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A novel time-domain linear ringdown method based on vector fitting for estimating electromechanical modes

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ABSTRACT

This paper proposes a novel method, called Ringdown Time-Domain Vector Fitting (RTD-VF), for estimating electromechanical modes in interconnected power systems. Such a method authentically extends, to the context of ringdown analysis, the well known Time-Domain Vector Fitting (TD-VF) method, which has already been successfully applied within other power systems areas. The proposed method is based on a state-space discretization framework which enables ringdown events to be effectively estimated when described as artificial unit impulse responses. Moreover, RTD-VF completely avoids the necessity to perform discrete Fourier transforms (DFTs) of ringdown data sequences. Three case studies are used to validate the proposed method. One of the examples considers a synthetic test signal, whereas the other two case studies consider actual ringdown data sets extracted from the North American Eastern Interconnection (NAEI) system and from the Brazilian Interconnected Power (BIP) system.

1. Introduction

Estimation of electromechanical oscillatory dynamics in interconnected power systems plays an important role to infer about their stability, especially when systems operate closer to their limits [1,2]. In this context, when a transient event (due to a disturbance or a fault) occurs, ringdown signals containing information about these oscillatory dynamics (modes) are induced in variables such as power flows and system frequency [3].

Worldwide, research groups have been expending substantial effort to install entire wide-band monitoring systems (WAMS) in order to collect real-time power system data not only from ringdown events but also from ambient (or normal) operation. Examples of WAMS based on the so-called phasor measurement units (PMUs) are found, for instance, in the Brazilian Interconnected Power (BIP) system [4,5] and in the North American Eastern Interconnection (NAEI) system [6–8].

Both ringdown and ambient data acquired through WAMS encounter their own applications when it comes to estimating oscillatory modes [3]. As far as linear methods based on ringdown data are considered, estimating methods can be divided into two groups: time-domain and frequency-domain methods. Time-domain methods such as Prony [9] and Matrix Pencil [10] consider the roots of characteristic polynomials (or matrices) as modal estimates. Although widely adopted, these methods may require extensive calculations due to singular value decompositions, leading to poor numerical conditioning [11,9,8]. On the other hand, frequency-domain methods may require fewer calculations since they usually generate oscillatory mode estimates by simply identifying peak frequencies in the discrete Fourier transform (DFT) of ringdown data sequences. However, since they rely on performing DFTs, frequency-domain techniques may suffer from poor or biased modal estimates due to the well known spectral leakage (windowing) effect. Such a windowing effect is a critical issue especially when ringdown data contain *increasing/decreasing dc components*. To cope with this issue, recently in [8], it has been proposed to remove such dc components by using the difference sequence between two sets of ringdown data, which must be measured from two different locations in the power system.

Now, from a broader perspective, it is well known that the so-called iterative *vector fitting* (VF) algorithms [12] appear within the power systems community as powerful system identification tools, with successful applications in areas such as modeling of frequency-dependent network equivalents for transient analysis [13–15], wideband modeling of transmission lines and transformers [16–18], and passive macromodeling [12,19,20].

Standard frequency- and time-domain VF implementations have been first proposed more than a decade ago [21,18]. However, VF has been only recently adapted for estimating oscillatory modes through ringdown data, in a specific DFT-based setting [22]

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that reveals the potential of VF for estimation of modal parameters in power systems. Nonetheless, as a frequency-domain (FD) approach, the FD-VF implementation in [22] naturally suffers from drawbacks which are inherent to DFT computation (poor or biased modal estimates).

The objective of this paper is to avoid drawbacks inherent to DFT-based methods by extending the standard Time-Domain VF (TD-VF) technique [21] to the context of ringdown analysis. TD-VF implementations intrinsically rely on input–output relations of linear time invariant systems. Therefore, since post-disturbance events in power systems are commonly assumed to be generated by unknown inputs [3], the *ringdown version* of TD-VF (RTD-VF) that we propose in this paper alternatively copes with the idea that a ringdown response can also be partially described by means of an artificial unit impulse excitation. From a practical point of view, RTD-VF estimates power system modes directly from time-domain samples by adopting a suitable state-space discretization. When compared with the RFD-VF approach described in [22], the main advantage of RTD-VF lies in the fact that it completely avoids the necessity to perform DFTs. As a consequence, the method can also be naturally applied to ringdown signals with increasing/decreasing dc components, without having to create auxiliary difference sequences (which is an advantage when compared to [8]).

The paper is organized as follows. In Section 2, we briefly summarize the context of ringdown response analysis. In Section 3, the proposed RTD-VF method is described. In Section 4, three case studies are used to validate the proposal. One of the examples considers mode identification of a synthetic test signal, whereas the other two case studies consider actual ringdown data sets extracted from NAEI [6,8] and BIP [5] systems. Finally, Section 5 addresses the conclusions of this work.

2. Ringdown response analysis

In power systems, one can define a ringdown event to have a starting time $t = 0$. The contribution of M_{OSC} oscillatory modes to such a ringdown response can be then modeled, for $t \geq 0$, by

$$\begin{aligned} y_{\mathrm{OSC}}(t) &= \sum_{l=1}^{M_{\mathrm{OSC}}} \frac{A_l}{2}\left(\mathrm{e}^{j\varphi_l}\mathrm{e}^{\lambda_l t} + \mathrm{e}^{-j\varphi_l}\mathrm{e}^{\lambda_l^* t}\right), \\ &= \sum_{l=1}^{M_{\mathrm{OSC}}} A_l \mathrm{e}^{\sigma_l t}\cos(\omega_l t + \varphi_l), \end{aligned} \tag{1}$$

where A_l and φ_l are, respectively, the amplitude and phase of the lth oscillatory mode, whereas $\lambda_l = \sigma_l + j\omega_l$ and $\lambda_l^* = \sigma_l - j\omega_l$, $l = 1, \ldots, M_{\mathrm{OSC}}$, with σ_l and $\omega_l = 2\pi f_l$ ($f_l \neq 0$) being, respectively, the attenuation and the oscillatory frequency of mode l.

A ringdown response may also be influenced by a set of real-valued eigenvalues $\lambda_l = \sigma_l$, $l = M_{\mathrm{OSC}} + 1, \ldots, M$, where M denotes the total number of modes. This influence can be modeled by

$$y_{\mathrm{R}}(t) = \sum_{l=M_{\mathrm{OSC}}+1}^{M} A_l \mathrm{e}^{\sigma_l t}, \tag{2}$$

and leads to the resulting ringdown response

$$y(t) = h_{\mathrm{dc}} + y_{\mathrm{OSC}}(t) + y_{\mathrm{R}}(t), \tag{3}$$

where $h_{\mathrm{dc}} \in \mathbb{R}$ represents the *dc* component of the ringdown response, which naturally corresponds to $y(t)$ as $t \to \infty$, given that $\sigma_l < 0\ \forall\ l$.

The Laplace transforms of $y_{\mathrm{OSC}}(t)$ and $y_{\mathrm{R}}(t)$ can be both readily expressed via partial fraction expansions,

$$Y_{\mathrm{OSC}}(s) = \sum_{l=1}^{M_{\mathrm{OSC}}} \left(\frac{\frac{1}{2}A_l \mathrm{e}^{j\varphi_l}}{s-\lambda_l} + \frac{\frac{1}{2}A_l \mathrm{e}^{-j\varphi_l}}{s-\lambda_l^*}\right), \quad \lambda_l \in \mathbb{C} \tag{4}$$

$$Y_{\mathrm{R}}(s) = \sum_{l=M_{\mathrm{OSC}}+1}^{M} \frac{A_l}{s-\lambda_l}, \quad \lambda_l \in \mathbb{R} \tag{5}$$

which can also be combined into a more compact form so that

$$Y(s) = \frac{h_{\mathrm{dc}}}{s} + Y_{\mathrm{OSC}}(s) + Y_{\mathrm{R}}(s) = \frac{h_{\mathrm{dc}}}{s} + \sum_{i=1}^{N} \frac{c_i}{s-p_i}, \tag{6}$$

where

$$p_i = \begin{cases} \lambda_{\frac{i+1}{2}}, & i = 1, 3, \ldots, 2M_{\mathrm{OSC}} - 1 \\ p_{i-1}^*, & i = 2, 4, \ldots, 2M_{\mathrm{OSC}} \\ \lambda_{i-M_{\mathrm{OSC}}}, & i = 2M_{\mathrm{OSC}} + 1, 2M_{\mathrm{OSC}} + 2, \ldots, N \end{cases} \tag{7}$$

and, similarly,

$$c_i = \begin{cases} \frac{1}{2}A_{\frac{i+1}{2}}\mathrm{e}^{j\varphi_{\frac{i+1}{2}}}, & i = 1, 3, \ldots, 2M_{\mathrm{OSC}} - 1 \\ c_{i-1}^*, & i = 2, 4, \ldots, 2M_{\mathrm{OSC}} \\ A_{i-M_{\mathrm{OSC}}}, & i = 2M_{\mathrm{OSC}} + 1, 2M_{\mathrm{OSC}} + 2, \ldots, N \end{cases} \tag{8}$$

with $N = M + M_{\mathrm{osc}}$. It is also important to observe that (7) and (8) establish direct relations between the partial fractions' residues $\{c_i\}$ and poles $\{p_i\}$ and the modal parameters in (1) and (2).

In the following section of this paper, we extend the standard TD-VF technique [21] to the context of modal estimation through ringdown data. Although TD-VF has a purely mathematical nature, we introduce this technique by adopting the nomenclature presented in Eq. (6), so that an evident link with ringdown analysis is maintained. During a first explaining, however, it is considered $h_{\mathrm{dc}} = 0$.

3. From standard TD-VF to the proposed ringdown TD-VF (RTD-VF)

In the case of strictly proper single-input single-output (SISO) systems, the TD-VF technique [21] is naturally intended to fit a scalar input–output relation

$$Y(s) \approx \sum_{i=1}^{N} \frac{c_i}{s-p_i} U(s), \tag{9}$$

where $\{c_i\}$ and $\{p_i\}$ are iteratively estimated by means of a two-stage procedure, described below.

Pole relocation stage: Based on a set of (known) starting poles $\{\bar{p}_i\}$, the following alternative approximation

$$\underbrace{\left(1 + \sum_{i=1}^{N} \frac{d_i}{s-\bar{p}_i}\right)}\sigma(s)Y(s) \approx \sum_{i=1}^{N} \frac{c_i}{s-\bar{p}_i} U(s) \tag{10}$$

is rewritten by its inverse Laplace transform

$$y(t) \approx \sum_{i=1}^{N} c_i\ \tilde{u}_i(t) - \sum_{i=1}^{N} d_i\ \tilde{y}_i(t), \tag{11}$$