Electric Power Systems Research 107 (2014) 258–267

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Development of short-term reliability criterion for frequency regulation under high penetration of wind power with vehicle-to-grid support

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ARTICLE INFO

Article history:
Received 13 November 2012
Received in revised form 28 May 2013
Accepted 6 July 2013

Keywords:
Wind power
LOLP
Battery
V2G
Frequency regulation
Reliability

ABSTRACT

Existing reliability indices for power systems provide measures of long-term stability; in this work, we propose a new reliability criterion that estimates the probability of a spinning-reserve shortage occurring, thus indicating the short-term stability of the grid frequency. In the formulation, load, wind power, and vehicle-to-grid (V2G) power are represented as random variables, and conventional generators are incorporated in a deterministic manner. Using the equilibrium of demand and supply and the physical constraints of automatic generation control (AGC), two inequalities are derived, from which the probability of successful frequency regulation is obtained. The inverted probability, referred to as the failure rate for frequency regulation (FRFR), is employed as a metric in the short-term reliability criterion. Then, the developed criterion was applied in several case studies. First, the impact of wind-power deployment was estimated in terms of the required spinning reserve. The acceptable penetration level of wind power was then investigated in the case that V2G power is also present. The variation of FRFR with respect to the commitment level of thermal (non-renewable) power plants was also investigated under the renewable portfolio standard (RPS) to illustrate the recursive effect of the policy. Finally, FRFR was calculated for the IEEE reliability test system and compared with conventional reliability indices.

1. Introduction

The nuclear crisis precipitated by the recent nuclear accident in Fukushima has accelerated the introduction of technology to exploit renewable energy. Wind power in particular is being highlighted as a sustainable energy source that could replace nuclear power, and many countries have already begun actively promoting wind power through subsidies and/or regulations [1,2].

The major obstacle to the large-scale introduction of wind power is the degradation of grid quality caused by intermittent generation [3,4]. Since a balance between consumption (load) and generation in a power grid must be maintained, the intermittent generation of wind turbines prevents them from simply being connected to the power grid. Instead, huge amounts of reserve generation or energy storage have to be incorporated to accommodate the inherent fluctuations in wind power [5]. Long-term fluctuations can be followed by commitment scheduling of generators; however, short-term fluctuations must be managed by adjusting output levels of the online generators in real time. In other words, short-term fluctuations can only be managed within the range of the spinning reserve. Although the term "spinning reserve" has been widely used throughout the scientific literature without definition, a survey found that the term has been used in different ways by different authors [6]. In this paper, we use the following definition [6]: the on-line power capacity that is available for automatic feedback control such as governor free and automatic generation control (AGC).

As of yet, penetration of wind power has been gradual and its relative proportion is negligible compared to other major generation sources. Consequently, many grid operators have simply been treating wind power as a disturbance in the grid, with the AGC system managing it with the existing spinning reserve. As the penetration level of wind power increases, however, grid operators must account for its impact on the grid, and thus, a quantitative criterion for the estimation of the required spinning reserve must be devised.

With respect to planning the expansion of power systems, various reliability criteria have been developed. L. Garver suggested the concept of the effective load carrying capability (ELCC) to evaluate the reliability of a power system with a newly incorporated power source for the first time [7]. Recently, the authors of Refs. [8–10] integrated one of the most popular reliability indices, the

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http://dx.doi.org/10.1016/j.epsr.2013.07.002

loss of load expectation (LOLE), into the ELCC to extend the practicality of ELCC. From this, they also derived a probabilistic reliability index, called a capacity credit, to represent the ratio of extra generation capacity. For a renewable power source, however, ELCC merely treats it as a suppressed power source with an average operational rate. In order to overcome the limit of the two-state on/off model for renewable power sources, J. Choi et al. employed a multi-state wind turbine generator (WTG) model to reflect the intermittency in a probabilistic way [11–14]. In addition, they recently applied a multi-probabilistic reliability criterion to maintenance scheduling [15].

Although the aforementioned studies suggest good reliability criteria for relatively long-term operations, they do not suggest a specific short-term metric, especially in terms of frequency fluctuations. As described previously, the intermittent output from large-scale WTGs can cause serious fluctuations in grid frequency, and thus, large amounts of spinning reserve are crucial for stabilizing the frequency. Considering that the spinning reserve is the extra power capacity of on-line load-following generators, it is important to commit the correct number and capacity to provide sufficient spinning reserve.

In this paper, in order to provide a quantitative measure of the required spinning reserve, we propose an extension to the loss of load probability (LOLP), namely *failure rate for frequency regulation* (*FRFR*), which addresses the failure probability of frequency regulation. In the calculation of this index, grid parameters are included either deterministically or probabilistically. The probability of achieving successful frequency regulation is estimated using physical constraints and the equilibrium condition between load and generation. The suggested reliability index is then obtained by inverting the estimated success probability. In addition, we incorporate V2G power to assess its impact on frequency regulation. From the derived criterion, the impact of wind power can be estimated in a quantitative manner, thus providing a good measure of the required spinning reserve.

We begin the article with an overview of the mechanism of frequency regulation followed by several design considerations for the suggested reliability criterion. In Section 4, a mathematical model is constructed using physical constraints, the components of which are represented either using real numerical parameters or random variables. The probability distributions of each random variable are constructed such that they reflect the real-world situation. Then, two inequalities are derived from the physical constraints and the equilibrium condition between load and generation to yield a probabilistic criterion. An analytic technique is discussed to derive the optimal operating point of the load-following generators, followed by a simulation to illustrate the effect of the operating point in two different situations. Finally, in Section 5, several case studies are performed to demonstrate the effectiveness of the suggested index.

2. Frequency regulation under high levels of wind-power penetration

In an electrical grid, load (demand) and generation (supply) must be balanced constantly. Traditionally, manipulation of the load has been considered difficult, and thus, only the generation side has been controlled to maintain the balance with the load. The cheapest, but uncontrollable, nuclear and coal plants supply the base power, and steam-driven thermal plants are usually employed to follow load variations over 24 h. Although combined-cycle generators have been widely employed as load-following plants, they still require certain amount of time for cold starts, and hence, have an accompanying start-up cost. Moreover, since each type of generator has a different fuel cost, the grid operator must also determine when and which generators should be committed from an economic perspective. This kind of scheduling is referred to as unit commitment (UC) and is usually performed 24 h before the actual operation on an hourly basis. For every time frame, the amount of power to be committed is determined based on the predicted load with a margin called spinning reserve. As seen in Table 1, the amount of spinning reserve varies depending on the jurisdiction [6], but the common goal is to secure the stability of the grid against fluctuations, which mainly arise from inaccurate prediction and physical constraints.

Table 1
Requirements for the spinning reserve in different areas [6].

Control area	Amount of the spinning reserve
PJM	1.1% of the peak + probabilistic calculation on typical days and hours
France	500 MW
Belgium	460 MW
Netherlands	300 MW

Grid frequency is a key measure of power quality, and therefore, a grid operator should constantly strive to maintain the frequency within a certain target range. The generation control mechanism can be classified into several categories depending on the period of the load fluctuations. For short load fluctuation of 2–3 min, a generator may run governor free (GF), which means that the output power is adjusted by directly controlling the steam valve without changing the amount of supplied fuel [16,17]. For longer periods of up to 10–15 min, however, the output power must be adjusted with an appropriate change in the amount of fuel being used. In this case, an integrated control called a load frequency control (LFC) is used to restore the frequency to its nominal value through an automatic generation control (AGC) system [16]. In either case, the required adjustment is determined in real-time by feeding back the frequency to the system. For longer periods, a feed-forward control called an economic dispatch (ED) is employed and provides an economic perspective on the regulation of the power grid (in fact, it is a partial feed-back control since the prediction error is compensated for in every calculation). That is, a centralized energy management system (EMS) dispatches the load to each generator such that the total fuel cost is minimized by predicting the load curve for the next period. In practice, both LFC and ED are performed by an EMS, and only GF is performed by the generators themselves.

Each generator reserves a certain amount of power, which is usually a few percent of the rated power, for frequency regulation. This reserved share is determined considering both economic feasibility and physical restrictions such as the ramp rate limit. Generally, it is known that the more frequency regulation a generator performs, the less fuel efficient the generator is. In terms of depreciation of a generator, frequency regulation is also unfavorable. Thus, even if a generator has sufficient power-adjustment capacity, it is not desirable to perform regulation in excess of the reserved range. Rather, it is better to employ another generator to share the load. As a result, a grid operator should ensure that there are sufficient generators such that each one can manage the frequency regulation (GF and LFC) within the reserved range.

Traditionally, load fluctuation was the only uncertainty in a power system. Thus, the total share of the reserve was calculated in a deterministic manner, as in Table 1. Recently, however, the high penetration of renewable power sources has introduced new uncertainties. As an alternative method of mitigating these increased uncertainties, plug-in electric vehicles (PEV) are expected to provide additional regulation power forming a new niche market. This vehicle-to-grid (V2G) power is a promising and attractive energy-buffering resource to stabilize the grid. Nevertheless, since the random behavior of vehicle users brings another