - Dealing with the question of Distributed Energy Resources in Long Term Power Planning.
3. **Perspective**:
   - Using this description of Electrical Losses in Long Term Power Planning Tools.



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Annex: Frequency Variations

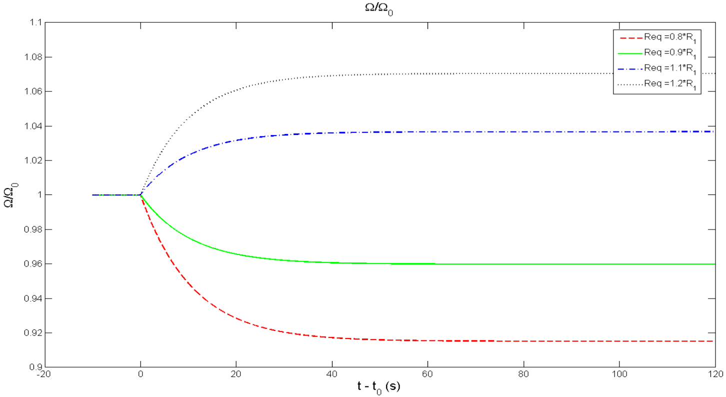

Figure: Frequency variations for different amplitudes of fluctuation for the One-loop Grid.