Reliability in future electricity mixes: the question of distributed and renewables sources

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10th IAEE European Conference (Vienna, 2009)

Supported by the Chair Modeling for Sustainable Development.

Context: *Renewable and Distributed Energy Sources*

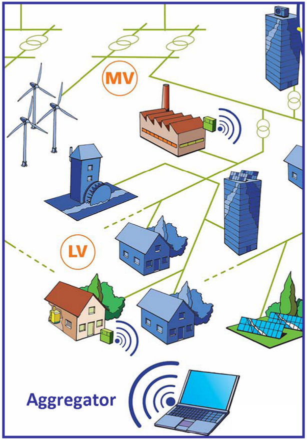


Figure: Smartgrid concept.
Source: EU-DEEP Project.

Pushed by

- the need for **carbon emission abatement**, and
- the expected **depletion of fossil fuels**,

Electricity generation is entering a period of significant change:

- in the generation share, with the integration of more **Renewable Energy Sources**;
- in the architecture of power systems, with the development of **Distributed Power Units**.

To what extent these trends can be followed ?

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

1. Recently, highly optimistic scenarios have promoted these trends.
2. But their quality of power supply is not assessed.

Energy modelers must take reliability issues into account to build **plausible long-term options**.

Outline

1. Reliability and Long-Term planning tools
2. Method
3. Results: the "reliability indicators"
4. Discussion

Reliability requirements: *in the generation planning tools*

In monopolies:

- Production cost efficiency was driven by bigger plant sizes.
- Centralized decision-making encouraged over-sizing investments, preventing from the reliability issues.
- Reliability was dealt with:
  - Loss of Load Probability (LOLP)
  - Expected Unserved Energy (EUE)

In competitive markets:

- Smaller installations are economically justified.
- Competition has become possible among power producers.
- Less attention is paid to investments in generation, **threatening the reliability of power supply.**

Reliability requirements: *subjacent technical issues*

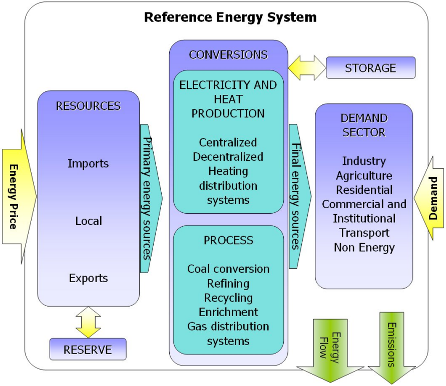
Electricity must comply with real-time adequacy:

1. **Energy flows** Adequacy in terms of energy exchanges.
2. **Power capacities** Dimensionning for the highest demand period.
3. **Ancillary services** Services to maintain reliable operations of the interconnected transmission system.

Key features of the ancillary services:

- i.e. the capability to handle load fluctuations.
- Involved in power systems regulation.
- Currently assessed with transient studies.
- Time scale: few seconds to few hours.

Long-term planning tools: *the MARKAL/Times models*



- **Inputs:**
  - Exogeneous demand;
  - Available technologies;
  - Energy prices.
- **Outputs:**
  - Optimal technologies;
  - Optimal timing of investment;
  - Global cost;
  - Emissions.

- MARKAL/Times are **technological** models driven by demand.
- Their objective function is the **minimization** of the global and discounted cost of the energy system.

Subsequent bias for future electricity systems

When ignoring the reliability requirements, the forecasted electricity systems may:

1. have a **poor quality of power supply**;
2. be **economically sub-optimal**, regarding the cost of:
    - the **additional investments** in back-up reserve (no over-sizing),
    - the level of **losses**.

Electricity 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,
  - i.e. **the generation share**,
  - the load profile.

Electricity Losses: duality

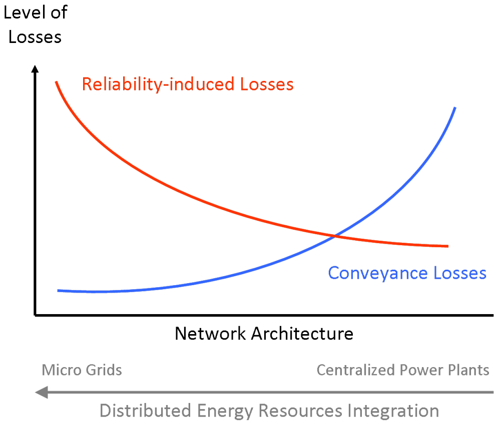


Figure: Qualitative level of losses versus network architecture.

- **Conveyance** losses decrease when capacities are close to the loads, encouraging the development of distributed units.
- Usually the only kind of losses considered in power planning.
- Conversely, **reliability -induced** losses decrease with centralized units.

The burden of electricity losses

Cost of losses in France in 2006:

- 487 M€ in the transmission network;
- 837 M€ in the distribution networks.

Power Plants	**Operating costs** ($/kW in 2015)	**Electricity losses** (€/kW in 2006)
Supercritical coal-fired	40	12
Gas-fired CCGT	15	"
Nuclear	108	"
Wind onshore	40	"
Wind offshore	90	"
Solar PV	23	"

Table: Forecasted operating costs for different power plants in Europe in 2015 (Source: OECD/IEA, 2008), and the cost of losses for the French electricity industry in 2006.

Frequency control and power variations

Reliability relies on the dynamic management of power systems.

Frequency control

1. Maintaining an equilibrium with the power consumed/provided.
2. Disturbances in this balance cause a deviation of the frequency, related to the **kinetic energy** of the rotating generating units.
3. A primary control re-establishes the balance, changing the frequency.
4. The secondary control restore the frequency and the contractual power exchanges.

Voltage control and reactive power management

Voltage control

1. Voltage levels are maintained locally by **reactive power**.
2. Generators, loads, lines, transformers are reactive power consumers and producers, depending on their operational state.
3. A primary control adjusts reactive power by voltage regulators of generating units.
4. Other controls rely on reactive compensation equipment.

Using a Thermodynamic Framework

Motivations:

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

View the thermodynamic system

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 provides the **One-loop Equivalent Circuit:**

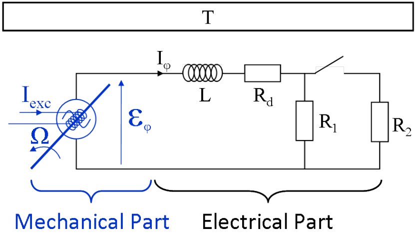


Figure: The One-loop Grid, a circuit equivalent for power systems. One-phase φ representation.

Mechanical equation:

$$\frac{d}{dt}\left(\frac{J\Omega(t)^2}{2}\right) = P_{Gene} - \sum_{\varphi} \varepsilon_\varphi(t) I_\varphi(t) \quad (1)$$

Electrical equation:

$$\varepsilon_\varphi(t) = L\frac{dI_\varphi(t)}{dt} + (R_d + R_1) I_\varphi(t) \quad (2)$$

Frequency and voltage variations

1. It provides frequency and voltage deviations **after an imbalance**.
2. We can state an **Optimisation Problem** as follow:

The best power transaction is achieved for:

$$\min \left(\underbrace{R_d I_\varphi^2(t)}_{\text{Power Transmission}} + \underbrace{\frac{d}{dt}\left(\frac{L I_\varphi^2(t)}{2} + \frac{J\Omega(t)^2}{2}\right)}_{\text{Dynamic Management}} \right) \tag{3}$$

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

- **However**, frequency and voltage variations are bound by stability limits, **shaping the feasible space for reliable electricity mixes**.

Key parameters in frequency deviations

- The relaxation time constant $\tau_{\text{mech}} = \frac{J\Omega_0^2}{P_{\text{mech}}}$.
- The kinetic energy stored, $\frac{1}{2}J\Omega_0^2$, explicitly depending on J.

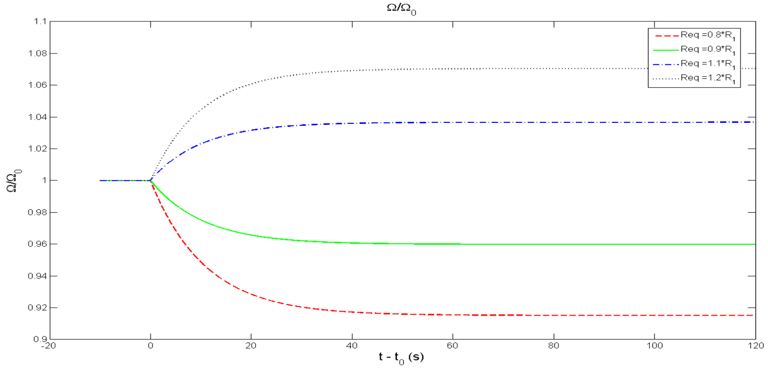


Figure: Frequency variations for different amplitudes of the load fluctuation.

Mechanical inertia of the system

- J is the constant of inertia of the whole production system.
- Frequency variations are bound by stability and contractual limits.
- Variation margins are ± 0.5 Hz, around 30s.

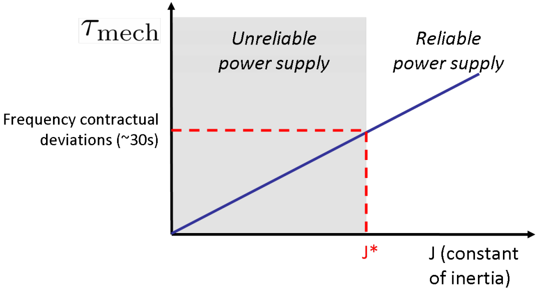
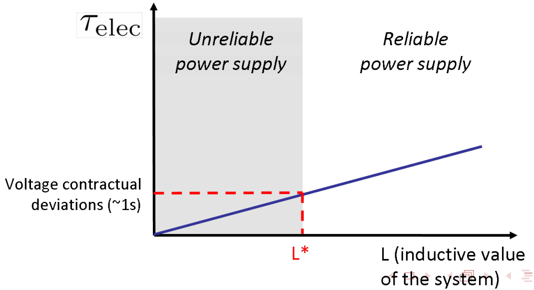


Figure: J* may define a limit between reliable and unreliable power supply.

Inductive properties of the system

- Voltage deviations:
  - The relaxation time constant is $\tau_{\mathrm{elec}} = \frac{L}{R_1}$.
  - The magnetic energy storage is more complex to model.

- L lumps the inductive properties of the generation and transmission means.
- Voltage variations are also bound:
  - Variation margins are ± 5 % and adjustment time is around a second.



Synchronism and power angle of the machines

- Synchronism is also an important issue for power system stability;
- Related to the power angle δ in the generators:
    - The power angle is a physical measure in the machines.
    - The power provided to the system depends on δ.
    - Variations margins are $-90^\circ \leqslant \delta \leqslant +90^\circ$.
- Otherwise, generators loose synchronism and disconnect.

The case of Distributed Power Units

- Microgrids and smartgrids are alternatives to centralized and conventional power plants.
- Power systems tend to be smaller and weakly interconnected.

Three main causes of dissastisfaction:

- The **energy stored decreases**, requesting investments in back-up units.
- τ_{mech} and τ_{elec} must stay high enough, and respectively **the properties $\mathbb{J}$ and $\mathbb{L}$ of power systems**.
- It is harder to benefit from the dispersion of energy sources.

Reliability requirements must be provided **locally (on-site)** in dispersed architecture.

The case of Renewable Energy Sources

- **With Renewable Energy Sources, dynamic management is not as efficient as with conventional power plants.**

Generating unit	H**(s)**
Thermal unit (a) 3600 r/min (2-pole) (b) 1800 r/min (4-pole)	 2.5 to 6 4 to 10
Hydraulic unit	2.0 to 4.0
Wind unit	3
Tidal energy unit	0.9

Table: Inertia constant (H) values for conventional and renewable power plants issued from. $H = \frac{\tau_{mech}}{2}$.

Renewable energy sources **tend to lower the reliability** of power supply.

Conclusive remarks

1. **Reliability requirements are crucial** when designing future electricity mixes. They induce:
   - extra-losses on the network ;
   - additional investments in capacities.
2. Reliability can be assessed through "**reliability indicators**", relying on **objective** features of power systems.
3. Ultimately, **integrating distributed and renewable energy sources** tends to lower reliability of power supply and **should be done carefully**.

Perspectives

- We consider **linking** this method with the **MARKAL/Times** models.
- **Small island grids** with few interconnecions may be the first case study.

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Annex: *the thermodynamic system*

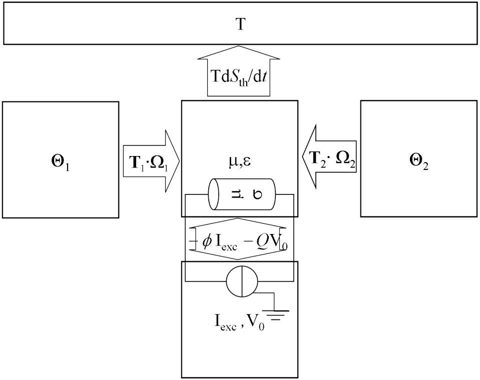

Figure: Chart of the energy exchanges between the subsystems.

- 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.

Return