Optimization of future power systems focusing on reliability of supply

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The efficiency of future power systems is expected to improve with the integration of renewable and distributed energy sources, as they decrease the level of losses induced by the Carnot cycles. However, these energy sources also challenge reliability of supply and may induce extra-losses. Actually, there are three main kinds of losses on power systems: the losses induced by the Carnot cycles, the conveyance losses and the reliability-induced losses. Their levels depend on the network architecture: in particular in distributed systems, reliability-induced losses are expected to increase, while conveyance losses and losses induced by the Carnot cycles are expected to decrease.

In this work, we introduce reliability of supply within an optimal discussion in order to assess properly the overall amount of losses on power systems. To do so, we apply variational principles – deduced from thermodynamics – to the electromagnetic field that conveys electricity from production units to consumption loads.

In this 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} is a measure 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. This is expressed in an optimal condition – called the reversibility condition – meaning that the system always tends to minimize the Joule losses during its evolution. *Ideally*, a centralized power system can be described from the Helmoltz free-energy, and the reversibility condition provides the very minimum amount of Joule losses during power transaction. These are the conveyance losses. Added to the losses induced by the Carnot cycles, we find the total amount of primary energy lowered in a centralized system.

Conversely, in order to explicitly take reliability into account, the description should include the inertial behavior of the electromagnetic coupling. *Actually*, the level of Joule losses should be assessed from another reversibility condition obtained from the Gibbs free-energy $G = F - \Phi I_{exc}$, where ΦI_{exc} is the electromagnetic coupling and I_{exc} the excitation of the rotor. As a physical result, the latter description gives the level of both conveyance and reliability losses. These are the losses needed to operate power systems in a reliable way. Compared to the previous case, the argument of the optimum is drastically changed, which leads to new stability requirements for dynamic management of power systems. Added to the losses induced by the residual Carnot cycles, we find the total amount of primary energy lowered in a distributed system.

This study enables to truly compare the overall amount of losses for centralized and distributed power systems, for a given demand and a given level of reliability. It also emphasizes the need to consider reliability requirements when designing future power systems.