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Estimating the additional operating reserve in power systems with installed renewable energy sources

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ABSTRACT

In this paper we present an improved probabilistic approach for estimating the additional operating reserve in power systems with installed renewable energy sources. This approach uses a novel method for determining the reliability of power systems, where the variable generation of renewable energy sources and the ageing of generating units are considered. The new approach also takes into account the fact that several generating units can share the same source of failure, which causes them to fail or become unavailable simultaneously. Improvements are achieved by the implementation of common cause failures. The obtained results of the reliability analyses are basis for estimating the additional operating reserve in the power system, so that the system operation is supplemented with the proposed reliability criteria.

The presented approach is tested on an IEEE Reliability Test System where the one-day-ahead circumstances are observed. The results show that the required additional operating reserve depends primarily on the power generation of the renewable energy sources and on the unavailabilities of the generating units, which are influenced by ageing and by common cause failures. The results show that the new method is suitable for achieving reliable power systems in the future, where a high penetration of variable renewable energy sources is expected.

Introduction

One of the main tasks of a power system is to supply all consumers with electrical power within defined reliability standards, including an uninterrupted power supply. To achieve an uninterrupted power supply reaching a balance between the generation and the consumption of electricity is needed. To ensure energy balance, additional generation operating reserves above the expected demand load are required. The operating reserves can be utilised in case of load and generation mismatch, which enables the power system to deal with unexpected changes in load or generation [1]. Achieving the system balance has become more difficult with the increasing number of renewable energy sources, as the generation of electrical power from most of these unconventional energy sources is intermittent by nature. In modern power systems operating reserves are often defined by reliability analyses, i.e., how much operating reserve is needed to maintain security of supply. New tools are required for power systems with a large number of renewable energy sources to take into account their variability when defining operating reserves and therefore ensure reliable power system operation [2–17]. Operating reserves can be either reserved at local or foreign conventional generators and are mostly done via yearly and daily energy purchases. In cases where foreign generators are used as operating reserves, transfer capacity on interconnection lines must also be reserved to avoid congestions at interconnection lines, i.e., enough line capacity must be ensured to transfer the needed energy in cases of system balance mismatch [18]. In cases where generation exceeds load, downward reserves can also be activated in the form of demand side management or large load disconnects [19]. In this paper only upward reserves are taken into account.

The determination of operating reserves has been approached with different methodologies. In [2–4] the risks tied to wind power generation fluctuation and prediction errors are tied to the operating reserves. In [5] operating reserves are determined from calculated probability functions of wind power generation in regards to the loss of load probability (LOLP). In [6] the economic aspect of operating reserves and their minimization for large scale wind power generation systems is investigated. In [8] the Singh-Gonzales approach is described. Here the renewable energy source are tied to power-system reliability by separating the conventional and unconventional generating units into specific

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subsystems. This allows the intermittent nature of unconventional generation to be taken into account in loss of load expectation (LOLE) calculation. The Singh-Gonzales approach has also been applied to reliability and economic analyses of power systems with a large number of photovoltaic power plants [9]. An update to the Singh-Gonzales approach has also been proposed [10], where similar subsystem states are grouped in order to reduce calculation time. A sliding-window technique for evaluating a power system's LOLP has also been proposed [11]. This enables a more accurate reliability assessment of power systems with a large number of wind-power plants. Advanced Monte Carlo methods for renewable energy sources and storage systems were implemented in [12–14]. Some of the developed methods based on the LOLE can be used for evaluating the impact of renewable energy sources on power-system adequacy [15], or may also be used for quantifying the operating-reserve demands in power systems with an increasing number of renewable energy sources [16,17]. In recent years, reliability methods have also started considering the ageing of components [20,21] and common cause failures [22–24]. These can improve the accuracy of reliability analyses by taking into account the age of equipment and possible common causes of failures and their effects on multiple generators.

Considering power systems with a large share of renewable energy sources, the main objective of this paper is to develop a method that will consider the impact of variable renewable energy sources in the observed power system for reliable day-ahead operation. The method also combines the influence of ageing and common cause failures of generation in LOLE calculation. LOLE calculations are then used as basis to estimate the required additional operating reserve for the day-ahead, i.e., daily operating reserves are defined based on the desired LOLE values. The results offer an additional input to the system operator for ensuring adequate operating reserves for day-ahead operation [18].

The reason behind considering the ageing of equipment is the desire to adjust the time-dependant unavailabilities of generation units in the reliability calculations, i.e., unavailability data can be several years old and the values can therefore be easily updated or used for future analysis. Furthermore, the consideration of failure mechanisms that may lead to the simultaneous failures of several generating units through the application of a common cause failure analysis may also lead to a more accurate assessment of reliability. All these attributes have not been combined so far in an integrated framework. The inclusion of ageing and common cause failures in operating reserve estimation via LOLE calculation presents a novel contribution and the difference from similar approaches. The results may provide important insights into the required additional operating reserve in order to ensure reliable power-system operation.

This paper is organised as follows. The theoretical background of power system reliability is described in Section 'Background'. Important terms required for the derivation of the presented novel approach are also given in Section 'Background'. The novel approach for estimating the additional operating reserve is described in Section 'The proposed new method'. The results obtained for the IEEE Reliability Test System are presented and discussed in Section 'Case study and results'. Finally, in Section 'Conclusion' the main contributions of the paper are summarized.

Background

In modern power systems reliability must be ensured to achieve an uninterrupted power supply. Power-system reliability is defined as the probability that the observed system will perform its functions within the proposed period of time under the prescribed operating conditions [25,26]. Due to the enormous extent of modern power systems, their reliability is assessed separately on different levels: generation systems, composite generation, transmission systems, and distribution systems [1]. Therefore, reliability indicators are defined separately on each level and generally describe the probability that the electrical power supply is interrupted for at least one consumer [1].

Due to the stochastic nature of both the load and renewable energy sources consumers can experience loss of load if the existing generation cannot adequately compensate for the system imbalances. Therefore sufficient operating reserve must be available. Operating reserve can be divided into the spinning (online, already synchronized capacity) and the non-spinning reserve (installed capacity, which can be started in about 15 min) [2], [16]. Operating reserves are most often ensured by an installed cold-capacity reserve, which is not considered as part of a reliability evaluation, by potential-energy storage facilities, by pumped-storage hydro-power plants, by de-loaded wind-power plants or they can be imported. If an additional operating reserve is purchased from foreign power systems, additional transmission reliability margin values must be reserved to ensure sufficient transmission capacity on the interconnection lines [27,28].

With the increasing amount of intermittent renewable energy sources, operating reserves play a key role in ensuring sufficient power system reliability [2–7]. Some utilities suggest that for each MW of installed power from unconventional energy sources another MW of backup must be available [16]. However, introducing such measures may lead to very high expenses, which may not justify the benefits of the high reliability.

The proposed operating reserve estimation presented in this paper is based on advanced LOLE calculations, which considers ageing and common cause failures of generation. The results are operating reserve margins for the day-ahead in order to achieve the desired LOLE values. In this section, the background needed for the implementation of the proposed approach for power systems with high renewable penetration is presented.

The basic reliability index LOLE is presented in Section 'Loss of load expectation'. LOLE is upgraded to include renewable energy sources in Section 'Incorporation of variable renewable energy sources'. Ageing and common cause failures are included in LOLE in Sections 'Consideration of ageing' and 'Implementation of common cause failures'.

Loss of load expectation

Power systems contain a large number of different components, where the operation of any component can be vital for the power system's secure and reliable operation. Any component can experience a random outage at any time; therefore, probabilistic methods are required, such as LOLE, which represents one of the most widely accepted approaches for power-system reliability assessments [1]. LOLE is defined on the generation-system level and takes into consideration the availabilities and unavailabilities of generating units. It indicates the probability that the combination of available and unavailable generating units will not meet the required load demand, i.e., it expresses the statistically calculated hours within a proposed time frame when the assumed power consumption is not covered [26]. A general expression for a LOLE evaluation is defined in [1].

$$LOLE = \sum_{i=1}^{n} p_i t_i \ [\text{h/year}] \tag{1}$$

where p_i is defined as the probability of the loss of one or more generating units, t_i is the consequent duration of the loss of power supply and n represents the number of all the possible outage states. LOLE is usually defined on a yearly basis, where the inputs