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Performance assessment of primary frequency control responses for thermal power generation units using system identification techniques[☆]

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ABSTRACT

Primary frequency control (PFC) responses for thermal power generation units are concerned about whether changes of turbine rotating speeds lead to proper responses of generator active powers. A new method is proposed to estimate performance metrics for PFC responses via system identification techniques. Dynamic models are identified from data samples of the turbine rotating speed and the main steam pressure as two inputs, and the generator active power as the output. Hypothesis tests are formulated to evaluate the qualities of identified models. If model qualities are satisfactory and the contribution from the turbine rotating speed to the generator active power is significant, then performance metrics are estimated from a noise-free unit step response of the identified model. The proposed method removes three major limitations of the most widely-used method in contemporary industrial practices, namely, (i) performance metrics are obtained from all data samples of PFC responses, instead of some specific data samples being sensitive to noises; (ii) the proposed method is applicable to arbitrary-type PFC responses, not limited to step changes of the turbine rotating speed; (iii) noticeable effects of the main steam pressure are separated to avoid erroneous performance assessment results. Examples from thermal power generation units are provided to illustrate the effectiveness of the proposed method.

1. Introduction

The primary frequency control (PFC) for a power generation unit refers to an ancillary service to power grids: the generator active power makes a response automatically according to a change of the generator rotating speed in order to suppress power grid frequency fluctuations [11]. The PFC is an integrated part of load frequency control [19,24], and becomes increasingly important for satisfactory power qualities, especially owing to a greater proportion of renewable energy sources and a larger size of connected power systems [1]. Hence, many power grid jurisdictions worldwide have been trying to formulate regulations on the PFC performances of power generation units in recent years [21,22,3,4]. In particular, National Energy Administration of China (NEAC) issued a national regulation on the operations of power plants in power grids, based on which detailed regulation rules are formulated for PFC responses [28]. The ones with satisfactory performances are remunerated for providing PFC services to power grids, and the others with poor performances are subject to financial penalties [16]. For instance, Shandong Regulatory Office of the NEAC has been publishing monthly the concrete amounts of financial remunerations or penalties based on performance metrics of PFC responses for all thermal power plants in Shandong province since January 2012.[1]

The PFC performance assessment has received increasing attentions from academic researchers and industrial engineers. Jones et al. [8] suggested using transfer functions of linear dynamic models for specifying PFC responses to step, ramp and random changes of frequencies for hydroelectric plants. Zhao & Chen [29] presented a high-order model to describe dynamic performances of system frequency responses for a large industrial area load shedding. Lobato et al. [15] developed a centralized frequency control monitoring system to measure the deviation between the real and desired primary and secondary frequency control responses for Turkish power plants. Efimov & Krylov [2] introduced various PFC criteria for thermal power generation units, e.g., absence of adequate reaction to frequency responses. Kilic & Arsoy [10] investigated the frequency control abilities in terms of the speed droop ratio for natural gas fired power plants in Turkey. Ozer et al. [18]

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[1] http://sdb.nea.gov.cn/new/list.asp?boardid=100.

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proposed an algorithm to extract PFC from secondary frequency control based on their characteristics in time and frequency domains. Guo et al. [6] derived the settling time from mathematical models of turbine regulating systems as the dynamic performance index for frequency responses of hydroelectric power plants with surge tanks. Saarinen et al. [23] identified dynamic models of governors and turbines for hydropower plants in PRC responses. Yang et al. [27] built a transfer function model between the PFC response time and the governor parameters for hydroelectric generation units. Guo & Yang [7] evaluated the stability performance of primary frequency regulation of hydro-turbine systems with surge tanks.

For the performance assessment of PFC responses for a thermal power generation unit, the essence is to evaluate whether a change of the turbine rotating speed leads to a proper response of the generator active power. The common performance metrics are the so-called response time, the settling time and the speed droop ratio (to be defined later in Section 2). To estimate these metrics, the most widely-used method in contemporary industrial practices is to find some specific data samples from a PFC response to a step change of the turbine rotating speed, and to read the values of performance metrics directly from these data samples. However, this method suffers from three major limitations, namely, (i) performance metrics from specific data samples are sensitive to random noises, (ii) the specific data samples are difficult to be determined for non-step types of PFC responses, and (iii) noticeable effects of the main steam pressure on the generator active power cannot be separated so that erroneous assessment results are often obtained.

The main contribution of this paper is to propose a new method to assess the performance metrics for PFC responses of thermal power generation units. By exploiting system identification techniques, linear time-invariant models are identified from collected data samples to describe the dynamic relation between the turbine rotating speed and main steam pressure as two inputs and the generator active power as one single output. The model quality is evaluated via a hypothesis test that is developed from model parameter uncertainties. If the model quality is satisfactory and the contribution from the turbine rotating speed to the generator active power is significant, then the performance metrics are obtained from a noise-free unit step response of the identified model.

The proposed method is able to remove the above three limitations of the most widely-used method. In particular, all data samples are exploited by the proposed method, instead of only some specific data samples. The models are identified without discriminating the PFC response types, and can be obtained from step, ramp and arbitrary-type responses. Moreover, the effects of the main steam pressure are separated so that the PFC performance assessment is not affected by variations of the main steam pressure. The system identification techniques had been exploited by Saarinen et al. [23] and Yang et al. [27] for the PFC responses of hydroelectric generation units. To the best of our knowledge, however, the related studies have not considered two important features of the proposed method, namely, the hypothesis test on the model quality and the separation of effects from the main steam pressure.

The rest of the paper is organized as follows. Section 2 describes the problem to be solved. Section 3 presents the main idea and detailed steps of the proposed method. Industrial examples are provided in Section 4 for illustration. Section 5 makes some concluding remarks.

2. Problem description

Denote $r(t)$ and $p(t)$ for $t \in \mathbb{Z}^+$ (the set of positive integers) respectively as the samples of the turbine rotating speed and the generator active power of a thermal power generation unit. The sampling period $h \in \mathbb{R}^+$ (the set of positive real-valued numbers) usually takes a small value of 0.2 s, 0.5 s or 1 s. Fig. 1 depicts the time trends of $r(t)$ and $p(t)$ in a step-type PFC response, where r_0 and p_0 are the nominal values of $r(t)$ and $p(t)$, respectively. There are three commonly-used PFC performance metrics, namely, the response time, the settling time and the speed droop ratio [21]. The response time τhin second as shown in Fig. 1 is the time delay between the time instant of $r(t)$ experiencing a change and the counterpart of $p(t)$ making the corresponding response. The settling time Th in sec is the time duration for $p(t)$ to complete the response to the change of $r(t)$ and reach another steady-state value. The speed droop ratio is defined as the ratio of the percentage of speed change with respect to the percentage of power change [11], i.e.,

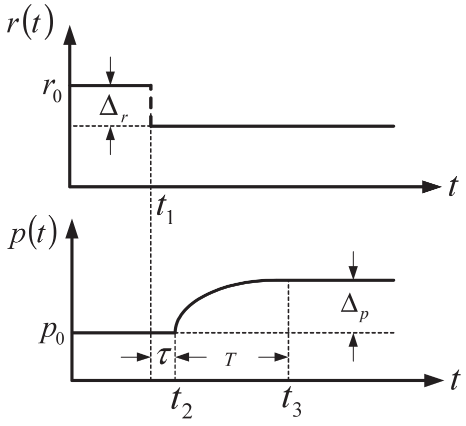

Fig. 1. Time trends of $r(t)$ and $p(t)$ in a step-type PFC response.

$$\delta = \frac{\Delta_r/r_0}{\Delta_p/p_0}. \tag{1}$$

Here Δ_r and Δ_p are the amplitude changes of $r(t)$ and $p(t)$, respectively.

In a PFC response, when the turbine rotating speed $r(t)$ experiences a large change (due to the power grid frequency fluctuations), the generator active power $p(t)$ is subject to control by adjusting the openings of main steam control valves to vary the main steam flow. However, $p(t)$ is also affected by the main steam pressure denoted by $d(t)$, serving as a disturbance to the relation between $r(t)$ and $p(t)$. As a result, $p(t)$ varies with $d(t)$ even if $r(t)$ does not change and the main steam control valves do not move. Let us take some data samples of $r(t)$,$p(t)$ and $d(t)$ in Fig. 2 from a 300 MW thermal power generation unit as an example. The first halves of $r(t)$ and $p(t)$ in Fig. 2 resemble the counterparts in Fig. 1, whereas $p(t)$ in the second half obviously decreases owing to the decrement of $d(t)$. Thus, along with $r(t)$ as one input, $d(t)$ serves as another input affecting $p(t)$. Note that the samples of $d(t)$ in Fig. 2 show several amplitude changes with short-time durations for 1 or 2 s only. Based on dynamics of steam turbines, the time constant from $d(t)$ to $p(t)$ takes at least 10 s [5] (Section 3.3 therein). As a result, $p(t)$ will not vary with such fast amplitude changes of $d(t)$, but does vary with the slow changes of $d(t)$.

In this paper, the problem to be solved is to estimate the performance metrics τh,Th and δ based on the data samples of $r(t)$,$p(t)$ and $d(t)$, in order to assess the PFC performance of a thermal power generation unit.

3. The proposed method

This section proposes a method to estimate the performance metrics from the samples of $r(t)$,$p(t)$ and $d(t)$. The main idea of the proposed method is presented first and the detailed steps are given afterwards.

3.1. Main idea

Let us recall the most widely-used method in contemporary industrial practices for estimating the performance metrics τh,$Th$and δ. The power grid frequency is 50 Hz so that the nominal value of $r(t)$ is $r_0 = 3000$ r/min. It is a common practice to take 2 r/min as the