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Electrical Power and Energy Systems 28 (2006) 65–74

ELECTRICAL POWER & ENERGY SYSTEMS

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Robust dynamic state estimation of power system harmonics

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Received 10 June 2004; accepted 20 October 2005

Abstract

In this paper, a Robust Extended Kalman Filter (REKF) technique is proposed for dynamic harmonic state estimation. The proposed state estimator is capable of estimating the harmonic states of the power system in real time even in the presence of bad data in the measurements and requires only a few number of actual field measurements, thereby reducing the number of harmonic meters required by this estimator. From the simulation results obtained from IEEE 14 bus test system under various operating conditions, it has been observed that the estimation performance of the proposed technique is always better than the Extended Kalman Filter (EKF) technique.

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Keywords: Dynamic estimation; Power system harmonics; Kalman filter

1. Introduction

The power system operating point, under quasi-static conditions, becomes fully characterized by the knowledge of the state vector defined by all complex nodal voltages for a given network topology and parameters. To assess the state vector, the state estimation algorithm processes all information available about the system at each sampling instant. On account of the dynamic nature of the system loads, the state vector of the system varies dynamically, so that the estimation process must be repeated for every change in load or in network. This fact justifies the use of an algorithm to estimate dynamically the state vector, which will assure a much better representation of the time evolution of the system states. The literature on fundamental frequency power system state estimation is quite rich [1–8]. Many more excellent papers on fundamental frequency state estimation would be available from the list of references of these papers [1–8]. Now, in a power system, apart from fundamental frequency state estimation, estimation of harmonics is also necessary to minimize harmonic line currents and optimize the load power factor [9]. To achieve this objective, several researchers have addressed this problem of harmonic state estimation in the literature.

The harmonic state estimation methods proposed in Refs. [9–13] are essentially static in nature, hence, they do not have the capability of dynamic harmonic state estimation. Beides and Heydt [14] have proposed a dynamic power system harmonic state estimator using extended Kalman filter. This method also does not take into account the effect of bad data and sudden load change condition. Haili Ma and Girgis [15] presented a Kalman filtering based dynamic state estimator for power system harmonics estimation without considering the effect of presence of bad data measurements. Therefore, there still exists a need of a dynamic harmonic state estimator having the capabilities of processing, identifying and replacing the bad data measurements, if any, in the measurement vector as well as find the states in the normal and sudden load change conditions. The present work aims to fulfill this need.

Towards this end, in this paper, a Robust Extended Kalman Filter (REKF) technique is proposed for dynamic harmonic state estimation. The salient feature of this technique is its ability for accurate harmonic estimation even in the presence of bad data in the measurement vector. Now, for reliable state estimation, generally a large number of measurements are required. As the number of harmonic meters physically installed in a power system is often limited due to higher cost of these devices, it is necessary to appropriately place these limited number of harmonic meters in the system and subsequently, the required pseudo-measurements need to be derived from these field measurements. In this work, such a methodology for appropriate placement of the harmonic meters as well as for derivation of pseudo-measurements from the field measurements has also been developed.

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0142-0615/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijepes.2005.10.004

This paper is organized as follows. In Section 2, the basic mathematical theory of the proposed REKF technique is presented. Section 3 describes the methodology for placement of harmonic meters and derivation of pseudo-measurements. Section 4 describes the proposed algorithm in detail. In Section 5, the main results of the proposed work are presented. Lastly, Section 6 gives the main conclusions of the present work.

2. Mathematical formulation

Following the methodology described in Refs. [2,14] in this work, a quasi-static model of a power system has been assumed. In this model, it is assumed that the oscillations in the state variables are small and thus the states of the power system at $(k+1)$th instant are the same as those at the kth instant except for some uncertainty (noise), which can be represented by a random variable. Accordingly, at any harmonic order 'h', the dynamic model of the power system can be described as [14],

$$x_{k+1}^h = F_k^h x_k^h + w_k^h \tag{1}$$

where, x_k^h represents the state vector at time instant $t = k \times \Delta t$, with k and Δt being the sampling instant and the sampling interval, respectively. The superscript 'h' indicates that all the quantities are referred at the harmonic order 'h'. w_k^h is the uncertainty (noise) in the states, which has been assumed to be uncorrelated and Gaussian in nature with zero mean and known diagonal co-variance matrix Q_k^h. As any power system is completely defined by its bus voltage magnitudes and phase angles, in the present work, the bus voltage magnitudes and phase angles at the harmonic order 'h' are taken to be constituting the state vector x_k^h. As the phase angle of the reference is assumed to be known, the total number of state variables in a N-bus system is $(2N-1)$.

To estimate these states, certain measurements from the power system are necessary. At any harmonic order 'h', the measurement vector can be related to the state vector by,

$$Z_k^h = g(x_k^h) + v_k^h \tag{2}$$

The measurement vector Z_k^h consists of bus voltage magnitude measurements as well as the line real and reactive power flow measurements at the harmonic order 'h'. The function $g()$ is a non-linear function of x_k^h. The measurement noise v_k^h is also assumed to be uncorrelated and Gaussian in nature with zero mean and known diagonal co-variance matrix R_k^h.

Under quasi-static operating condition, Eq. (2) can be linearised by Taylor's series around an operating point $x_{k\text{o}}^h$ and after neglecting second and higher order terms; Eq. (2) can be written as,

$$Z_k^h = g(x_{k\text{o}}^h) + \frac{\partial g}{\partial x_k^h}(x_k^h - x_{k\text{o}}^h) + v_k^h \tag{3}$$

or,

$$\Delta Z_k^h = G_k^h \Delta x_k^h + v_k^h \tag{4}$$

where, $\Delta Z_k^h = Z_k^h - g(x_{k\text{o}}^h)$, $\Delta x_k^h = x_k^h - x_{k\text{o}}^h$ and G_k^h is the Jacobian matrix (at harmonic order 'h').

Along with the knowledge of the initial state vector $x_{k\text{o}}^h$, Eqs. (1) and (4) are sufficient to be used by some suitable technique to determine the system states any time instant 't'. In the literature, EKF technique has been used so far for the dynamic harmonic state estimation [14,15]. The detailed analysis of the EKF algorithm can be found in Ref. [16]. In the EKF algorithm, a constant measurement error co-variance matrix (R_k^h) is used. This matrix can also be shown to be reciprocal of the diagonal weighting matrix (W_k^h), or $R_k^h = (W_k^h)^{-1}$ [6,7]. Now, for constant R_k^h (or W_k^h), any anomalous measurement, if present, also gets equal importance in the estimation process, which, in turn, leads to the deterioration of the estimation performance of the EKF. Clearly, to improve the estimation accuracy, the anomalous measurements need to be given lesser weights. To achieve this objective, instead of the constant weight matrix, in the present work the following exponential weight matrix has been used:

$$W_k^h = W_k^h \times e\{-|Z_k^h - g(x_k^h)| \times h\} \tag{5}$$

In the above weight function, the residual factor $|Z_k^h - g(x_k^h)|$ is multiplied by the harmonic order 'h'. As the magnitudes of the harmonic voltages decrease with the increasing harmonic order, this scaling of the residual terms with the harmonic order 'h' helps to provide improved results. For normal operating condition with measurements noise less than 5%, the residual vector becomes very small and hence, the weight matrix becomes a constant matrix. On the other hand, for anomalous measurement noise, or with high measurement noise, the residual vector increases thereby decreasing the weighting matrix, which in turn, improves the estimation accuracy of the Kalman filter under these conditions.

Now, in order to apply Eq. (5), the measurement vector Z_k^h is required. As it is not feasible to install harmonic meters physically at all the required locations due to high cost, it is proposed to install the minimum possible number of meters at some strategic locations and subsequently, rest of the 'measurement need' is to be fulfilled by 'pseudo measurements'. In Section 3, the strategy for actual meter placement and technique used to obtain the 'pseudo measurements' are described in detail.

3. Method for locations of harmonic meters and pseudo-measurements

In the proposed method, the permanent harmonic meters are placed in those lines, which are sensitive to the known injected harmonic bus currents. As the location of the harmonic sources are assumed to be known a priori, the sensitivity of the harmonic line current $\tilde{I}_{k,ij}^h$ with respect to the injected harmonic current $\tilde{I}_k^h$ can be found out analytically. According to the current injection method [17],

$$[\tilde{V}_k^h] = [\tilde{Z}_{k,\text{bus}}^h][\tilde{I}_k^h] \tag{6}$$

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