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Analysis of the impact of interpolator's order on the accuracy of electric current spectrum estimation method in the presence of noise

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ABSTRACT

In the nonlinear analysis of electrical power supplying networks, it is often necessary to determine the frequency domain model of the network. This model is usually determined from time domain measurement data. One of the most demanding tasks is to determine the frequency spectrum of the currents flowing through the nonlinear elements with sufficient accuracy. The paper describes the results of the accuracy analysis of an electric current spectrum estimation method. The method is applied using different orders of Newton's interpolator to restore the optimal sampling parameters of a noisy signal. The presented frequency spectrum estimation method is characterized by its high accuracy in comparison with similar methods, such as WIFTA (Window Interpolated Fourier Transform) or TDQS (Time Domain Quasi-Synchronous Sampling), while still being relatively fast when contrasted with higher order Prony's methods. The conducted research shows that the accuracy of the method evidently depends on the order of the Newton's interpolator and best results, in terms of accuracy and computing power, are achieved for interpolator's order equals 7.

1. Introduction

In modern methods of modeling and simulation of electrical power supplying networks, it is often necessary to perform a steady-state analysis of the system. Good examples are the power flow analysis and harmonic flow analysis [1]. Especially the latter one might provide important information about the harmonic distortion of voltages and currents, which are becoming one of the most significant problems in power quality assessment [12]. Harmonic flow analysis might be performed using time domain or frequency domain models [1]. In many situations, frequency domain modeling is much more convenient because the models are relatively simple and allow fast and stable numerical implementation with sufficient accuracy. These models are particularly preferred in situations when dozens or even thousands of repeated simulations are performed, for example, when the model is used in an iterative optimization loop [8]. The main problem related to frequency domain modeling is to obtain the parameters of the network elements using time domain measurement data [1,7]. Usually, the measurement data are the electric current and voltage waveforms recorded at the terminals of the considered power system element. For example, for a nonlinear load described using the current injection model, it is necessary to determine the frequency spectrum of the recorded current and the phasor (magnitude and phase) of the first harmonic of

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the voltage [9]. There are many methods of current frequency spectrum estimation. Some of them use spectrum analysis [5,10,13], Kalman filters [6,10], Prony's method [17] or even neural networks [4,14] and genetic algorithms [2]. The method proposed in [9] can be characterized by its high accuracy in comparison with other competitive methods, such as WIFTA (Window Interpolated Fourier Transform) or TDQS (Time Domain Quasi-Synchronous Sampling) [16], while maintaining a relatively small demand for computing power in comparison with higher order Prony's methods [3]. The quality of the method is widely discussed in [9] (including comparative benchmarks with the competitive methods) and it is shown that it depends on two main factors: the accuracy of the signals fundamental frequency estimation and the accuracy of the interpolation performed during the resampling process. The estimation of the fundamental frequency is done using a first order Prony's estimator, whose properties are explained, among others, in [11]. To perform the signal interpolation, the method uses a fourth order Newton's interpolator. However, it is not shown in [9] how the interpolator's order affects the accuracy of the method. It is also not shown how the Newton's interpolator behaves in the presence of noise in the analyzed signal, which is a typical real-life scenario. It is known from the theory of interpolation [15], that the accuracy of the interpolation depends on both: the type and the order of the interpolator and the interpolated signal parameters, including the signal to noise ratio. In the following sections, the impact of the interpolator's order on the accuracy of the method shown in [9] is presented. Newton's interpolator with orders from 0 to 20 is analyzed using two different test signals containing white Gaussian noise.

2. Current injection model of nonlinear load

In case of a steady-state analysis of the linear power systems, each source and load connected to the network can be represented by a voltage or current source and impedance [1]. From the mathematical point of view, these values are represented by complex numbers and the linear system analysis using complex numbers is a well known and widely used method in electrical engineering. The direct extension of this method to the nonlinear systems is the current injection model of nonlinear elements [1,9]. For a single-phase power system, this model can be defined as follows:

$$i(t) = \sqrt{2}\mathrm{Re}\left\{\frac{U_1}{Z_1}e^{j\omega_1 t} + \sum_{h=2}^{N} I_h e^{jh\omega_1 t}\right\} \tag{1}$$

where:

$i(t)$ – load input current,
ω_1 – angular frequency of the first harmonic,
N – number of the highest considered harmonic,
U_1 – complex value of the first voltage harmonic on the load terminals,
Z_1 – impedance of the load for the first harmonic (evaluated from the values of the first voltage and current harmonic),
I_h – complex value of the hth current harmonic.

As it can be noticed from (1), for the first harmonic the model is described by its complex impedance just like in the linear case. For higher harmonics, the model is described by a series of current sources which comes directly from Fourier series expansion of the current flowing through the element. Usually, the most demanding task during the evaluation of the current injection model is to calculate the Fourier spectrum of the higher harmonics with sufficient accuracy [9].

3. Current spectrum estimation method

The current spectrum necessary to determine the current injection model of a nonlinear element can be calculated from time domain data using the spectrum estimation method proposed in [9]. The diagram presenting the main idea of the method is shown in Fig. 1. A discrete current signal $i[n]$ is processed by a semi-parallel algorithm (Fig. 1). First, the input current $i[n]$ is filtered by a band-pass filter to extract the base frequency of the signal. The base frequency might not exactly equal to 50 Hz due to the frequency swing present in the power system so the pass-band of the filter is set to range from 48 Hz to 52 Hz. Next, using filtered signal $i_f[n]$, the base frequency is estimated using the Prony's estimator. The estimated frequency f_1 is used during the second stage of the algorithm for the coherent resampling (new sampling frequency is an integer multiplication of f_1). Afterwards, the resampled signal is cut to the length of k signal periods with M samples for each period. Then, the resampled and cut signal is used to estimate the current frequency spectrum $I_c(f)$ with the FFT algorithm. The result of the coherent resampling is that the sampling frequency is synchronized with the base frequency of the signal and thus the FFT operation is free of its negative effects such as the transform leakage. The presented method has proved its effectiveness and accuracy. More details about the method as well as the comparison with other competitive methods can be found in [9]. As it was mentioned in the introduction, the quality of the resampling depends on two main factors: the accuracy of the signals fundamental frequency estimation and the accuracy of the interpolation performed during the resampling process, which is discussed in the following sections.