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The cost of reliability of supply in future power systems

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Abstract

In order to build plausible options for future energy systems, long-term planning models must consequently address the technological feasibility and associated cost of these options. This paper focuses on the electricity sector and on problems of reliability of supply for future power systems. We propose a methodology for assessing the reliability of power systems based on a number of aggregated physical properties. Our aim is to take reliability into account when designing future power systems and to improve results provided by long-term planning exercises.

Keywords: Long-term energy planning. Power systems. Reliability of supply.

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1 Introduction

Electricity generation has entered a period of significant change pushed by major challenges, namely: the need for carbon emission abatement, the expected depletion of fossil fuels, the crucial population densification, the tremendous growth in developing countries and the liberalization of electricity markets. In this context, renewable and distributed energy sources seem to be attractive alternatives for cleaner and unlimited power generation.

However, two critical features challenge forthcoming changes in power systems:

- the emergence of different paradigms for serving electricity than those for which the system was designed [1]. For instance, high shares of renewable energy

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sources may become a critical aspect of future energy systems, both for centralized scheme, with the Desertec concept [2], and for distributed architecture, with the smartgrid concepts [3].

- the will to improve the energy efficiency of electrical power transmission, given that the current system clearly lacks of efficiency. For instance, since 1950 in the US, electrical losses have been twice as high as electricity consumption as pointed out in [4] and illustrated in figure 1 for the industrial sectors (same trends for the commercial and residential sectors).

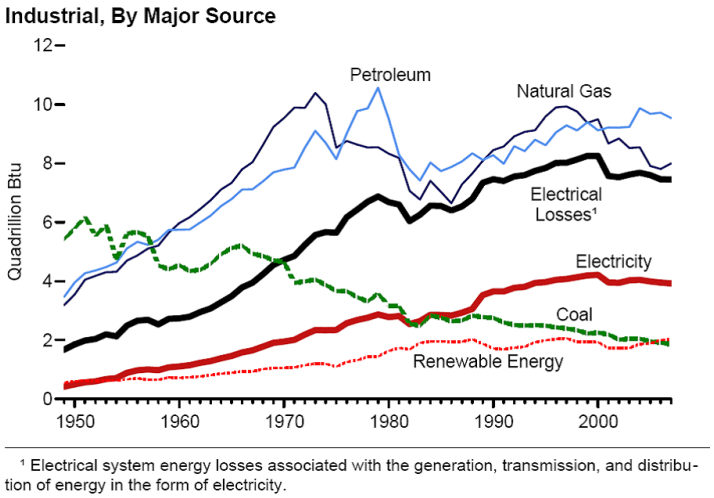


Figure 1: *Industrial Total Energy Consumption, Major Sources [4]: electricity use (and related losses) expanded dramatically.*

Current power systems clearly lack of efficiency because this sector is severely disadvantaged by the efficiency of the Carnot cycle of the thermal units, which are about one order of magnitude greater than electrical losses at the transmission, distribution and consumption levels (as shown in the figure 2).

Moreover, the world net generation of electricity increasingly relies on fossil fuels as shown in figure 3, which implies a higher impact on the environment due to the level of greenhouse gas emissions emitted by the electrical sector.

Furthermore, with high shares of renewable energy sources, the overall efficiency of the electricity sector is expected to increase. However, this gain in efficiency may be counterbalanced by a decrease in the reliability of supply, which is the capacity of a power system to be operated in a reliable way. As an illustration, reliability of supply may decrease with intermittent energy sources, as their intermittency induces abundant production fluctuations.

Consequently, restoring an appropriate level of reliability on power systems requires additional investments and extra-losses, which both add to the cost of reliability of supply. The aim of this paper is to introduce the reliability within an optimal discussion (section 2), in order to assess its cost for future power systems (section 3).

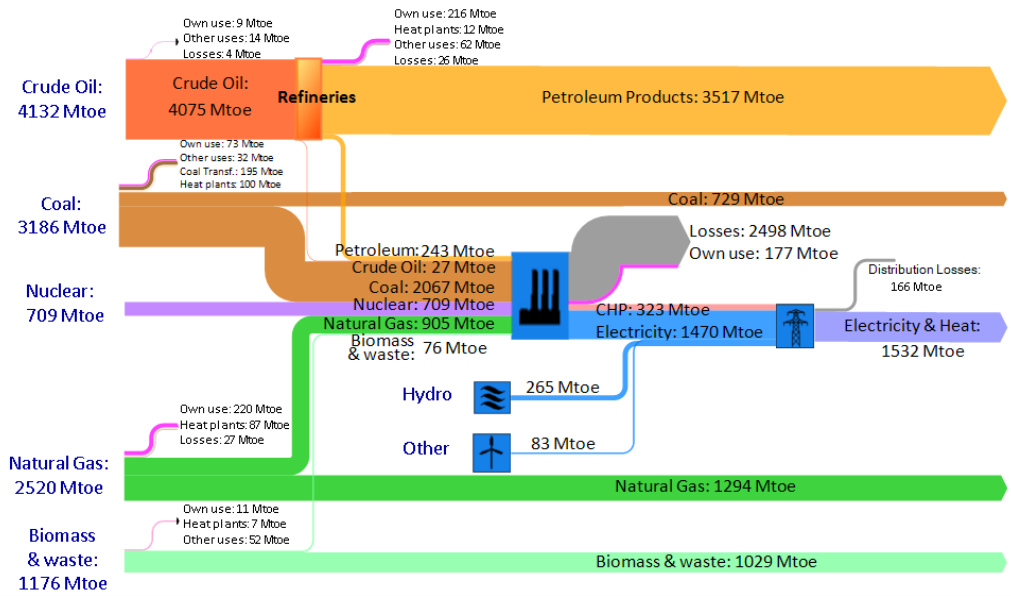


Figure 2: *Energy supply-chain in Mtoe in 2007 (e!Sankey diagram). The electricity sector is severely disadvantaged by the efficiency of the Carnot cycle of the thermal units, and by the electrical losses at the transmission, distribution and consumption levels [5].*

2 Methods

This section is divided into three main contributions. First, the study relies on a deep understanding of reliability requirements in power systems. Then, we present the Markal/TIMES family of long-term planning models and stress their strengths and weaknesses in the light of the reliability requirements. Finally, we describe a methodology for assessing the reliability of power systems based on a thermodynamic approach.

2.1 Description of reliability of supply

As explained in [6], electric system reliability can be addressed by considering two basic and functional aspects of the electric system:

- Security – The ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.

- Adequacy – The ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.

From a technical point of view, reliability of supply is ensured by the electromagnetic coupling energy on the system and by available levels of kinetic and spinning reserves. Indeed, power systems rely on frequency and voltage management [7] described as follow:

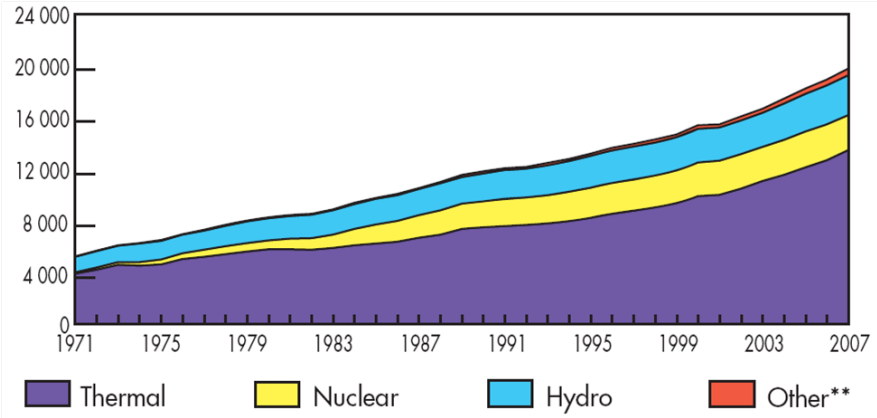


Figure 3: *Electricity generation in TWh by fuel since 1971 [5]. Other includes geothermal, solar, wind, combustible renewables and waste, and heat.*

- Frequency and voltage are crucial quantities, whose deviations can lead to brownouts or power outages. This typically occurs when the system experiences transient states (e.g. lightning), or is recovering from production or load fluctuations.

- Maintaining voltage and frequency between appropriate limits depends respectively on the electromagnetic coupling energy and on the kinetic and spinning reserves. This emphasizes the need for electromagnetic power and for appropriate levels of reserves on power systems.

- Furthermore, most renewable energy sources, and in particular intermittent ones, do not provide the required levels of reserves as efficiently as conventional power units (for example thermal units and hydroelectricity) [8]. Besides, intermittent energy sources commonly induce frequent and higher magnitude production fluctuations further increasing the need for reliability of the electric system.

Maintaining sufficient amounts of the coupling, kinetic and spinning energies, induce extra-losses and may require additional investments. Consequently, in order to provide relevant comparisons between future electrical systems in terms of reliability of supply, losses over the network must be assessed properly. For that purpose, we define the conveyance and reliability losses:

- Reliability-induced losses are related to the additional costs consented for maintaining the electromagnetic coupling and eventually investing in kinetic and spinning reserve capacities (e.g. wheighing generation machines, flywheels). When production capacities are distributed on smaller and less hierarchically organized grids (e.g. distributed ones), reactive power and kinetic reserve are critical to ensure a given reliability level because each "small" grid relies on fewer generation capacities, without counting on capacities from a large-scale system.

- Conveyance losses occur during power transmission through the network. They mainly depend on whether or not the transmission grid is congested, on the voltage level, or on the network architecture. They can be assessed from the duration

of peak, semi-base or base loads. When production capacities are centralized, transmission takes place through longer distances, and conveyance losses may increase, despite high voltage lines. In fact, for a given geographical distribution of loads and generators, the more the meshing of the grid increases, the more the Joule losses decrease, the voltage profile improves and the system becomes more stable. Besides, if the installed generation capacities increase, the power system also has similar benefits.

The balance between the conveyance and reliability losses is highly dependent on the energy generation shares and the associated network architecture. However, it is difficult to allocate these two kinds of losses as they take place in the same system.

2.2 The Markal/TIMES family of models

Long-term global prospective models permit the assessment of multi-sectoral energy policies and are therefore persuasive. Among these models, Markal is a technological model developed since the mid-eighties [9] under the auspices of the International Energy Agency [10]. Markal, in its basic version, is a technically optimum model. It relies on an explicit formulation of the input/output relationships for each technology and minimizes - over the chosen time horizon and for a given final outcome - the actualized global cost. The optimization is subject to constraints such as energy management features, caps for CO_2 emissions, limitations on fuel shares in electricity generation, etc. The decision variables depend on the choice of the activity level of technologies, and of capacity investments. The equilibria of energy flows are generally expressed over the year and evaluated on total energy rather than on hourly power demand. A synthetic description of the input/output relationships is given in the scheme covering the whole energy chain depicted in the figure 4. It is usually called the Reference Energy System.

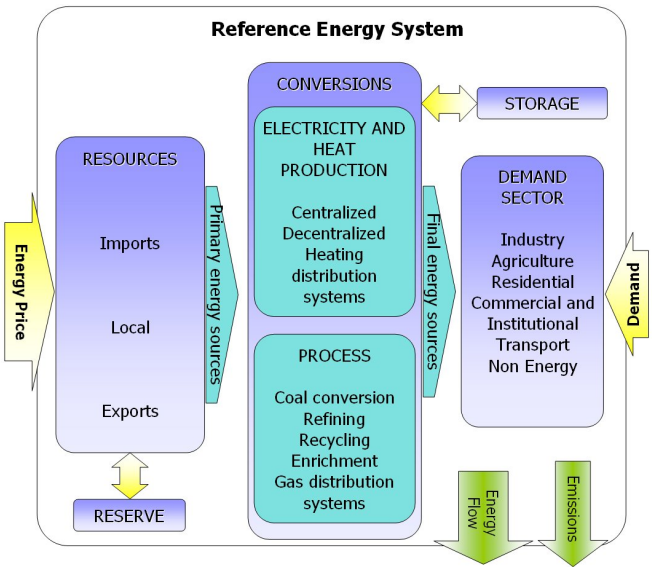


Figure 4: *Synthetic view of the Reference Energy System, issued from [11].*

Markal offers a more detailed description for the electricity sector, whereby flows

are represented as energy units. Specific technical constraints [12] are represented in the model:

- *Flow equilibrium constraints:*
  Electricity and heat are represented in more details in the model. The time divisions applied to these two energy vectors are shorter and each period is broken down into six sub-periods showing the combinations between, on the one hand, three seasons (summer, winter, intermediate), and on the other hand, day and night. The flux equilibrium equations are then published separately for each of these sub-periods.

- *Peak reserve capacity constraints:*
  A peak reserve constraint guarantees the setting-up of a supplementary capacity reserve to show what level of over-capacity is actually necessary to cope with high demand periods. In such cases, the user stipulates a global electricity or heat reserve factor. It is described by two features. On the one hand, each electricity or heat production technology is represented by a supplementary coefficient of participation in the realization of the reserve[1]. On the other hand, the peak equation itself stipulates that the total production capacity, counterbalanced by these peak coefficients, must be oversized by a certain percentage to satisfy the demand (for exports, processes and demand technologies) and to insure against several contingencies. It forces the model to increase the production capacity by the chosen level of reserve. For instance, in France, the value of this peaking factor can be set to 1.6.

2.3 Assessing the cost of reliability

In this section, we intend to compare the level of network losses for power systems with different production shares of renewable energy sources – in particular intermittent ones. To do so, we apply variational principles deduced from thermodynamics to achieve a global description of power systems and of the subsequent level of losses [13, 14].

The system on which we apply the variational principles is the electromagnetic field, conveying electricity from the generation units to the consumers:

1. In the thermodynamic framework, the deviation between the mechanical power flowing through the network and the variation with time of the Helmoltz free-energy F gives an evaluation of the Joule losses P_{Joule}, at the transmission, distribution and consumption levels. P_{Joule} gives an evaluation of the irreversibility experienced by the system. According to the thermodynamics, Joule losses are always positive and the lower they are, the more reversible is the evolution of the system. The latter statement can be expressed with an optimal condition, which means that the system always tends to minimize the Joule losses during its

[1] This coefficient (from 0 to 1) specifies the fraction of the technology's capacity that is allowed to contribute to the peak load and makes it possible to differentiate between the contributions of different power plants. Nuclear power plant has a peak coefficient of 1, whereas wind farm has a peak coefficient of 0.2 or 0.3.

evolution. *Ideally*, a centralized power system can be described from the Helmoltz free-energy, and this reversibility condition provides the very minimum amount of Joule losses during the power transaction and matches the conveyance losses.

Added to the losses induced by the Carnot cycles, it gives the total amount of primary energy lowered in a centralized system.

2. *Conversely*, in order to explicitly take reliability into account, the description should include the inertial behavior of the electromagnetic coupling. Hence, the actual level of Joule losses should be assessed from another reversibility condition obtained with the Gibbs free-energy $G = F - \Phi \mathrm{I}_{\mathrm{exc}}$, where $\Phi \mathrm{I}_{\mathrm{exc}}$ is the electromagnetic coupling and $\mathrm{I}_{\mathrm{exc}}$ the excitation provided to the generator. As a physical result, the latter description provides the level of both conveyance and reliability losses. Compared to the case (1), the argument of the optimum is drastically changed. This leads to new stability requirements for dynamic management.

   Added to the losses induced by the residual Carnot cycles, it gives the total amount of primary energy lowered in a distributed system.

This analysis can provide the level of Joule losses P_{Joule} for operating electric power systems in a reliable way. It allows to compare the overall amounts of losses for a centralized power system and for a distributed one, when the electrical demand and the level of reliability of supply are the same. As a consequence, the cost of electricity production in centralized systems is severely disadvantaged by the efficiency of the Carnot cycle of the thermal units, whereas in distributed system it is penalized by the cost of the reliability of supply.

3 Results

Thanks to the latter reversibility condition, the thermodynamic approach enables to take into account the dynamic terms of the electromagnetic coupling and of the kinetic energy. Following these developments, we propose to derive thermodynamics to assess power transactions through the network. As a first step, we introduce a one-loop equivalent circuit lumping the main features of power systems and study the dynamical behavior of reserves that participate in reliability of supply. This work is on-going and in this section we present encouraging results.

3.1 Working with a one-loop equivalent circuit

With the thermodynamic framework, the description of a power system can be reduced to an upper scale, coming down to a one-loop equivalent circuit depicted in the figure 5. As seen previously, there are three main reserves of energy that participate in the stabilization of the system after a load disturbance. The system relies on the following reserves to handle properly a load fluctuation :

1. The electromagnetic coupling $\mathrm{E}_{\mathrm{mag}} = \Phi \mathrm{I}_{\mathrm{exc}}$ enables to soften voltage fluctuations (under 1s);

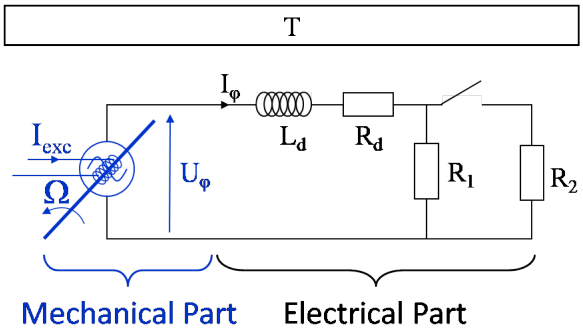


Figure 5: *The one-loop grid, a circuit equivalent for a wide power system, described with a one-phase φ representation. U_φ is the voltage of the stator, i.e. the voltage supplied by the generator to the circuit. L_d and R_d are the inductive and resistive values of the transmission capacities. R_1 models the load and connecting R_2 models a load fluctuation. T is the thermostat considered in the thermodynamic framework.*

2. The kinetic energy $\mathrm{E_{kin}} = \frac{1}{2}J\Omega^2$ limits the frequency deviation (within 30s);

3. The spinning reserve contributes to restore the power balance and the system frequency to its set-point.

Data for the one-loop circuit The mechanical part represents the producers, and the electrical part the consumers. In the electrical part, the impedances gather the inductive and resistive properties of the loads and the transmission capacities of the system. We model a load fluctuation by connecting the load R_2.

The system has the following characteristics:

- the generator delivers 1 GW to the electric system;
- the transmission is at very high voltage (400 kV);
- the length of the line is 100 kms, which is roughly the average length of very high voltage lines in France.
- The load fluctuation is modelled as an increase by 10% of the power dissipated in the circuit.

3.2 Dynamic behavior of the reserves after the load fluctuation

We perform a transient state analysis of this system and study the dynamical behavior of its levels of kinetic reserve and electromagnetic coupling energy. The load fluctuation occurs at t=0.

In this analysis, we focus on the electromagnetic coupling $\mathrm{E_{mag}}$ and the kinetic energy $\mathrm{E_{kin}}$. We study the variation with time of these stocks of energy in the one-loop equivalent circuit to highlight their role in load fluctuation management (see the figure 6). For a load increase, the figure exhibits a sharp decrease in the stock of electromagnetic coupling $\mathrm{E_{mag}}$ after the load fluctuation, while the kinetic energy $\mathrm{E_{kin}}$

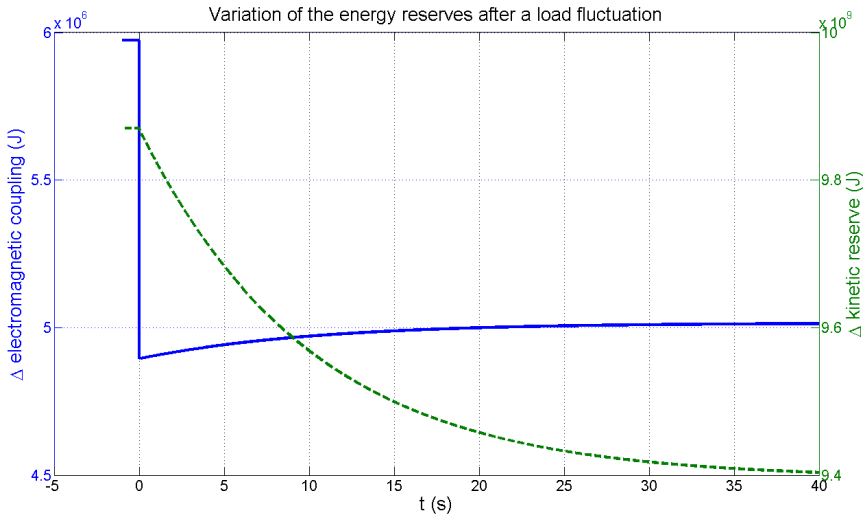


Figure 6: *Variation with time of the electromagnetic coupling (solid line) and the kinetic energy (dashed line).*

decreases more smoothly. It shows that the levels of the reserve are crucial to soften the impact of the load fluctuation. For instance, if the load increase requires more energy than the amount stocked by the system, the system collapses after the fluctuation: to handle properly a load fluctuation, levels of electromagnetic coupling and kinetic reserve must be sufficient. Such a result corroborates the need for the reliability requirements developed in the previous section, and is though very promising.

3.3 Levels of reserves for different systems

We now exhibit the available levels of the electromagnetic coupling $\mathrm{E_{mag}}$ and the kinetic energy $\mathrm{E_{kin}}$ depending on the energy mix.

Key parameters of network architecture The share of renewable and distributed energy sources in the energy mix is related to a serie of key parameters, such as the physical characteristics of the generators (the power angle δ, the mechanical inertia J), the properties of the transmission system (the average line length l, the inductive properties of the transmission systems) and the characteristics of the load (the state of the load R, the load angle φ).

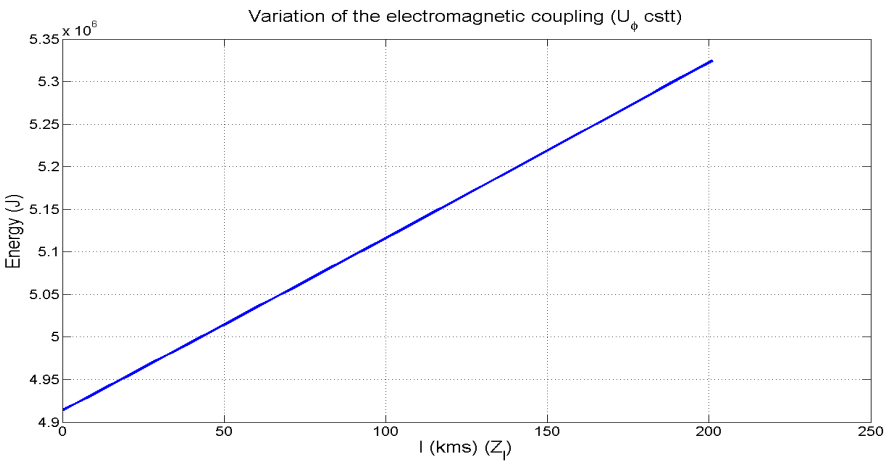
The values of these parameters are mostly dependent on the network architecture and the kind of generation units. Studying the levels of electromagnetic coupling and the kinetic energy with the variation of these parameters provide valuable insights for comparing the levels of reserves with different architectures. The aim is to find drivers for the levels of reserves depending on the integration of renewable and distributed energy sources on power systems.

We start with the study of the electromagneting coupling $\mathrm{E_{mag}}$ with the variation of the following parameters:

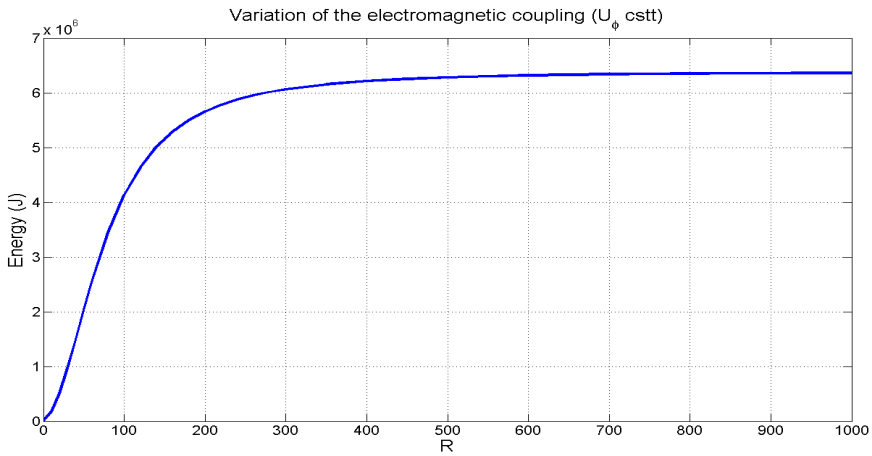
- with l, the average length line. In figure 7(a), the electromagnetic coupling increases with the length of the line.

- with R, the state of charge of the load. In figure 7(b), the electromagnetic coupling increases with the value of the load.

As far as the kinetic energy is concerned, its value does not change with these parameters. However, the kinetic energy explicitly depends on the mechanical inertia J of the generator. The greater J is, the greater the kinetic energy, which is mostly the case for power systems relying on conventional, and subsequently centralized, power units.



(a) Variation with the length of the line l.



(b) Variation with the value of the load.

Figure 7: *Variation of the electromagnetic coupling ΦI_{exc} with key parameters of the system.*

4 Conclusion

In this paper, we have emphasized the need to take reliability requirements into account for the design of future power systems, in particular with long-term planning models such as Markal/TIMES. This study enables to analyze the dynamic behavior of power systems and provides results for electromagnetic coupling and kinetic reserve that corroborate the need for reliability requirements in order to operate power systems properly.

Further developments will analyze, among other things, the level of Joule losses on power systems with different energy mixes or power architectures. It will enable to compare the overall amounts of losses for a centralized power system and for a distributed one, when the electrical demand and the level of reliability of supply remain the same. Indeed, the cost of electricity production in centralized systems production is severely disadvantaged by the efficiency of the Carnot cycle of the thermal units, whereas in distributed system it is disadvantaged by the cost of reliability of supply.

Fortunately, this work is part of a larger project which aims at integrating the cost of reliability in prospective studies and is implemented in a TIMES model dedicated to the Reunion Island. Interestingly, this case study is a good illustration of the previous results: its small island grid without interconnection and the forecasted shares for renewable – intermittent – energy sources are challenging issues for future reliability requirements.

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