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Uncertainty Sources in Observer-based Power Harmonics Measurement

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Abstract

Power harmonics, inter-harmonics and sub-harmonics are among the most challenging issues in power quality and electromagnetic compatibility. Harmonics are known to cause overheating of transformers, increased transmission losses and inadvertent operation of remote relays. Accurate and fast measurement or estimation of harmonics amplitude and phases is an important task for conformity assessment of electrical devices, harmonics mitigation, issuance of electricity bills for industrial sector and many other purposes. Harmonic measurement techniques are diverse and numerous. One of the most common approaches is to use state observers or Kalman filters to measure harmonics. In this paper, different uncertainty sources in observer-based harmonic measurement techniques are discussed. Two common approaches, namely; methods based on the Fourier transform and observer-based approaches are discussed in this regard. Identification and quantification of these uncertainty sources is of vital importance in laboratory accreditation according to ISO/ IEC 17025 standard for quality management in testing laboratories. After each source of uncertainty is identified, it should be quantified using either of the two existing evaluation methods.

Keywords Electromagnetic compatibility; power harmonics; harmonic distortion; Measurement uncertainty

Introduction

The voltage or current in the power grid are supposed to be a single tone sinusoidal (with frequency of either 50 or 60 Hz). However, the actual signals are a summation of a sinusoidal of fundamental frequency (50 or 60 Hz) and some other sinusoids of frequencies which are products of the fundamental frequency. These additional sinusoids are called harmonics. Figure 1 shows an electrical current consisting of two harmonic components of amplitudes 1 and 0.4 amperes and angular frequencies 1 Hz and 3 Hz respectively.

Harmonics are present in the very beginning of electricity production due to non-uniform magnetic field of generators.

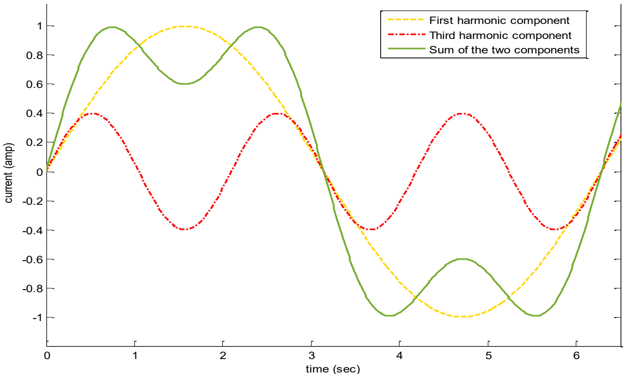

Figure 1. Summation of two harmonic components

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They are also caused by nonlinear and switching loads [1]. Power harmonics cause many undesirable issues in power grid since the transformers, motors and switching relays are designed to work for pure sinusoidal and therefore have limited tolerance to harmonic pollution. The measurement of power harmonic is an important issue in conformity assessment of electrical and electronics industry. There are requirements dictated by different international and national standards regarding the admissible limits of voltage harmonics in the power grid [1] and the harmonic current of electrical and electronic equipment [2]. Power generation and distribution utilities are responsible to comply with the standard requirements like [1]. On the other hand, electrical and electronics components should be compliant to current harmonics limits including those mentioned in [2]. Excessive harmonics causes overheating of transformers and cables and unattended functioning of remote relays [3, 4]. The increasing use of brush-less direct current motors and variable frequency drives in ventilation systems raises concerns regarding harmonics pollution and demands for a balance between reduced active power consumption and harmonic pollution.

The aforementioned standards require harmonics measurement with high accuracy. This measurement should be on-line and dynamic for active harmonic filters and when the harmonic components are significantly varying with time [4, 8 and 9]. For most of other application purposes, the measurement does not need to be on-line and dynamic. However, it is still important to have fast and accurate measurements. The limits for harmonics are defined in terms of amplitude of harmonic components and Total Harmonic Distortion (THD) [1, 2 and 10]. This requires computation of the harmonic components from the measurement of a sum of sinusoids [5]. International standards [11] and common practice assumes measurement of up to 40 harmonic orders. The largest harmonic components are usually in 3rd, 5th and 7th components caused by rectifiers and other switching devices and some higher orders arising from non-uniform air gap of generators [2]. From a laboratory point of view, inaccurate measurement of harmonic components leads to inaccuracies in THD computation and therefore results in uncertainty in the decision for compliance to standards. THD is a contributing factor in the computation of other indices including the displacement factor used in compliance testing of Light Emitting Diode lamps and luminaires [14]. The accurate measurement of harmonics becomes more crucial in active harmonic filter applications where the filter operates by generating the harmonic components with 180-degree phase shift to cancel the harmonic current [4]. In this situation, inaccurate harmonic measurement deteriorates the performance of the active filter [4]. Aside from compliance testing, harmonics measurement has other applications. For instance, in a recent paper [12] the harmonic pollution pattern of cryptocurrency mining farms is utilized to detect electricity theft. Another application is to detect generator faults from the harmonic pollution pattern [13]. The international standard IEC 61000-4-7 describes harmonic measurement methods based on the Discrete Fourier Transform (DFT) as the computation algorithm, but it allows for other methods if they are compliant with the prescribed requirements [11]. Fourier transform has been used for computing harmonics for several decades. DFT and the algorithm of Fast Fourier Transform (FFT) are now the main method in many commercial power harmonic analyzers [5]. Several variants of DFT-based methods have been proposed in the literature for faster response and better accuracy [22, 23]. Another method which received less attention is to use observers and Kalman filters [5, 6]. The latter is a dynamic measurement and enjoys relatively low computational burden [5]. Kalman filter-based approaches are generally deemed better than DFT-based methods [38]. In this paper, uncertainty sources common in different variants of observer-based harmonic estimation are listed. For other methods of harmonic measurement and estimation see [23]. The existing literature is surveyed by searching the paper keywords in google database. The most relevant publications are listed from journals and conferences excluding general-content publications. Table 1 summarizes different methods in power harmonic estimation.

Table 1. Power harmonic measurement techniques

Approach	Relevant works	Dynamic/ static estimation	Computational burden	Uncertainty evaluation	Factors contributing to uncertainty
DFT-based	See [23]	static	medium	straightforward	known
AI-assisted	See [23]	static	high	complicated	Requires further research
Observer-based	[5], [32]-[39]	dynamic	low	straightforward	known

In the following sections, observers and observer-based harmonic measurement are introduced. Then different uncertainty sources in observer-based harmonic measurement are listed and discussed.

2. State observers in harmonic measurement

State observers are dynamical systems which asymptotically estimate the value of one or more signals based on one or more measured quantities. Numerous observer structures have been practiced for dynamic estimation in diverse applications. For example, unknown input observers [24], Kalman filters [5], descriptor approach observer [25], cubic observers [26, 27], proportional, integral observers [28] can be named as a few. Comprehensive treatments of Kalman filtering methods for frequency tracking and harmonic estimation can be found in [29]. In [30], a model-based framework is proposed to estimate the frequency and of a single tone signal. This model is further enhanced by [31]. Reference [5] improved the models of [30, 31] and used it to estimate the frequency and harmonics. The results shown significant accuracy improvement in presence of different uncertainties [5].

In [32], a Kalman filter-based method is proposed to estimate both the fundamental and harmonics of the power grid voltage. In this work, a continuous time model is firstly proposed for the frequency dynamics. This model is then discretized in order to facilitate the use of discrete time filters. Reference [33] investigates the performance of Kalman filter-based harmonics estimation methods in a simulated power grid. In [45] an Ensemble Kalman filter is utilized to estimate harmonics and fundamental frequency of the grid. An advantage of state observers and Kalman filters in harmonic estimation is their faster response and their known tolerance for measurement noises [31]. Several variants of Kalman filters have been used to tackle the harmonic estimation problem [29]. Linear Kalman Filters (KF) can be used to estimate harmonics, if the fundamental frequency is exactly known [5, 29]. However, when the fundamental frequency is subject to deviation or there exists sub/inter-harmonics with approximately known frequencies, one may utilize nonlinear filtering techniques including Ensemble Kalman Filter (EnKF), Unscented Kalman Filter (UKF) and Extended Kalman filters (EKF) [30-35]. As mentioned in [5], using UKF leads to slight performance improvement compared to the added computational burden. EKF is more suitable when several parameters (including amplitude, phase and frequency) are to be estimated together.

Some works like [5] recommend a two-stage method; firstly, the fundamental frequency is estimated via EKF and then an augmented linear Kalman filter is utilized for the estimation of power harmonics. A notch filter may be used in between the two stages for each harmonic frequency. This method can also be used for inter-harmonics and sub-harmonics of known frequencies.

Table 2 compares the existing observer-based approaches in harmonic measurement based on the results of [5], [29], [33] and [40].

3. Sources of uncertainty in observer-based harmonic measurement

The major sources of uncertainties in harmonic measurement can be summarized as follows:

1- *Analog to Digital Conversion.* In order to compute harmonic components and consequently THD, most of existing devices rely on analog to digital data conversion [15]. A data conversion circuit or more commonly analog to digital converter, samples the analog voltage (current) and converts it to digital data. No data conversion system is perfect. The sampling frequency can’t be reduced indefinitely. Technological and financial issues limit the maximum sampling frequency [15]. Measurement noise and harmonic pollutions themselves cause overlaps (known as aliasing) in the frequency spectrum of the sampled data. Quantization of the digital numbers to limited number of digits and dynamic response of the data conversion system cause computational errors and measurement uncertainties in the digital data.

Approach	Relevant works	Computational burden	Accuracy	Convergence speed	Robustness/ adaptability
KF	[35]	low	low	high	low
Self-tuning KF	[36]	high	high	medium	high
EKF	[5], [33], [39]	Medium to low	medium	medium	medium
UKF	[37]	Medium to high	medium	medium	medium
EnKF	[34]	high	medium	medium	high

Figure 2. Observer-based power harmonic measurement techniques

2- *Source voltage Harmonic Pollution.* The computed current harmonic is affected by the harmonic pollution in the grid voltage. IEC 61000-4-7 requires that for the measurement of current harmonics the supply voltage has less than 5% THD. This guarantees that the effect of voltage harmonics on the accuracy of current harmonic measurement is insignificant. However, in portable measuring instruments using clamp meters the voltage can’t be supplied from a clean voltage source.

3- *Measurement Noise.* Electromagnetic fields induce measurement noises and disturbances in the measurement of voltage and current harmonics. The noise covariance should be accounted for in the determination of measurement uncertainty for harmonics. Voltage or current bias may also affect the measurement accuracy [6].

4- *Impedance matching.* The meter used for voltage or current measurement has an input impedance which slightly affect the measurement result. A clamp meter measuring the current should have very low input impedance while the volt meter should have very one. Since many commercial meters have acceptable characteristics. The instrument transformer ratio [17] has a similar effect.

5- *Calibration Uncertainty of Meters.* The meters (including voltage, current meters and harmonic computation algorithm) shall be calibrated via a reference meter of higher accuracy class.

6- *Propagation of Uncertainty in the Computation of THD.* Reference [19] provides an explicit expression of the measurement uncertainty of THD computed via the well-known formulae (1). The uncertainty is calculated via direct insertion of each component uncertainty into the formulae.

$$THD = \frac{1}{A_1}\sqrt{\sum_{i=2}^{N} A_i^2} \qquad (1)$$

In (1), each A_i represents the amplitude of the i^{th} voltage or current harmonic component. The number of components is represented by N and is usually assumed to be 40 [3, 5 and 10]. But in some references, higher orders up to 60 are also considered [20].

An approximation to the expression of [19] can be more simply derived via the rule of propagation of uncertainty (2) which is described in more details in [16, 18].

$$v = f(c_1, \dots c_m); \qquad u_v^2 = \sum_{j=1}^{m}\left(\frac{\partial f}{\partial c_j}\right)^2 u_{c_j}^2 \qquad (2)$$

In (2), each c_j represents a contributing factor in the combined uncertainty u_v assigned to the measured quantity v. The measured quantity is explicitly described by a function f(.) of all contributing factors. Each contributing factor c_j has its own uncertainty given as u_(c_j). The symbol ∂(.) represents partial derivatives. Applying (2) to (1), one derives the following for propagation of uncertainty in computing THD as:

$$\frac{\partial f}{\partial c_1} = \frac{\partial}{\partial A_1}\left(\frac{1}{A_1}\sqrt{\sum_{i=2}^{N} A_i^2}\right) = \frac{-1}{A_1^2}\sqrt{\sum_{i=2}^{N} A_i^2} = \frac{-THD}{A_1} \qquad (3)$$

$$\frac{\partial f}{\partial c_j} = \frac{\partial}{\partial A_j}\left(\frac{1}{A_1}\sqrt{\sum_{i=2}^{N} A_i^2}\right) = \frac{A_i}{A_1\sqrt{\sum_{i=2}^{N} A_i^2}} = \frac{A_i}{A_1^2 . THD} \qquad (4)$$

Equations (3) and (4) together with (2) determine how the uncertainty of determining one harmonic component contributes to the combined uncertainty of THD. The uncertainty in determination of each component is mostly due to voltmeter calibration uncertainty. Assuming constant uncertainty for all components as:

$$u_{c_j}^2 = u^2\, ; j = 1, ..N \qquad (5)$$

We derive from (2), (3) and (4);

$$u_{THD}^2 = u^2\left(\frac{-THD}{A_1} + \frac{1}{A_1^2 . THD}\sum_{j=1}^{m} A_i\right) \qquad (6)$$

7- *Finite Display Resolution.* The digital display of many portable harmonic analyzers is small having a limited number of digits. This causes an uncertainty in the measurements. See [16] for details.

8- *Model and observer structure.* Observer-based techniques are crucially dependent on parameter selection, used model and observer structure [5]. A comprehensive simulative comparison among many observers and Kalman filters in frequency estimation is given in [6]. However, the results of [6] cannot be readily used to compare the performances in harmonics estimation. For this aim, one may use several observers to estimate the amplitude of each harmonic component using different state observer structures. This is reserved as future research.

9- *Noise and disturbances.* The optimal choice of observer gains and structure depends on the noise and disturbance types and severity [5, 6]. Therefore, one can't simply find the best choice for observer structure or gains. Harmonic components may change due to changes of the loads [7]. This hinders the possibility of finding the optimal observer and model via off-line optimizations. However, one may evaluate the best choice for a local grid or a specific device. Some works including [39] evaluated the harmonic measurement in presence of noise. However, to quantify the uncertainty bounds requires further research.

10- *Other contributing factors.* Environmental factors, device repeatability, meter nonlinearities, etc. may also affect the measurement uncertainty. This should be accounted for by the measurement expert if it is believed to have a significant effect.

The uncertainties of aforementioned factors are usually reported in a form recommended in [18]. Aside from [18], a very good tutorial is given in [16] for the computation and expression of uncertainty in measurements. Some examples of such calculations are provided in [21]. It is required by international standards for laboratory competency [22] to identify and quantify the uncertainty sources whenever deemed significant.

4. Conclusion

In this paper, different uncertainty sources in Observer-based power harmonic estimation methods are introduced. A comprehensive laboratory/ field experimental study is recommended for quantification of uncertainties and evaluation of the overall performance for different observer-based methods (including Kalman filter and its variants) in a realistic setting.

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Declarations

Ethics approval and consent to participate

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Consent for publication

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Competing interests

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