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Robust estimation of power quality disturbances using unscented H_∞ filter

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ABSTRACT

This paper proposes a novel adaptive filtering method for tracking the power quality disturbances present in distorted power signals. The proposed filter known as unscented H_∞ filter (UHF) is the robustification of unscented Kalman filter (UKF) and is based on state space modeling. The performance of unscented H_∞ filter has been compared with other adaptive filters considering signals, which can represent worst case measurement and network conditions in a typical power system. State space modeling is used to estimate power quality disturbances like sag, swell, notch in presence of additive white Gaussian noise (AWGN). Also the amplitudes and phases of different harmonics under high noisy conditions and decaying DC are also estimated which shows the robustness of the filter. Comparison results demonstrate that under identical conditions, the performance of UHF is better compared to UKF.

Introduction

Power quality has been an issue of growing concern amongst a broad spectrum of power customers over the past few years. Electric utilities are becoming more concerned about power system harmonics and voltage distortion. This increased concern is due to the increase in the application of power electronic devices in almost all kind of operation. The power system components continuously inject varying harmonics in the system giving rise to non stationary harmonics voltages and currents in the distribution system. These disturbances cause problems, such as overheating, equipment failures, inaccurate metering and malfunctioning of protective equipments. Some of the major factors, which contribute towards deteriorating power quality, are voltage sags, swells and the presence of harmonics. A voltage dip implies that the required energy is not being delivered to the load and this can have serious consequences depending on the type of the load involved, which sometimes lead to power service outage. The presence of harmonics often cause interference in communication circuits, over heating of magnetic portions of electrical systems, resonance of mechanical devices etc. Detection and subsequently elimination of harmonics using suitable harmonic filter as well as prediction of voltage dips has therefore been a major research concern of power engineers in recent years. Adaptive parametric estimation techniques [29] are popular approaches that have been widely used not only for estimation of non-stationary signal parameters but also to identify unknown nonlinear dynamic plants. Various estimation methods have also been proposed in each field such as linear-prediction (LP)-based methods [1] like forward–backward LP (FBLP) method, singular value decomposition (SVD), iterative filtering algorithm (IFA). All the above-mentioned methods have been basically developed only for frequency estimation. Therefore, they have not been able to directly estimate a sinusoidal signal itself (or amplitude and phase of each component) from the observed data [2,3]. In order to provide the quality of the delivered power, it is imperative to know the harmonics parameters such as magnitude and phase. This is essential for designing filter for eliminating or reducing the effects of harmonics in a power system. Adaptive algorithms based on Fourier analysis and linear combiners are proposed to evaluate the harmonics and flicker magnitude [4–6] in a power system. Online tracking of harmonics in power systems using variable gain filtering approach was described by Girgis et al., which was still unable to track abrupt changes of signals. Recently developments of soft computing techniques [13,14] have encouraged the researchers to use these methods for harmonic estimation. Since estimation of harmonic parameters is a nonlinear problem, Genetic Algorithm (GA), being a heuristic and stochastic global searching algorithm [7,8] was used for estimation. But GA suffers from larger time

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requirement for convergence when estimating multiple frequency components because of large number of parameters should be identified simultaneously. Due to different quantitative values of amplitudes and phases of harmonics, it is difficult to get a homogeneous genetic pool with respect to the final solution. LAV state estimation based algorithm [9] is also proposed for measurement of voltage flicker. Wavelet and S-transform [10–12] are effectively used to detect and classify power quality events Forgetting Factor Recursive Least Square (FFRLS) approach [15] is also used for estimating not only voltage sag, swell, momentary interruption but also the amplitudes and phases of harmonics in case of time varying power signals. But RLS has poor convergence properties in case of time-varying and non-stationary environments. On the other hand, extended Kalman filter (EKF) has often been applied to frequency estimation. Although it can estimate the amplitudes and phases of frequency components, the non- linearity could cause the EKF to diverge in some poorly initial conditions. However, the EKF approach [16–20] has the advantages that the estimates are computed recursively and that it can cope easily with time variation in the signal parameters, whereas the SVD or MLE approach assumes that the parameters remain constant in time. Unscented Kalman filter [24–26] is based on the unscented transformation to propagate the sigma points and the calculation of jacobian matrix can be avoided as done in case of EKF.

In contrast to Kalman filter which requires exact and accurate system model as well as perfect knowledge of the noise statistics, the H_∞ filter [21–23] requires no aprior information of the noise statistics but finite bounded energies. Unscented H_∞ filter (UHF) [27,28] is based on state-space representation of noisy sinusoidal signal and passing the sigma points through unscented transformation. But the filter performs better than UKF under high noisy condition due to auto tuning of measurement error covariance when state variables of the signal model are updated. The paper is organized as follows: Section 'Signal modeling for power quality estimation' develops signal model in state space for power quality estimation. The nonlinear unscented H_∞ filtering algorithm is presented in Section Unscented H_∞ filtering algorithm. Section 'Stabil ity analysis of unscented filter' demonstrates the stability of the proposed filtering approach. The simulation results of the proposed filter are presented in Section 'Simulation results' and conclusion is presented in Section 'Conclusion'.

Signal modeling for power quality estimation

Two types of signal models are proposed to estimate power quality disturbances like voltage sag and swell, notch, momentary interruption as well as amplitudes and phases of different harmonics like fundamental, third and fifth harmonics.

Signal model for power quality disturbances

Consider a signal y_k at time k is a sinusoid z_k in the presence of white Gaussian noise υ_k.

$$y_k = z_k + \upsilon_k \tag{1}$$

where

$$z_k = a_1 \sin(k\omega_1 T_s + \phi_1) \tag{2}$$

and

ω_1 = fundamental of angular frequency.
ϕ_1 = fundamental of phase angle.
a_1 = fundamental amplitude of the signal.

The observation noise υ_k is a Gaussian white noise with zero mean and variance σ_υ^2. The covariance of measured errors is $R_k = E[\upsilon_k \upsilon_k^{*T}]$, where $*$ means the complex conjugate and T is the transpose.

For notice of the fundamental frequency, here we consider a single complex sinusoid z_k with angular frequency ω_1 in the presence of white noise. The state variables used for noisy signal modeling are given as:

$$x_{1k} = \cos(k\omega_k T_s + \phi_k)$$
$$x_{2k} = \sin(k\omega_k T_s + \phi_k)$$
$$x_{3k} = \omega_k T_s$$
$$x_{4k} = A_k$$

The measured value of the signal can then be written in state space form as:

$$\text{State equation } x_{k+1} = f(x_k) + \omega_k \tag{3}$$

$$\text{Measurement equation } y_k = h(x_k) + \upsilon_k \tag{4}$$

where state vector is given by

$$x_k = [x_{1k} \quad x_{2k} \quad x_{3k} \quad x_{4k}]^T \tag{5}$$

The functions used for unscented transformation of sigma points are given as

$$f(x_k) = \begin{bmatrix} x_{1k}\cos(x_{3k}) - x_{2k}\sin(x_{3k}) \\ x_{1k}\sin(x_{3k}) - x_{2k}\cos(x_{3k}) \\ x_{3k} \\ x_{4k} \end{bmatrix} \tag{6}$$

$$h(x_k) = x_{1k}x_{4k} + \upsilon_k \tag{7}$$

Signal model for harmonic estimation

Harmonics are electric voltages and currents that appear on the electric power system as a result of non-linear electric loads. Three test signals are considered for estimation, which contains higher order harmonics and also slowly decaying dc component. The test signal 2 containing the third and fifth order harmonics is considered as:

$$z_k = a_1 \sin(kw_1T_s + \phi_1) + a_3 \sin(kw_3T_s + \phi_3) + a_5 \sin(kw_5T_s + \phi_5) \tag{8}$$

The test signal 3 is given by:

$$z_k = (1.5 + a_1(k))\sin(kwT_s + \phi_1) + (0.5 + a_3(k))\sin(3kwT_s + \phi_3) + (0.2 + a_5(k))\sin(5kwT_s + \phi_5) + a_{DC}\exp(-\alpha_{DC}kT_s) \tag{9}$$

where

$$a_1(k) = 0.15\sin 2\pi f_1 kT_s + 0.05\sin 2\pi f_5 kT_s$$
$$a_3(k) = 0.05\sin 2\pi f_3 kT_s + 0.02\sin 2\pi f_5 kT_s$$
$$a_5(k) = 0.025\sin 2\pi f_1 kT_s + 0.005\sin 2\pi f_5 kT_s$$

The test signal 4 is given by

$$z_k = a_1(k)\sin(k\omega T_s + \phi_1) + a_3(k)\sin(3k\omega T_s + \phi_3) + a_5(k) \times \sin(5k\omega T_s + \phi_5) + a_{DC}\exp(-\alpha_{DC}kT_s) \tag{10}$$

where

$$a_1(k) = 8\exp(-\alpha_1 kT_s)$$
$$a_3(k) = 1.5\exp(-\alpha_1 kT_s)$$
$$a_5(k) = 0.75\exp(-\alpha_1 kT_s)$$

The distorted power signal in presence of harmonics as mentioned in Eq. (8) can be modeled in a state space form in different ways. But here the main concern is to estimate the amplitude as