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Extraction of primary and secondary frequency control from active power generation data of power plants

B. Ozer [a,*], O. Arikan [a], G. Moral [a], A. Altintas [a,b]

[a] Department of Electrical and Electronics Engineering, Bilkent University, Ankara, Turkey
[b] ISYAM, Bilkent University, Ankara, Turkey

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ABSTRACT

Frequency control is a vital component of a secure and robust power grid and it ought to be closely monitored. Frequency control consists of two main components; primary and secondary control and their contributions are usually aggregated in the active power generation data of a plant, which is acquired via Supervisory Control And Data Acquisition. In many cases, such as in Turkey, they are demanded to be evaluated separately due to different impacts on power system or different financial policies. However, this is not usually a straightforward process since primary and secondary response cannot be obtained distinctly.

In this work, Extraction of Primary and Secondary Control (EPSCon) algorithm is introduced to extract primary and secondary response over active power generation data. Based on time and frequency domain characteristics of primary and secondary response, EPSCon is developed on a Expectation-Maximization type recursive scheme employing Generalized Cross Correlation and ℓ^1 Trend Filtering techniques. Favorably, EPSCon uses a simple plant model built upon basic governor and plant load controller technical characteristics as an initial estimate of primary and secondary response.

Introduction

Load–frequency control (LFC), is an essential requirement for a secure and robust power system [1]. Due to increasing size and complexity of power systems [2] and the liberalization of the electricity supply industry [3], it became inevitable to monitor and evaluate frequency control performed by plants. As focused in this paper, primary and secondary frequency control are two main parts of LFC. They have often different remuneration policies [4]. Nevertheless, in a typical Supervisory Control And Data Acquisition (SCADA) application, as in the Turkish system, primary and secondary responses are not acquired distinctly but as an aggregation in the active power generation data of a plant. Using signal processing techniques, this paper introduces Extraction of Primary and Secondary Control (EPSCon) algorithm to extract primary and secondary control components from active power generation data, allowing distinct evaluation and remuneration of primary and secondary control.

LFC aims to stabilize system frequency within limits around nominal frequency by properly adjusting the MW outputs of the generators [5]. Primary frequency control is the automatic response of turbine governors against deviations in system frequency. It depends on the speed-droop characteristics [5] of a plant and performed within a few seconds [6]. Secondary frequency control is dictated by the Automatic Generation Control (AGC) based on the Area Control Error (ACE). For the purposes of this paper, Turkish system is based on a single control area and the system frequency is monitored by the national control center. EPSCon utilizes the reference model introduced in [7] to characterize primary and secondary response of typical power plant in Turkish power system. Secondary frequency control is based on up/down ramp rates of generating plants and realized within the time frame of minutes [8]. In this work, the signals denoting primary and secondary frequency control are referred to as primary and secondary frequency response, respectively.

In the literature, there are many studies regarding optimal load–frequency control strategies, e.g. classical approaches [9–11] or recent techniques [12–16]. Monitoring of power systems draws also attention of many researchers such as estimation of required power generation to balance the load [17], estimation of stability index [18] or assessment of the security of the power system [19]. However, to the best of our knowledge, there is only a limited work [20] on the separate estimation of primary and secondary response components over measured power generation

* Corresponding author. Tel.: +90 5336839342.
E-mail addresses: ozer@ee.bilkent.edu.tr (B. Ozer), oarikan@ee.bilkent.edu.tr (O. Arikan), gm@ee.bilkent.edu.tr (G. Moral), altintas@ee.bilkent.edu.tr (A. Altintas).

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data. The motivation behind separate estimation lies on the fact that even though primary and secondary response cannot be individually measured, transmission system operators (TSOs) may have different financial policies. For instance, correct provision of primary and secondary control performed by plants are differently remunerated, or primary and secondary control shall be subject to different penalties, since unavailability of these services may pose different system-wide events. Furthermore, some plants are not obliged to secondary control yet they ought to perform primary control. Primary response component of such plants have to be extracted from total power generation to be able to evaluate primary response for remuneration or penalty.

EPSCon provides separate offline estimates of primary and secondary response of a plant from (total) active power generation data available in SCADA. Time and frequency domain characteristics of primary and secondary response are investigated. Based on the observations that secondary response can be modeled as a piecewise linear signal and it has a much sparser derivative compared to primary response, ℓ^1 trend filter [21] is used to filter out primary response from active power generation. It is possible to improve the estimation performance by initially predicting primary response using the reference model introduced in [7] and subtracted from the active power generation before ℓ^1 trend filter. It is also observed that the reference model provides close estimates of primary response with a time delay and attenuation. Such time delay and attenuation is computed by the correlation between predicted and modeled primary response. A recursive mechanism is used to improve the accuracy of time delay and attenuation computations iteratively. Owing to recursion, better estimates of primary and secondary response are acquired in each iteration. Simulations are provided with synthetic and real data to demonstrate that EPSCon converges to reliable estimates of primary and secondary response after a few iterations.

This paper is organized as follows: In Section 'Nomenclature', signals used in the present research are summarized. In Section 'Time and frequency domain analysis of frequency control', primary and secondary frequency response are analyzed in time and frequency domain, providing constraints for the design procedure of EPSCon. In Section 'Modeled primary and secondary response', a frequency control model is introduced to enhance estimation accuracy. In Section 'EPSCon algorithm', EPSCon algorithm is presented. In Section 'Experimental results', experimental results with both synthetic and real data are illustrated. Finally, conclusions are drawn in Section 'Conclusions'.

Nomenclature

Table 1 covers the signals that are used either as input or as output in EPSCon.

Time and frequency domain analysis of frequency control

Analysis of input signals is a crucial step before delving into EPSCon algorithm covered in Section 'EPSCon algorithm'. In this section, both time and frequency domain based analyses are carried out, which are widely used in the design procedure of EPSCon. Active power generation of a plant (P_{GEN}), sampled by SCADA, is taken to comprise of (actual) primary (PPR_A) and (actual) secondary frequency response (PSR_A) as follows:

$$P_{GEN}[n] = \mathrm{PPR}_A[n] + \mathrm{PSR}_A[n] + \omega[n], \tag{1}$$

where $\omega[n]$ is the noise in data which is commonly modeled as a Gaussian variable and n is the discrete time index. Since the signal-to-noise ratio (SNR) is generally very high, $\omega[n]$ will be neglected in the remaining of this work. It should be emphasized that PPR_A and PSR_A are not individually acquired but their combination P_{GEN} is available through SCADA as a sampled analogue data. In this work, based on P_{GEN} signal, PPR_A and PSR_A are individually estimated, which are represented as $\widehat{\mathrm{PPR}_A}$ and $\widehat{\mathrm{PSR}_A}$ respectively.

Table 1
Signals and their description used in the presented work.

Signal	Description	Availability
Δf_s	Deviation in system frequency	SCADA
P_{SET}	Power-set point levels send by AGC	SCADA
P_{GEN}	Active power generation of a plant	SCADA
PPR_A	(Actual) Primary response of a plant	Unavailable
$\widehat{\mathrm{PPR}_A}$	Estimated primary response of a plant	Estimated
PPR_M	Modeled primary response	Available
PSR_A	(Actual) Secondary response of a plant	Unavailable
$\widehat{\mathrm{PSR}_A}$	Estimated secondary response of a plant	Estimated
PSR_M	Modeled secondary response	Available

PPR_A is the dynamic response against system frequency (f_s) deviations. Deviations in system frequency (Δf_s) is defined as $\Delta f_s[n] = f_u[n] - f_s[n]$, where f_u is the nominal frequency which is 50 Hz for Union for the Co-ordination of Transmission of Electricity (UCTE). Since the generation-load balance of a power system is highly variable in time, Δf_s and PPR_A are expected to vary rapidly and consequently have considerable amount of high frequency content. In Fig. 1, an acquired Δf_s and a representative PPR_A with their spectrum are shown. Spectrum of PPR_A reveals that it has substantially uniform spectrum. Thus, PPR_A cannot be associated with a specific frequency range.

PSR_A is dispatched by power set-point (P_{SET}) values which are sent by AGC. P_{SET} can be regarded as desired active power generation level with the assumption of steady-state f_s, i.e., $f_s[n] = f_u[n]$. In this case, excluding primary response, active power generation of a plant should follow P_{SET}, i.e., if P_{SET} remains constant, active power generation ought to be equal to P_{SET}. Otherwise, power generation of a plant is increased or decreased until P_{SET} level is attained. Such a behavior is denoted as PSR_A. Typically, PSR_A is the response when a plant is controlled by AGC. However, in this work, (1) is assumed to be also valid for plants which are not connected to AGC. In such a case, steady-state active power generation is dictated locally with P_{SET} levels denoting daily declaration of hourly active power generation schedule. With this extended definition of PSR_A and P_{SET}, it is possible to estimate steady-state active power generation of plants which are only responsible with primary frequency control. As illustrated in Fig. 2, P_{SET} and PSR_A can be modeled as piecewise linear signals.

Comparison of the spectra of PPR_A and PSR_A shows that frequency content of PSR_A decays faster than PPR_A. Average of PSR_A is also much higher than average of PPR_A since PSR_A represents levels of steady-state power generation, it usually has an average

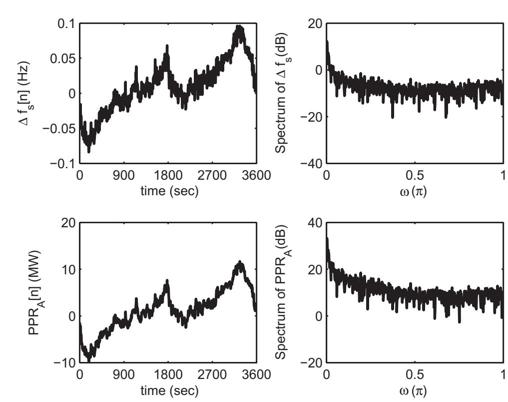

Fig. 1. Δf_s, PPR_A and their corresponding spectrum.