

Overview

Electricity generation has entered a period of significant change pushed by major challenges, namely: the need for carbon emission abatement, the expected depletion of fossils 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. Besides, 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 ten times greater than electrical losses at the transmission, distribution and consumption levels (figure 1).

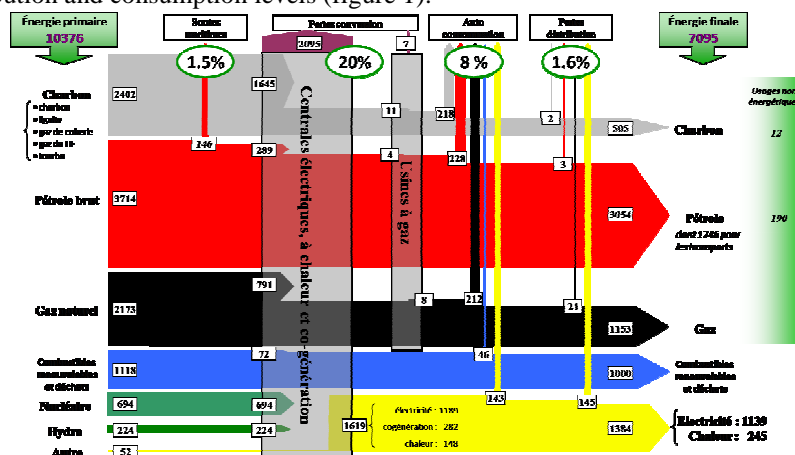


Figure 1: Energy supply-chain [1]. Electrical energy is strongly disadvantaged by the efficiency of the Carnot cycle of the thermal units.

Thus, high shares of renewable energy sources may become essential features of the future electricity industry, as presented both for centralized scheme, such as the Desertec concept [2], and for distributed architecture, such as those presented in [3]. Consequently 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. Reliability of supply relies on the ability of the electric system to withstand sudden disturbances [4] and it is ensured by available levels of kinetic and spinning reserves and the electromagnetic coupling energy on the system. With intermittent energy sources, these levels decrease in comparison with conventional energy units: for instance, their intermittency induces abundant production fluctuations and threatens reliability even more.

Finally, 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, in order to assess its cost for future power systems.

Methods

The study first relies on a deep understanding of reliability requirements in power systems. According to the UCTE handbook [4], electric system reliability can be addressed by considering both the adequacy of the system, i.e. its ability to supply the aggregate electrical demand and energy requirements of the customers at all times, and the security of the system, i.e. its ability to withstand sudden disturbances such unanticipated loss of system elements. To ensure these two elements, power systems rely on dynamic management, namely frequency and voltage management [5]. Indeed, frequency and voltage are crucial quantities, whose great deviations can lead to brownouts or power outages when the system recovers from production or load fluctuations or when it experiences transient states (e.g. lightnings). Basically, maintaining appropriate variations of frequency and voltage depends respectively on the kinetic and spinning reserves and on the reactive power of the system.

However, under competitive electricity markets and because smaller and renewable energy units are economically justified, the capability of markets to create decent investments for reliability requirements is questionable [6]. This has not been the case under monopolies, where the question of reliability of supply has been efficiently dealt with Loss of Load Probability (LOLP) or Expected Unserved Energy (EUE) indices [7].

Furthermore, with high shares of renewable energy sources on power system, levels of kinetic and spinning reserves and of electromagnetic energy decrease, whereas intermittent energy sources induce abundant production fluctuations, with high magnitude. Consequently, restoring dynamic management and a suitable level of reliability may increase the level of electrical losses over the system.

Then, we intend to compare the level of network losses for power systems with different production shares of renewable energies – 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 [8]:

- The system we consider is the electromagnetic field, which conveys electricity from the generation units to the consumers.
- In the thermodynamic framework, the variation with time of the Helmholtz 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. *Ideally*, a centralized power system can be described from the Helmholtz free-energy, and the reversibility condition provides the conveyance losses.
Added to the losses on the Carnot cycle, it gives the total amount of losses of a centralized system.
- *Conversely*, in order to explicitly take reliability into account, the description should include the inertial behavior of the electromagnetic coupling. Then, variation with time of the Gibbs free-energy $G = F - \Phi I$, where ΦI is the electromagnetic coupling, gives an accurate evaluation of the Joule losses. As a physical result, the latter description provides higher level of Joule losses, whereas the argument of the optimum is drastically changed. This leads to new stability requirements for dynamic management.
Added to the losses on the Carnot cycle, it gives the total amount of losses of a distributed system.

Results

This analysis provides the level of Joule losses P_{Joule} for operating electric power systems in a reliable way. It allows us 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. 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.

Then, we focus on the effects of different shares of intermittent energy sources on this level of losses. In particular, we express the cost of reliability of supply from the level of losses, where this cost of reliability is divided into the additional investments cost and the operating cost to compensate the losses.

Conclusions

In this paper, we have emphasized the need to take reliability requirements into account for the design of future power systems. Our method provides the cost of reliability of supply and may consequently increase the assumed total cost of future energy systems. This work is a part of a larger project, which aim at integrating the cost of reliability in prospective studies. Another aspect of this project is to link the present work with long-term planning models MARKAL/Times [9,10]. This is carried out for the case of the Reunion Island.

References

- [1] *Key world energy statistics from the IEA*. Paris, France: Organization for Economic and Co-operation and Development / International Energy Agency, 2004.
- [2] DESERTEC website http://www.desertec.org/downloads/summary_en.pdf
- [3] “The green grid: Energy savings and carbon emissions reductions enabled by a smart grid.” O. Siddiqui, Electrical Power Research Institute, Palo Alto, CA, Tech. Rep. 1016905, June 2008.
- [4] *Operation Handbook – Glossary*, European Network of Transmission System Operators for Electricity, 2004.
- [5] *Power System Analysis – 2nd edition*, A. R. Bergen and V. Vittal, Prentice-Hall Series 2000.
- [6] Joskow, P. and Tirole, J., “Reliability and Competitive Electricity Markets,” Cambridge Working Papers in Economics 0450, Faculty of Economics, University of Cambridge, 2004.
- [7] “A method of evaluating transmission network expansion plan considering security constraints and supply reliability index,” Furusawa K et al., in *IEEE – PES Power System Conference and Exhibition*, Seattle, March 2009.
- [8] Mazauric V., “From thermostatics to Maxwell’s equations: a variational approach of electromagnetism,” *IEEE Transactions on Magnetics*, vol. 40, no. 2, pp.945-945, 2004.
- [9] Energy Technology Systems Analysis Programme website: <http://www.etsap.org>
- [10] “Long term planning and sustainable power system: a focus on flexibility needs and network reliability,” Maïzi, N. et al, in *IEEE – PES Power System Conference and Exhibition*, Seattle, March 2009.