Electric Power Systems Research 154 (2018) 423–432

Contents lists available at ScienceDirect

Electric Power Systems Research

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

On-line parametric estimation of damped multiple frequency oscillations

F. Beltran-Carbajal [a,*], G. Silva-Navarro [b], L.G. Trujillo-Franco [b]

[a] Universidad Autónoma Metropolitana, Unidad Azcapotzalco, Departamento de Energía, C.P. 02200 Mexico City, Mexico
[b] Centro de Investigación y de Estudios Avanzados del I.P.N., Departamento de Ing. Eléctrica, Sección de Mecatrónica, C.P. 07360 Mexico City, Mexico

ARTICLE INFO

Article history:
Received 10 May 2017
Received in revised form 17 August 2017
Accepted 7 September 2017

Keywords:
Vibration mode estimation
Damped frequency oscillations
Frequency estimation
Damping estimation
Algebraic estimation

ABSTRACT

Undesirable harmonic pollution is currently a reality in many electric power systems. Damped transients generated by the growing use of electronically controlled devices are an important source of harmonic distortion of voltage and current waveforms. Accurate real-time estimation of harmonics parameters during the on-line operation of some electric power system is thus an active and pertinent challenging research issue. In this paper a novel on-line algebraic parametric estimation method in time domain, for damped harmonic components on electric power system signals is introduced. Algebraic formulas to directly compute amplitude, damping, frequency and phase parameters and dc offset component into a small time window for variable multi-frequency oscillations are proposed. Parameter estimators enable the on-line and direct reconstruction in finite time of harmonic components and deviations of some measurable signal. Experimental results confirm the effectiveness of the algebraic parametric estimation on uncertain multi-frequency oscillating transient signals.

1. Introduction

Harmonic pollution represents an undesirable problem in many practical applications of electric power systems [1–5]. Harmonics could also provoke interference with communication circuits and equipment, increase losses and heating in electromagnetic devices, and possibly induce resonance instability conditions when capacitors are used to improve the power factor [6]. Harmonics are conventionally considered as sinusoidal components with integer multiples of the power system fundamental frequency [6–8]. For this scenario, Fourier analysis is an excellent tool for detection of harmonics for known fundamental frequency signals [9]. Thus, harmonics can be computed into a fundamental time period of the signal. In fact, it is recommended a measurement window of 12 cycles for 60 Hz power systems and 10 cycles for 50 Hz power systems for estimation of harmonics by employing the Discrete Fourier Transform (DFT) [6].

In situations when uncertain deviations of the fundamental frequency are expected, frequency estimators should be also implemented. In this regard, frequency estimation or measurement is very important for protection, control and energy quality of interconnected electric power systems [10–13]. Additionally, it is well known that nonlinear loads such as static power converters and other electronic control devices can also cause atypical frequency harmonic distortion on electric voltage and current signals [7]. As a consequence, presence of non-integer multiple harmonic components (interharmonics) is currently also evident in electric signals.

Diverse valuable techniques for amplitude, frequency and phase estimation of harmonic components based on the Fast Fourier Transform (FFT), various spectral estimation approaches, Kalman filtering theory, linear regression, least squares and zero crossing techniques have been proposed (see, e.g., [8,14,15] and references therein). Most of those techniques are usually synthesized to be implemented off-line. A fundamental time-versus-frequency tradeoff is commonly required for Fourier-based algorithms into an observation time equal to at least one waveform cycle [16]. Moreover, large errors in fundamental frequency estimation often occur when some unknown dc offset is involved in the measured signal [17].

Otherwise, a different real-time algebraic parametrical identification procedure for controlled linear dynamic systems has been recently introduced in [18]. This identification approach is based on powerful algebraic tools based on operational calculus, module

* Corresponding author.
E-mail addresses: fbeltran@azc.uam.mx (F. Beltran-Carbajal), gsilva@cinvestav.mx (G. Silva-Navarro), ltrujillo@cinvestav.mx (L.G. Trujillo-Franco).

http://dx.doi.org/10.1016/j.epsr.2017.09.013
0378-7796/

Nomenclature

A	$2n+1 \times 2n+1$ matrix
B	$2n+1 \times 1$ vector
γ_1	invariant low-pass filter gain
$\lvert\cdot\rvert$	denotes absolute value
ρ_i	auxiliar variable equals to $A_i sin(\alpha_i)$
ξ_i	auxiliar variable equals to $A_i cos(\alpha_i)$
$y(t)$	measurable oscillating signal with damped harmonic contents
s	complex variable in terms of operational calculus
$*$	complex conjugate
$P_c(s)$	characteristic polynomial
$y^{(n)}$	n-th order derivative of the signal $y(t)$
p_i	positive constants
a_{ij}	components of the matrix A depending on iterated integrations of the signal $y(t)$
b_i	components of the vector solution of the matrix B depending on iterated integrations of the signal $y(t)$
F_0	positive constant equals to the product of the constant offset and the squared frequencies
$\int^{(n)}\varphi(t)$	iterated integrals of the form $\int_{t_0}^{t}\int_{t_0}^{\tau_1}\cdots\int_{t_0}^{\tau_{n-1}}\varphi(\tau_n)\ \mathrm{d}\tau_n\cdots\mathrm{d}\tau_1$
θ_1	$r \times 1$ vector of system parameters to be estimated with $r=2n+1$
A_0	constant offset or DC component of the signal
Δ	determinant
$(\hat{\cdot})$	denotes estimated parameter
C	$2n \times 2n$ matrix
D	$2n \times 1$ vector
θ_2	$2n \times 1$ vector with the estimations of phases and amplitudes
A_i	amplitude of the i-th harmonic component
ζ_i	damping ratio
ω_i	undamped frequency
ω_{di}	damped frequency
α_i	phase angle
$y_{i,0}$	unknown initial conditions of each oscillator
$\dot{y}_{i,0}$	unknown initial conditions of each oscillator (first derivative)

theory and differential algebra. It has been proved that Mikusiński operational calculus is an excellent choice to create a greatly useful connection with other algebraic tools. The interested reader is also referred to excellent books [19–21], where the theoretical foundations of operational calculus are clearly described.

In the theoretical framework of algebraic identification described in [18], ordinary differential equations are firstly expressed in operational calculus notation. Then, linear differential operators are properly applied to annihilate polynomial perturbations due to unknown initial conditions. Parameter identifiers are obtained by transforming back to time domain resulting expressions and making additional elemental algebraic operations [18,22]. From a theoretical viewpoint, parameters are identified almost instantaneously into a quite small time window. Moreover, least squares and statistical methods become unnecessary in the algebraic parametric identification. Robustness of algebraic identification with respect to a large variety of additive disturbances and measurement noises has been also proved in [18,23]. Hence, the algebraic parameter identification approach in the sense established in [18] offers relevant opportunities to be applied and extended to solve challenging open problems in electric power systems, where real-time estimation of parameters and signals is required.

In fact, a fast algebraic estimation scheme for amplitude, frequency and phase parameters in electric power system signals with multiple frequency harmonics has been recently introduced by the authors in [24]. The present paper constitutes a natural extension of this previous contribution to the on-line and direct algebraic parametric estimation problem of damped multiple frequency oscillating signals. Natural frequencies and damping ratios (modal parameters) of some electric power system are also considered to be estimated by using real-time measurements of some available signal. Thus, estimated modal parameters of dominant vibration modes can be forwarded to power system stabilizers (PSS) to damp oscillations [12,25]. We also refer the interested reader to recent contributions [26,27], where the Hopf bifurcation analysis and control of power systems are well addressed.

In this paper, explicit algebraic (estimators) formulas to compute amplitude, damping, frequency and phase parameters, including modal parameters, and dc offset component into a small time window, for variable multi-frequency oscillating signals are proposed. During the synthesis of algebraic estimators, any multi-frequency oscillating signal is considered as a (measurable) known mathematical function into a sufficiently small time interval, which is solution of an uncertain dynamical system described by ordinary differential equations. Consequently, the dynamic model of the output signal supplies information to algebraically and quickly perform the parametric estimation. In this fashion, the possibly damped multiple frequency signal and its harmonic components are directly reconstructed in time domain. Moreover, we have considered that any *a priori* knowledge of the fundamental frequency is unavailable and, unrelated and arbitrary multiple frequencies may be present into the signal. Furthermore, it is assumed that all the initial conditions and parameters of the dynamic signal model are completely unknown. Therefore, algebraic estimators can be reseated and updated continuously to observe possible parametric variations of harmonic components or vibration modes, independently of initial conditions. Integration operators in time domain are properly applied to the dynamic signal model to avoid measurements of time derivatives of signals and avoid additional mathematical transformations. Integral operators can be also used to reject disturbances affecting some dynamic system [28,25] and attenuate external noise contaminating the output signals without knowing its probabilistic and statistical properties [29,30]. Some experimental results are included to depict the effectiveness of the proposed parametric estimation method for harmonic components or vibration modes. The experiments confirm that, the proposed algebraic estimation approach represents a very good alternative choice to estimate amplitude, damping, frequency and phase parameters and dc offset component of oscillating signals into a small time window.

2. Algebraic estimation of frequency, damping and dc offset

An overview of the design process of the proposed on-line algebraic parametric estimation technique in time domain for damped harmonic components of some multiple frequency oscillating signal is depicted in Fig. 1. Algebraic parametric estimation is based on the dynamic modelling of damped harmonics constituting some measurable oscillating signal. A mathematical model of the measurable signal is first obtained and then parameters of the signal model are estimated. In this way, algebraic formulas to compute amplitude, damping, frequency and phase parameters and dc offset component are finally synthesized.