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Quantitative frequency security assessment method considering cumulative effect and its applications in frequency control

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ABSTRACT

Rising wind and solar generation penetrations change power system frequency behaviors significantly. Large disturbances may cause serious frequency deviations and lead to stability problems. It is important to provide a comprehensive and quantitative frequency security assessment (FSA) method for situation awareness and control decision-making in power systems. In this paper, a new FSA approach considering cumulative effect of frequency deviations on power equipment is proposed to quantitatively assess the impact of power system frequency deviations. It provides a unified expression of frequency security index (FSI) and has advantages of linearity, smoothness and monotonicity over existing methods. The FSI is calculated based on frequency trajectory obtained from wide-area measurement system (WAMS) or numerical simulations by which wind and solar generation can be taken into account. With sensitivity analysis of frequency security margin, the proposed FSA method has been applied to critical disturbance and critical control amount searching with frequency security constraints. The searching procedure is easy to implement, and computationally efficient with good convergence. The feasibility of the proposed FSA method and its applications are demonstrated on the 10-machine 39-bus New England test system.

Introduction

Quantitative assessment on the risk and security infrastructure and operation states have been playing an important role in keeping power systems safe and reliable [1,2]. In the past decades, large frequency deviations led several power systems into instability and caused large scale power system blackouts and significant economic losses [3,4]. Moreover, environmental issues and concerns over global warming have led to rapid expansion of renewable energy industry in recent years while the rising wind and photovoltaic generation penetrations substantially affect system frequency behaviors and frequency control [5–7]. Small islanded power systems with low inertia are particularly vulnerable to the occurrence of large frequency deviations which will affect the security of the system [8]. Active power control measures, such as underfrequency load shedding (UFLS), are used to prevent severe frequency drop by electric power utilities. Evaluating the severity of frequency deviation and designing proper frequency control schemes are critical aspects of power system operation and control.

Frequency security assessment (FSA) is essential for power system operation and various controls, such as adjustment of frequency relays of load shedding schemes [9], limitation of load pick-up amount [10], and calculation of wind power generation limits [11]. In Ref. [11] a method was proposed to estimate the maximum perturbation power that thermal plants can bear under a given frequency deviation constraint. Taking into account responses of different governor-prime movers, an improved frequency response model was proposed to estimate maximum frequency deviations in small isolated power systems [8]. Time-frequency transformation was applied to assess frequency deviation due to wind power fluctuations [12] and was used in Ref. [13] for smoothing control of wind fluctuation. Furthermore, considering different levels of wind power penetration, available control options were explored to facilitate wind power plants participation in frequency control [14]. The above mentioned works can only provide approaches to estimating frequency deviations, but have nothing to do with comprehensive frequency security assessment.

A more precise and comprehensive FSA method is needed in order to facilitate power system situation awareness and control decision-making. Moreover, quantitative information about frequency security is also essential for an efficient adjustment and optimization of the UFLS schemes [15]. In the literatures, there

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are several indices been used for FSA, such as the frequency maximum deviation [5,16–18], frequency change rate [19–21], generation deficiency and frequency decline ratio [22]. However, these indices can only measure the severity of disturbance at one time. They are insufficient to measure the frequency violation along with its affecting period to consumers. Besides, they are unable to reflect different frequency deviation acceptability of different buses (consumers) [23]. To overcome these disadvantages, another formula of frequency security index, the transient frequency deviation acceptability (TFDA), was proposed in Ref. [24], which is an extension of the transient voltage dip acceptability margin [25], and a curve fitting technique was applied to improve the linearity of the index. In Ref. [26], a computationally efficient frequency security index (FSI) was defined based on frequency deviation extent or duration in different circumstances. The index has good linearity when margin is positive, but lacks of linearity at global scope. All the above mentioned indices cannot take into account the cumulative effect of frequency deviation, which is very important for revealing the effects caused by frequency deviations on power equipment and improving control measures for system and facility security [27].

Estimating the amount of necessary spinning reserve, adjusting load shedding amount, and limiting load pick-up amount are key examples where an efficient searching method for critical disturbance and control amount contributes a lot. Various types of load shedding adjustment approaches have been implemented by utilities. Some load shedding schemes are set with the System Frequency Response (SFR) model [28], where oscillations between generators are filtered out. An improved simplified frequency response model was presented to takes into account the regulation speed of spinning and different governor models [29], however, model simplification is still needed. To overcome the limitations of model simplification, full time-domain simulation can be used to obtain more detailed frequency responses, and frequency control decision-making procedure with complex models needs to be developed. The effects of increasing wind and photovoltaic generation can be easily considered in full time-domain simulation. In addition, with the roaring up of computing power of modern computers, full time-domain simulation can be achieved on-line. An efficient and model adaptable frequency control decision-making procedure is urgently needed in power system security defense system design.

The contributions of this paper are twofold. Firstly, an improved FSI considering cumulative effect is proposed. It takes more information of frequency trajectories into account, and performs better in linearity, smoothness and monotonicity than existing methods. Based on the proposed FSI, quantitative FSA and sensitivity analysis of frequency security can be efficiently carried out. The proposed FSI can be calculated based on full time-domain simulations. Thus, FSA based on the proposed FSI is not limited to simplified models. Wind and solar integrations can also be taken into account. Secondly, an efficient and robust searching method for critical control amount is presented based on the sensitivity analysis of the proposed FSI. Due to the aforementioned features of the proposed FSI, the searching method converges rapidly and shows high performance.

The rest of this paper is organized as follows. Section 'Frequency security assessment and discussions' further discusses the inherent needs to improve FSA method. Section 'Improved FSA considering cumulative effect' describes the formula of the proposed FSI in detail. Section 'Numerical verifications of the proposed FSA' evaluates the characteristics of the index by numerical simulations on the New England test system. Section 'Critical disturbance and control amount searching method' presents a critical control amount searching method, and its applications in power system state awareness and control decision are demonstrated. Conclusions are drawn in Section 'Conclusions'.

Frequency security assessment and discussions

Generators, transformers, and turbines all have operational frequency limitations. There are two principal considerations associated with the operation of synchronous generators beyond the normal frequency range: (1) accelerated aging of mechanical components, which happens during both under and overfrequency and (2) thermal considerations, which are of principal interest for underfrequency operation [27]. Another concern of operation at abnormal frequencies is excitation of mechanical resonances and high cycle fatigue damage which can be rapid, cumulative, and destructive.

Event-driven and response-driven under/overfrequency relays protect the system against large frequency swings. Response-driven protection schemes usually operate based on inverse-time strategies. Their limits and durations of frequency deviation are carefully chosen to maintain frequency stability and rule out relay actions due to routine operational activities. According to the operational requirements and guides, frequency deviation constraints both in extent and in duration are usually given as a two-element table $[f_{cr}, t_{cr}]$, which consists of the deviation extent f_{cr} and the corresponding acceptable maximum duration t_{cr} [23]. Usually, the frequency security status is violated if and only if the actual duration of frequency going beyond f_{cr} is longer than t_{cr}.

In the literatures, frequency security indices are defined by different formulas according to the relationship between f_{cr} and $f_{\min}$, where $f_{\min}$ is the minimum frequency following an event [5,16,24,26]. If $f_{cr} < f_{\min}$, it is defined by the frequency difference between f_{cr} and $f_{\min}$. If $f_{cr} \geqslant f_{\min}$, it is defined by the time difference between the threshold t_{cr} and the actual duration of frequency going beyond f_{cr}, namely t_b. These two cases are schematically shown in Fig. 1(a) and (b), respectively. The index is a piecewise function of $f_{\min}$, shown as follows

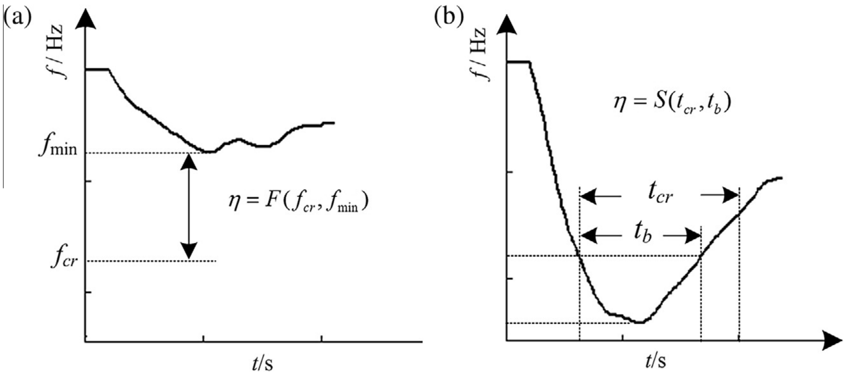

Fig. 1. Schematic diagram of FSA in the literature.