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Impacts of intermittent sources on the quality of power supply: The key role of reliability indicators

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HIGHLIGHTS

- The paper addresses the reliability of power supply in future electricity mixes.
- We present the framework used to discuss the conditions ensuring reliability of supply.
- The approach provides two indicators to assess the kinetic and magnetic reserves.
- Their relevance is demonstrated through a study conducted for Reunion Island.
- Results exhibit a link between reliability and shares of intermittent sources.

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ABSTRACT

The reliability of power supply, defined as the ability to recover a steady-state condition after a sudden disturbance, is crucial for operating power systems. It is usually ensured by controlling voltage and frequency deviations and involves events occurring from a few milliseconds to a few hours. However, reliability requirements are largely ignored when dealing with long-term issues. To reconcile such contrasting timescales, it seems logical to rely on energy considerations based on thermodynamics. Two reliability indicators, assessing the magnetic and kinetic energy reserves of a power system, are derived from this approach. They enable to quantify the reliability of a given production mix and make it possible to choose between increasing shares of intermittent sources and maintaining an expected level of reliability. Since the indicators tackle reliability issues without focusing on a specific timescale, they are effective for both discussing the long-term evolution of reliability and improving the real-time management of a power system.

1. Introduction

A reliable power supply is crucial for operating power systems. Defined as the ability of power systems to lock back into a steady-state condition after sudden disturbance (e.g. load or generation fluctuations), reliability is usually ensured through appropriate management of voltage and frequency and involves events whose time scales range from a few milliseconds to a few hours. However, when focusing on power systems' long-term development (typically several decades), reliability requirements are largely ignored thus providing unrealistic options in this area. Yet this aspect is of tremendous importance, especially when high shares of renewable energy sources, and in particular intermittent energy sources, are expected in electricity generation and may threaten supply reliability.

The International Energy Agency anticipates a major growth in electricity consumption over the coming decades, as a result of the predicted population densification, the development of energy markets in developing countries, and the replacement of existing capacities in developed countries, while several issues, such as the mitigation of greenhouses gases, call for new ways of producing electricity to increase the shares of cleaner and inexhaustible energy sources [1]. In this context, the emergence of different paradigms for serving electricity than those for which the system was designed [2] challenges the forthcoming changes in power systems. In particular, high shares of renewable energy sources may become a critical aspect of future energy systems, both for centralized scheme and for distributed architecture. The integration of renewable energy sources in electricity production has indeed been widely studied to determine their development's challenges and options. [3–6]. Different energy system analyzes of 100%

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renewable energy systems were conducted for different areas [7–9] and tools are developed to model future energy systems with high penetration of renewable energy sources [10,11]. The previous analyzes rise several technical challenges posed by the large-scale integration of renewables, mainly wind power and photovoltaics, that are listed in [12,13]. They point out that accurate short-term forecasts of power output (over the next few hours or days) are important factors for a secure and economic operation of power systems. Besides, to increase the variable power integration in the generation mix and consequently increase their share of renewables, it is possible to take advantage of the electricity systems' flexibility which exists on both the production side [14,15] and the consumption side [16,17].

This power generation evolution brings the quality of power supply into question. High shares of intermittent sources expected may indeed threaten the reliability of future power systems, where reliability is intended as the ability of the power system to lock back into steady-state conditions after power imbalances. So far, power systems' reliability requirements in the long-term have been investigated through cost and market prices' issues [18–20].

In this paper, we propose to assess reliability of power supply. Indeed it is necessary to provide plausible energy strategy in the electricity sector especially when including high shares of intermittent production. As defined in the ENTSO-E handbook [21], reliability corresponds to the adequacy and security of power supply, which describe its ability to respectively comply with electrical demand at all times and withstand the system's contingencies such as unanticipated loss of a system element. So far, system operators have addressed the different aspects of reliability of supply by employing various methods that we have divided into:

- short time scales methods (assessing reliability from a few milliseconds to a weekly or monthly basis);
- long-term methods (assessing reliability from one to twenty years).

Short time scales methods include real-time controls and optimal power flow (OPF) studies. During daily operations, real-time frequency and voltage controls manage the active and reactive power outputs of generators to prevent frequency and voltage deviations in the system. Primary, secondary and tertiary reserves of active or reactive power are respectively activated for frequency or voltage management at different time steps varying from a few milliseconds to a few minutes [21]. Beyond the real-time management, OPF are typically used for scheduling daily or weekly production plans while maintaining a reliable power supply thanks to a set of constraints including transmission line limits and other security limits or margins [22–24]. The OPF aim to minimize the operating cost of the power system subject to satisfying power flow constraints and constraints on generator power, line power flow or voltage magnitude.

Long-term methods refer to methods assessing reliability of supply over several years. For five years or so, power supply reliability is assessed in terms of whether generation matches the expected demand [25–27]. Due to the random nature of parameters involved in the calculations (unit availability, weather conditions), the match between supply and demand is assessed using common statistical measures: Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE) and Expected Unserved Energy (EUE). LOLP and LOLE measure respectively how long and how frequently, on average per year, the available capacity is likely to fall short of demand, while EUE evaluates the corresponding unsatisfied demand. LOLP and LOLE are also used in PV sizing methodologies to get the most probable insight of the power output the system may deliver during a day and also the next days in a short term approach for power prediction. Beyond a decade, planning exercises, such as generation expansion planning models, determine the generation units to be constructed, the timing of investments, and the amount of power to be produced, while minimizing the total cost of a utility over ten to twenty years. Such exercises only focus solely on adequacy issues regarding reliability of supply and reliability is ensured through constraints on LOLP or on the levels of active and reactive power reserves [28]. Similarly, reliability is only assessed with statistical measures in transmission expansion planning exercises [29].

However, both short time scales methods and long-term methods are insufficient to analyze in a long-term perspective the ability of the power system to lock back into steady-state conditions after power imbalances. On the one hand, short terms actually give insights to power systems dynamics and stability but cannot be processed with long-term studies for guiding energy strategies. On the other hand, the statistical measures used in the mid- to long-term methods do not give any indications as to the dynamical properties of the generation mix, and subsequently do not fully assess the system's ability to withstand sudden disturbances.

Since reliability requirements and the long-term development of power systems involve significantly different timescales, it is therefore appealing to rely on energy considerations in order to reconcile the timescales. Given that energy conservation results from the uniformity of time [30], we develop herein an approach that assesses the reliability of supply by evaluating the evolution of the energy reserves stored in a power system. Therefore, the thermodynamic framework, which is a natural framework to study energy exchanges, provides an original way to quantify the reliability of power supply for a production mix, whatever the timescale studied (*i.e.* long and short timescales).

The method proposed in this paper is rooted in energy-based analysis. The method however differs from energy-based methods derived from [31,32] and used to study power system transient stability that aim at estimate whether or not a power system will remain in synchronism after a large disturbance. Inversely, the approach presented in this paper can be used to discuss both in short- and long-term perspectives the conditions enabling to ensure a minima reliability of supply (as described aforementioned). Yet, this is of critical importance to determine plausible shares of intermittent sources in electricity production.

Section 2 presents the theoretical developments based on a variational formulation on which the proposed methodology relies. It exhibits the energy reserves stored in a power system during power transactions and highlights their role in efficiently managing transient states. Section 3 introduces two reliability indicators that are deduced from a quantitative evaluation of the energy reserves. The indicators provide valuable insights for debating the reliability of power systems' management according to their dynamical properties. Lastly, the relevance of the indicators is demonstrated in the fourth section through reliability analyzes that study both the long-term evolution and the real-time management of supply reliability in the remote power system on Reunion Island.

2. Applying a variational formulation to power systems' analysis

This section describes the dynamics of a power system relying on energy considerations based on thermodynamics. We present a variational formulation of electromagnetism that provides an understanding of power transactions including an explanation of transient regimes with the variations of the magnetic and kinetic energy reserves stored in the system.