International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 1091

SPACE ANALYSIS OF RELIABILITY-CONSTRAINED SCENARIOS WITH INCREASING SHARES OF RENEWABLES FOR THE FRENCH POWER SECTOR IN 2050

Raphaël Cluet[1,2], Nadia Maïzi[1], Vincent Mazauric[2*]

[1]MINES ParisTech, PSL Research University, Center for Applied Mathematics, CS 10207 rue Claude Daunesse 06904 – Sophia Antipolis, France

[2]Schneider Digital, 38TEC building, 38050 – Grenoble cedex 9, France

ABSTRACT

This paper reviews the conditions for ensuring the space consolidation and time reconciliation of all scales involved in power system energy planning. At the upper space scale, a simplified description of the grid based on the Kuramoto model is adopted to assess the stability of the synchronism state of the power system. The consequences of a massive dissemination of renewables for the future of the power system is addressed in the case of France in a long-term planning exercise up to 2050. Attention is paid to how the new capacities are dispatched among the administrative regions. While a favorable impact of sparse generation on the synchronism is obtained, the constraint on the inertia provided by the kinetic energy has to be endogenized to enforce an operable power mix under admissible disturbances.

Keywords: Power generation, Energy planning, Transient stability, Space aggregation, France.

NONMENCLATURE

Abbreviations	
BAU	Business As Usual
RES	Renewable Energy Sources
VRE	Variable Renewable Energy

1. INTRODUCTION

Power system generation has to adapt in real time to consumption, which is highly fluctuating and only partly predictable. Two intricate problems concern grid operators and utilities, involving several time-scales [1]:

- Maintaining ancillary services, especially power system quantities, within security margins during normal and transient operations, notably the frequency and voltage plan [2].
- Handling the evolution of power systems, which is driven by political, economic, social and environmental issues addressed through long-term energy planning models to ensure the system adequacy.

In order to address the considerable challenge of grid decarbonization, the massive introduction of VRE generation is taken for granted. Hence, a general framework is needed to:

- Aggregate the space characteristics of the power grid to capture the sparse generation of renewable energy sources (RES).
- Reconcile the short-term dynamics of power system management and long-term analysis in the context of implementation of non-dispatchable Variable Renewable Energy (VRE).

The next section recalls the global conditions for ensuring the transient stability and reliability of the power supply from a thermodynamic point of view. This theoretical framework is then applied to provide a long-term analysis dedicated to the French power system. Attention is paid to space analysis. To our knowledge, this is the first attempt to provide such a full description for an electro-intensive country by deriving reliability-constrained scenarios with their space analysis from first principles [3].

2. POWER SYSTEM OPERATIONS

For local design or power management purposes, the electrical power P_{elec} is expressed from the power deviation in the domain Θ, typically surrounding an electrical machine, to [4]:

- Locally enforce the integral form of Poynting's conservation equation:

$$\mathrm{P_{mech}}(\Theta) + \mathrm{P_{elec}}(\Theta) = \mathrm{P_{Joule}}(\Theta) + \frac{\mathrm{dF}}{dt}(\Theta) + \frac{\mathrm{dE_{kin}}}{dt}(\Theta) \quad (1)$$

- Globally satisfy:

$$\sum_{\Theta} \mathrm{P_{elec}}(\Theta) = 0 \quad (2)$$

where:

- $\mathrm{P_{mech}}$ denotes the net mechanical power received externally by the actuators; and
- $\mathrm{P_{Joule}}$ the Joule losses;
- F is the electromagnetic (Helmoltz free-) energy; and
- $\mathrm{E_{kin}}$ the kinetic energy.

Basically, the steady state of any power grid is operated within a time-harmonic regime at the frequency $f = \omega/2\pi$ typically operated at 50 or 60 Hz. Each machine is then mechanically balanced between a running electrodynamic torque – obtained with a suitable voltage plan – and a motor torque. Under admissible load fluctuation, the huge inertia of the machines prevents an abrupt frequency deviation. Therefore, such deviations should only occur over several periods. However, some frequency discrepancies can be observed between the domains Θ according to the location of the fluctuation. Denoting harmonic peak-to-peak values with ^ and long-time averaged values with ~, the power dynamics undergone by the whole power grid follow a low-pass filtering on (1):

$$\tilde{\mathrm{P}}_{\mathrm{mech}}(t) = \tilde{\mathrm{P}}_{\mathrm{Joule}}(t) + \tilde{\mathrm{Q}}(t) + \frac{\mathrm{d}\tilde{\mathrm{E}}_{\mathrm{kin}}}{\mathrm{d}t}(t) \quad (3)$$

where $\tilde{\mathrm{Q}} = \frac{\mathrm{d}}{\mathrm{d}t}(\hat{\mathrm{F}}/2)$ is the so-called reactive power, i.e. exchanged with the electromagnetic field. In addition, the useful kinetic energy, i.e. that which acts as a dynamic reserve for the stability of the whole power grid, obeys the set of inequalities:

$$\min_{\Theta} \mathrm{E_{kin}}(\Theta) \le \tilde{\mathrm{E}}_{\mathrm{kin}}(t) \le \sum_{\Theta} \mathrm{E_{kin}}(\Theta) \quad (4)$$

where the upper bound is reached only if the synchronism is achieved over the whole power grid during the transient regime. In other words, some locally available kinetic energy has been lowered in Joule losses by the inrush currents during the transient and discarded by the low-pass filtering performed on (1).

In order to maintain the kinetic energy as high as possible in the face of a sudden disturbance, it appears critical to enforce the synchronism to examine power system reliability. In the framework of a power system, it is convenient to tackle this problem using the Kuramoto model. This model was devised to describe the interaction between any population of non-linear coupled oscillators connected to each other [5]. The Kuramoto model has been extended to cover more general, heterogeneous, and not necessarily complete networks [6]. It has also been adapted to power grids with a formulation that describes the transient swings in the power angle of generators connected to a grid [7]. A condition for keeping a stable solution – i.e. backing locally and exponentially to a synchronous steady state after any slight disturbance – was established in [8]. This condition expressed that the grid's algebraic connectivity $\lambda_2(G)$ of the graph G underlying the power grid (LHS) is higher than the infinite norm on the product between the incidence matrix B of the grid and the vector of mechanical powers connected to the grid (RHS):

$$\lambda_2(G) \ge \left\| \mathrm{B}^T \mathrm{P_{mech}} \right\|_\infty = \max_{(i,j)\in\varepsilon_G} \left| \mathrm{P}_{\mathrm{mech},i} - \mathrm{P}_{\mathrm{mech},j} \right| \quad (5)$$

where ε_G denotes the set of edges of the graph G and $\mathrm{P}_{\mathrm{mech},i}$ the mechanical power supplied at node i.

Hence, the intrinsic stability of a power system, given the grid topology and the list of connected generators, consists in the ratio between the LHS and the RHS of (5):

$$H_{\mathrm{sync}} = \frac{\lambda_2(G)}{\max_{(i,j)\in\varepsilon_G} \left| \mathrm{P}_{\mathrm{mech},i} - \mathrm{P}_{\mathrm{mech},j} \right|} \quad (6)$$

If this indicator is above the unit, the power system will be able to maintain the synchronism, and the kinetic inertia of the turbines can be aggregated at the scale of the whole power system, enabling the calculation of a kinetic indicator [9]. The latter may be interpreted as the time available for an operator to activate regulations when generation and consumption are unbalanced.

3. RESULTS

In order to better understand this issue, we built a prospective model from the MARKAL-TIMES family [10] describing the French power system and endogenized the kinetic indicator within the model, as previously done for the Reunionese power system [3]. Despite intermittent sources (wind, solar and ocean energy) that are assumed to provide no kinetic reserves, it was shown that up to 100% renewable energy scenarios that do not jeopardize kinetic reserves could be proposed (Fig. 1) [11,12].

From these aggregated results, renewable energy capacities were dispatched between the 13 French administrative regions based on the least expensive potential algorithm (Fig. 2). In other words, a higher cost slice is not implemented if the lower cost-effective potentials are not saturated in all of the regions. This method depicts a purely technico-economic optimum independent of regional attributes (regional demand, political influence, etc.), hence reflecting a national cost-effective policy which does not seek infra-regional power balances.

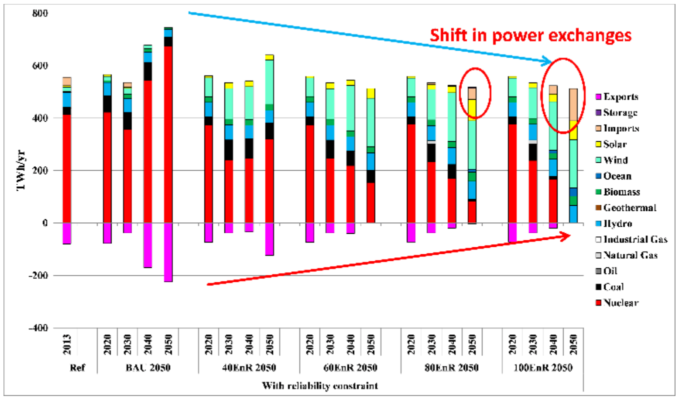

Fig 1 Evolution of the power mix in five reliability-constrained scenarios enforcing RES generation from BAU to 40%, 60%, 80% and 100%. Note the shift in the power exchange with the increase in RES penetration objectives (from [11,12]).

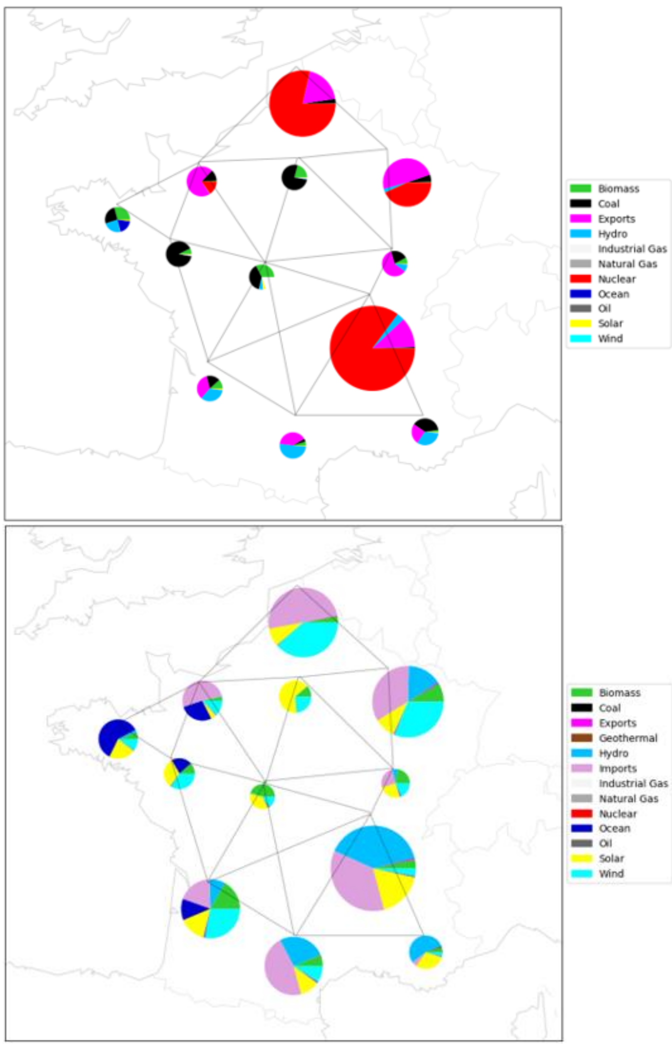

Fig 2 Regional energy mix in 2050 for BAU (top) and 100% RES. (bottom) scenarios. The solid lines depict the inter-regional transmission grid after a reduction keeping the synchronism indicator constant for the year of reference (2013).

In addition, the transmission grid has been reduced to an inter-regional network keeping the synchronism indicator (6) constant for the year of reference (2013). Subsequently, this indicator was followed until 2050 for the two scenarios, BAU and 100% RES (Fig. 3). At the inter-regional scale, these results show an improvement in transmission over the grid as the use of renewables increases. This is due to a sparser implementation of renewables compared with conventional assets persistently concentrated in historically productive regions, which decreases the tension on the RHS of (6).

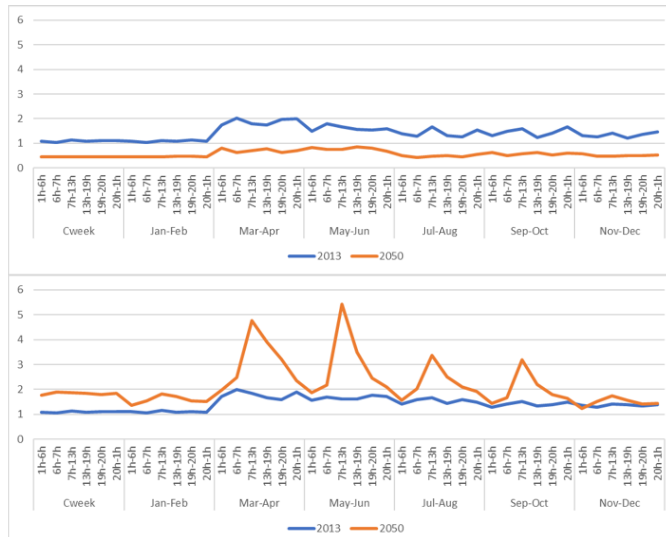

Fig 2 Synchronism indicator in 2013 (blue) and 2050 (red) for BAU (top) and 100% REN (bottom) scenarios. The assesment is plotted for relevant time slices of the year, including a ”critical week” with low solar and wind production and no imports.

Nevertheless, the increase in renewables, and especially VRE which does not contribute to the kinetic reserve, might jeopardize the transient stability if the kinetic indicator is not endogenized within the model (Fig. 4) [11].

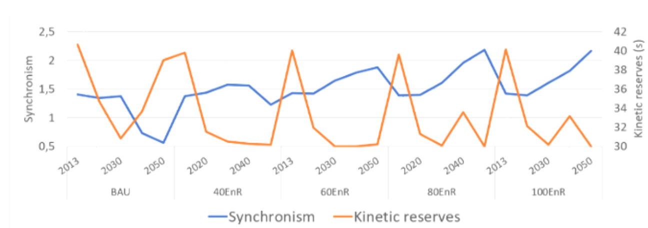

Fig 4 Evolution of the synchronism indicator (left axis, blue line) and averaged kinetic reserves (right axis, red line) for relability-constrained scenarios involving inceasing levels of REN. Note

the lower bounded fulfillment of the kinetic reserve for a high share of RES.

Lastly, it should be noted that only four regions, i.e. those maintaining high levels of conventional assets, self-fulfill their needs in ancillary services, limiting the actual energy empowerment of the other territories solely to system adequacy (with overgeneration and extra investments).

4. CONCLUSION

Thanks to indicators derived from a thermodynamics approach to electromagnetism, we successfully analyzed the stability of a power system and determined that:

- The kinetic indicator is related to the kinetic energy embodied in the power system. However, this indicator needs synchronism to be aggregated over the entire power system.
- The synchronism indicator, by expressing competition between the grid's connectivity and the expected congestion, guarantees that the power system will naturally return to synchronism after a small disturbance.

When implementing increasing amounts of VRE up to 2050, the kinetic indicator must be endogenized to enforce transient stability of the mix, while the synchronism is naturally improved due to a local improvement of the supply-demand balance. This study could help policy makers disentangle the issue of high RES penetration in the French power system and assess under which conditions it could evolve from a low-carbon nuclear base to a different system relying on a totally different generation model.

ACKNOWLEDGEMENTS

This research was supported by the modelling for sustainable development chair, led by MINES ParisTech, Ecoles des Ponts ParisTech, AgroParisTech and ParisTech; and supported by ADEME, EDF, GRT Gaz, RTE, Total and Schneider Electric.

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