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Efficient time domain power quality state estimation using the enhanced numerical differentiation Newton type method

Rafael Cisneros-Magaña[a], Aurelio Medina[a,*], Juan Segundo-Ramírez[b]

[a] *Facultad de Ingeniería Eléctrica, División de Estudios de Posgrado, U.M.S.N.H., Ciudad Universitaria, C.P. 58030, Morelia, Michoacán, Mexico*
[b] *Facultad de Ingeniería, Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*

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ABSTRACT

This contribution presents an efficient method for the time domain state estimation analysis in power systems. The proposed methodology evaluates the power quality state estimation using the enhanced numerical differentiation (END) method, which obtains the periodic steady state solution of a power network. This method exploits the half wave symmetry in the voltage and current waveforms. With the periodic steady state as initial condition, the estimation of harmonics and transients is evaluated by means of the Kalman filter (KF). This END-KF methodology determines the harmonic estimation under a time varying harmonics condition and the transient estimation due to fault transients. The results are compared against the Power Systems Computer Aided Design/Electromagnetic Transients Program including Direct Current (PSCAD/EMTDC) response.

Introduction

This paper proposes a methodology to evaluate the power quality state estimation applying the END and the KF methods [1–3]. The numerical differentiation (ND) method is based on the Poincaré map and the extrapolation to the limit cycle [4,5]; its variant, the END method takes the half wave symmetry in the waveforms of voltages and currents in a power system to obtain the periodic steady state more efficiently, as it processes only half waveform to determine this steady state [6], the advantages of the END compared against the ND are the fast solution with less computational effort, a requirement is the application of the half wave symmetry test. In this contribution, methodologies for harmonic and transient state estimation in time domain based on the END method [6,7] and KF are introduced. The END method allows fast and accurate harmonic state estimation (HSE) and transient state estimation (TSE) solutions. It allows an initial periodic steady state condition for the KF to be rapidly and accurately obtained, thus avoiding possible divergence of the filter. With this initial condition, time domain state estimation is obtained, being possible to consider transient phenomena, as well as variant and invariant harmonics. The END takes advantage of the half wave symmetry of voltage and current waveforms to reach the periodic steady state of the network. If zero initial condition is defined for the KF, the divergence can be present during the initial transient of the time domain state estimation [8], the KF needs of an adequate initial state.

Methodologies for HSE and TSE in time domain based on the END method and KF are introduced in this contribution. The END method allows a convenient initial condition for the time domain state estimation using the KF or its extensions, i.e., extended and unscented versions for nonlinear systems, to be obtained. This allows the KF to accurately assess the state estimation with a smaller error, mainly during the initial period of analysis.

The main motivation of this paper is to obtain an alternative for state estimation assessment in cases where the Kalman filter diverges. This alternative of solution consists on the application of a Newton method based on an enhanced numerical differentiation procedure, Poincaré map and extrapolation to the limit cycle; to obtain a better initial condition for the KF to solve the state estimation, especially when the system is under-damped and may present an initial transient of significant duration.

Ref. [9] presents the KF to evaluate dynamically the HSE and the harmonic flows in a power system. Ref. [10] uses the KF to obtain the HSE modifying the process covariance matrix each time step according with the steady or transient system condition. In this work, the approach is to apply the KF to determine the time domain state estimation beginning with the periodic steady state determined by the END method.

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* Corresponding author.
E-mail addresses: rcisneros@faraday.fie.umich.mx (R. Cisneros-Magaña), amedinr@gmail.com (A. Medina), juan.segundo@uaslp.mx (J. Segundo-Ramírez).

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The KF is based on a state space model and measurements from the power system. It can follow the dynamic behavior of a system under the presence of harmonics generated by nonlinear electrical loads and together with the END, can evaluate the harmonic state estimation under a periodic steady state condition in a fast and direct way. Since the system model has a more stable condition, the state estimation is evaluated more accurately [11,12].

The proposed END-KF methodology can be applied to estimate the transients due to disturbances, short circuits or sudden load fluctuations in the power system [13]. The transient state estimation is evaluated under the periodic steady state obtained by the END method, with smaller fluctuations in the state variables allowing a more precise state estimation [14].

The paper presents in Section 'The Kalman filter algorithm' the KF formulation in a discrete form to evaluate the time domain state estimation, in Section 'Enhanced numerical differentiation method' presents the END method to obtain the periodic steady state of a power network, in Section 'Case studies' case studies review the harmonic and transient state estimation using the END-KF methodology. The results are validated by direct comparison against the response from the PSCAD/EMTDC simulator [15,16] due to its ease of use, reliability, time domain solution to analyze the power quality issues and transients phenomena of practical power systems modeled in detail, however also different time domain simulators can be used such as Simulink and the alternative transients program (ATP), among others. The main conclusions drawn with the development of this research work are given.

Methodology

The END-KF method to assess the power quality state estimation in the time domain is based on the next steps:

(1) State variable waveform test of half wave symmetry.
(2) END obtains the periodic steady state for the power system providing an adequate initial condition to the KF.
(3) The KF solves the state estimation with a smaller error using a network model and a partial set of measurements from the power system.
(4) The state estimation result is used to evaluate all the variables in the power system, e.g., nodal voltages, the line, generator and load currents. Fig. 1 shows this method.

The time domain state space model of a power network is a set of first order differential equation derived from the application of the physical equilibrium laws governing its operation behavior through appropriate state variables as [17],

$$d\boldsymbol{x}/dt = \boldsymbol{Ax} + \boldsymbol{Bu} \tag{1}$$

$$\boldsymbol{y} = \boldsymbol{Cx} + \boldsymbol{Du} \tag{2}$$

The time domain approach is applied when the system has time-varying voltage and current signals, variant harmonics, faults or transient load conditions; this approach is useful for state estimation assessment under these sceneries.

The continuous state space model is transformed to a discrete time form through the approximation of the differential equations to difference equations [8,18] with $\boldsymbol{D} = 0$, i.e.,

$$\boldsymbol{x}_{k+1} = \boldsymbol{Ax}_k + \boldsymbol{Bu}_k + \boldsymbol{Fv}_k \tag{3}$$

$$\boldsymbol{y}_k = \boldsymbol{Cx}_k + \boldsymbol{w}_k \tag{4}$$

where $\boldsymbol{v}$ is the process noise and $\boldsymbol{w}$ is the measurement noise. They are assumed to be stationary, Gaussian, uncorrelated and zero averaged noises.

The discrete linear measurement equation is,

$$\boldsymbol{z}_k = \boldsymbol{Hx}_k + \boldsymbol{e} \tag{5}$$

$\boldsymbol{z}$ is the measurement vector, $\boldsymbol{x}$ the state vector, $\boldsymbol{H}$ the measurement matrix, relating the measurements to states in a linearly independent form and e is the error estimation vector, which is the difference between the estimate and actual measurement values [11,17]. The main objective of the state estimation is to minimize the square errors sum.

The Kalman filter algorithm

The KF takes the discrete state space model (3) and the measurements from the physical system defined with Eq. (5), to follow the dynamics of the system and estimates the state and output variables in the time interval under analysis. The harmonic levels and the transient conditions in an electrical system vary with time and can be obtained with this algorithm [3,19,20].

The waveform of the measurement variables are sampled from the system in a discrete form. The discrete KF algorithm has the following two stages [1,8], i.e.,

1. The time update. Project the state and the covariance error matrix.

$$\bar{\boldsymbol{x}}_{k+1} = \boldsymbol{A}\hat{\boldsymbol{x}}_k + \boldsymbol{Bu}_k \tag{6}$$

$$\bar{\boldsymbol{P}}_{k+1} = \boldsymbol{AP}_k\boldsymbol{A}^T + \boldsymbol{FQ}_k\boldsymbol{F}^T \tag{7}$$

2. The measurement update. Evaluate the KF gain, update the estimate state vector and the covariance error matrix.

$$\boldsymbol{G}_{k+1} = \bar{\boldsymbol{P}}_{k+1}\boldsymbol{H}^T(\boldsymbol{H}\bar{\boldsymbol{P}}_{k+1}\boldsymbol{H}^T + \boldsymbol{R}_k)^{-1} \tag{8}$$

$$\hat{\boldsymbol{x}}_{k+1} = \bar{\boldsymbol{x}}_{k+1} + \boldsymbol{G}_{k+1}(\boldsymbol{z}_{k+1} - \boldsymbol{H}\bar{\boldsymbol{x}}_{k+1}) \tag{9}$$

$$\boldsymbol{P}_{k+1} = (\boldsymbol{I} - \boldsymbol{G}_{k+1}\boldsymbol{H})\bar{\boldsymbol{P}}_{k+1} \tag{10}$$

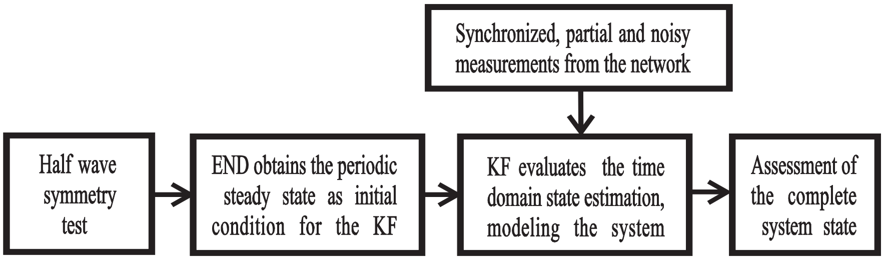

Fig. 1. END-KF method.