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COMPUTATION OF THE NETWORK HARMONIC IMPEDANCE WITH CHIRP-Z TRANSFORM

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Abstract

An innovative technique for power system harmonic impedance computation is presented in the paper. We present a brief introduction to harmonic impedance estimation problems as well as a detailed description of the proposed method. Frequency analysis with DFT is strongly affected by frequency leakage and picket fence errors. A number of methods was developed to reduce the impact of these phenomena including hardware solutions like PLL-based sampling synchronization, or software solutions like time- or frequency interpolation. Our work presented in the paper concerns new software-based method for reducing frequency leakage and picket fence errors and an application of this method of power system harmonic impedance estimation. The proposed method of harmonic impedance computation is based on Chirp-Z transform (CZT) instead of discrete Fourier transform (DFT). CZT enables arbitrary sampling of the frequency axis when computing spectra of discrete signals. We apply CZT to fundamental frequency estimation and for evaluating voltage and current frequency bins for higher harmonics. The spectral leakage is reduced by a standard Hanning window. The accuracy of the proposed method was verified by laboratory experiments and compared with the results of DFT-based computation. The proposed method is robust against non-synchronous sampling, thus it is dedicated for widely used data acquisition systems with a fixed sampling frequency. The proposed method is more accurate then DFT-based computations in case of voltage and current signals sampled at a fixed frequency. The advantages of the proposed method are evident for signals with off-nominal frequencies especially for higher harmonics.

Keywords: Chirp-Z transform, Fourier transform, impedance, harmonic analysis, power quality.

1. Introduction

The harmonic impedance of the power system is an important quantity describing the state of the power system. The term harmonic impedance means the equivalent spectral impedance of the power system, as seen from the measurement point towards the supply source of the system [1]. The knowledge of the harmonic impedance value allows one to evaluate the quality of the supply line *i.e.* its ability for harmonics transfer [2], the risk of failure in case of overload and the risk of resonance between the system and the loads [3]. It is also helpful in making the decision whether it is safe or not to connect a new load to the existing power line or whether to redesign and rebuild the line. Moreover, the harmonic impedance value is used for designing passive harmonic filters and for controlling the active ones [4]. Some methods of harmonic source location also utilize the harmonic impedance value [5].

2. Network Harmonic Impedance

Both measurements and computations of harmonic impedance are difficult tasks without general solutions. Recommendations for measurements and computations of harmonic impedance are given in [1]. It is important to take notice that harmonic impedance is a time-varying quantity. It varies due to reconfiguration of the power system and due to variation of loads connected on the measured side of the system. Nevertheless the assumption of time invariance of the system parameters during the measurement is typically made.

Measurement and computation of harmonic impedance is a part of power system identification. Numerous methods of power system identification were developed over about 20 years of interest in the field. Most of them utilize the Thevenin model of the power system (*e.g.* [4, 6-12]). The Thevenin model includes an equivalent voltage source in series with an equivalent impedance. It can also be generalized to include 3-phase systems.

The equivalent Thevenin circuit shown in Fig. 1 corresponds to a single frequency of interest. The superposition (under the assumption of system linearity) of many equivalent circuits, identified for the range of harmonic frequencies, gives a complete description of the power system dynamics. Thus the equivalent impedance Z_h shown in Fig. 1 is a function of frequency and is called network harmonic impedance (h is the harmonic's order).

As the equivalent voltage source value is unknown, the harmonic impedance has to be calculated from voltage and current harmonics changes ΔU_h and ΔI_h respectively [1]

$$Z_h = \Delta U_h / \Delta I_h \,, \tag{1}$$

where ΔU_h and ΔI_h stand for the differences of harmonic currents and harmonic voltages respectively, caused by the change of the power system state. They are complex quantities, obtained using DFT (discrete Fourier transform) [1]. Harmonics changes ΔU_h and ΔI_h are the results of power system state change, which is caused by a load change, at the assumption of constant source voltage and harmonic impedance values during the measurement.

Power system identification experiments can be divided into three groups depending on the excitation source:

1) *Harmonic current injection (invasive experiment)*. The state change is intentionally caused by so-called harmonic generation devices [10], which inject current harmonics into the system. The frequencies of the injected current should be close to but different from the harmonics existing in the system [7, 13], *e.g.* those caused by nonlinear loads. This kind of experiment is the most common one, because it offers the highest accuracy. On the other hand it is difficult to conduct it in MV and HV networks, because it is necessary to consume/dissipate very high energy in a very short time in order to significantly disturb a MV or HV system. For example the disturbing load designed for identification of a 132 kV network, built by the Electricity Council Centre in England, occupies a specialized truck and its rated power equals 180 kW [13].
2) *Planned switching of network equipment*. This kind of experiment utilizes planned switching or system reconfiguration as an excitation source. It includes capacitor bank switching [8] and transformer energization, power line disconnection [14] or starting a big load [15]. Such a switching operation causes transients and delivers a sufficient amount of information about the system, thus it offers high accuracy. The disadvantage is that such an experiment cannot be performed anytime and usually cannot be repeated. It should be well planned and agreed with the utilities.
3) *Observation of voltage and current changes caused by natural load variations (non-invasive experiment)*. Such an experiment theoretically may be conducted at any point of the system and at any time, because it does not disturb the system. However significant load variations at the point of measurement are required to achieve satisfactory accuracy. In most cases such an experiment requires long observation and offline data processing (load change detection, averaging, *etc.*) [12, 16]. A relatively small number of publications concerns non-invasive experiments [11, 24].

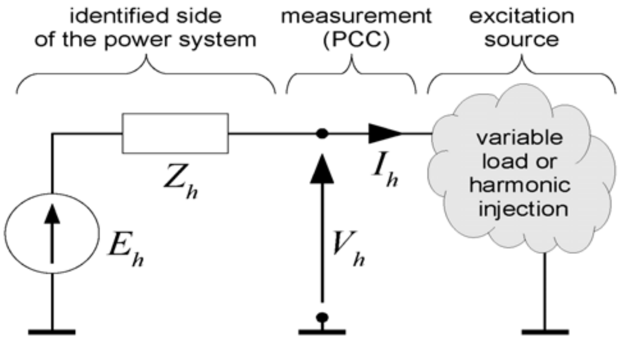

Fig. 1. Measurement of harmonic impedance.

There are some issues connected with a non-invasive experiment which complicate this apparently simple measurement problem. They are:

1) *Insufficient excitation*. This problem is common in non-invasive experiments, because current and voltage changes are often small (especially at higher frequencies) in comparison to noise (low SNR problem) [12].
2) *Synchronization problems*. The lack of sampling synchronization with varying fundamental frequency of the signals plays an important role in DFT computations. It results in spectral leakage and calculation of harmonic impedance for nonexistent components of the signals [17]. The lack of synchronization between two states of the power system leads to wrong phase angles of the voltage and current increments and increases errors of harmonic impedance estimation.
3) *Time variability of the identified power system* (*i.e.* variability of equivalent voltage source value or equivalent impedance). Time variability leads to erroneous identification results. For example, if the variation of the identified side of the system (from the measurement location) is greater than the load variation, then the measurement results will be closer to the equivalent load impedance [2]. Time variability enforces proper selection of the measurement location (*e.g.* at the secondary winding of a substation transformer [12]) as well as use of relatively short measurement periods.

The researchers took into account various aspects of harmonic impedance measurement. General recommendations for measurements and computations of harmonic impedance in various cases are given in [1]. Time domain ARMA modeling and frequency domain modeling were analyzed in [6, 18]. Continuous, real-time LV power line impedance evaluation is proposed in [10, 19]. Spectral leakage and synchronization problems are solved in many ways, because these problems are important also in other kinds of measurements. Most popular are hardware PLL- (Phase-Locked Loop) [20] and software PLL- [21] based methods which control the sampling rate of the signals. Other authors use frequency domain [22] and time domain [17] interpolation methods or both [23].

The proposed chirp-z transform- (CZT) based method for harmonic impedance computation belongs to the group of software-based methods.

In practice, evaluation of (1) is based on digital signals processed with DFT and thus the results are strongly influenced by sampling conditions. The standard [25] recommends synchronous sampling of network voltages and currents that may be realized by a DAQ (Data Acquisition) system with PLL as a synchronization circuit [20]. The lack of sampling synchronization with varying fundamental frequency of the power system is the reason of spectral leakage in spectrum computations and causes significant errors of harmonic impedance estimation using (1). The lack of sampling synchronization may also be the reason of misinterpretation of harmonic frequencies. The frequency step in DFT computations equals 5 Hz (for 50 Hz systems) [25] thus nominal (*i.e.* integer multiplies of 50 Hz) harmonics are evaluated. In case when the fundamental frequency changes by a small amount of *df* Hertz, each harmonic changes *h* times more *i.e.* for $df \cdot h$ Hertz, where *h* is the number of the harmonic. For example, a 0.25 Hz change in the fundamental frequency changes the 20-th harmonic frequency by 5 Hz, but DFT still considers 1000 Hz as the 20-th harmonic, although it actually equals 995 Hz (for 49.75 Hz fundamental frequency) or 1005 Hz (for 50.25 Hz fundamental frequency) and 1000 Hz is not even present in the signal.

Spectral leakage and insufficient frequency resolution are important sources of errors of harmonic impedance computed by DFT. Those errors are typically reduced by hardware (sampling with PLL) or software (signal resampling [12]) solutions. In the following sections, we propose a new method for network harmonic impedance computation that is robust against non-synchronous sampling. The method is based on application of CZT instead of DFT for harmonic impedance computations. In case of synchronous sampling results of harmonic impedance computation based on CZT and DFT are the same, but for non-synchronous sampling the accuracy of the CZT-based algorithm is significantly better. The algorithm consists of two stages: 1) fundamental frequency estimation, and 2) spectrum evaluation for actual harmonic frequencies that may differ from nominal values. Both stages are based on CZT and exploit its property of arbitrary sampling of the frequency axis. The spectral leakage is reduced by a standard Hanning window [25].

3. Chirp-Z Transform

The CZT algorithm was introduced in [26] with the early applications in high- resolution, narrowband frequency analysis and time interpolation of data from one sampling rate to another sampling rate. Since then, only few papers appeared concerning the application of CZT to power system signals. In [27], [28] CZT is used for the accurate estimation of the power system fundamental frequency which is next used for synchronization in PLL. In [29] CZT is used for the harmonic analysis of the supply current of an induction motor. The results reported in [27-29] confirm the superior accuracy of CZT performance over the classical DFT approach for analysis of power system signals.

In the proposed method we use CZT for fundamental frequency estimation and next for harmonic frequency computation.

The continuous spectrum of the discrete time signal $x[n]$, $n = 0, 1, ... N - 1$ is defined by Fourier Transform (FT) as

$$X(e^{j\omega}) = \sum_{n=0}^{N-1} x[n] e^{-j\omega n} . \tag{2}$$

For the special case when the frequency axis is sampled with the step $\Delta\omega = 2\pi/N$ the DFT obtained from (2) is

$$X[k] = \sum_{n=0}^{N-1} x[n] e^{-j(2\pi/N)kn} , \quad 0 \le n \le N-1, \quad 0 \le k \le N-1 . \tag{3}$$

The useful property of the CZT is that the frequency axis in (2) may be arbitrarily sampled. It means that one can choose any starting frequency ω_0, frequency step $\Delta\omega$ and the number of computed frequency bins M. For the special case when $\omega_0 = 0$, $\Delta\omega = 2\pi/N$ and $M = N$, the CZT equals DFT. The algorithm for computing CZT on the unit circle in the Z transform plane is presented in Fig. 2. The CZT parameters are defined as follows

$$\omega_k = \omega_0 + k\Delta\omega, \qquad k = 0,1,...M-1\,,$$

$$W = e^{-j\Delta\omega}\,,$$

$$h[n] = \begin{cases} W^{-n^2/2}, & -(N-1) \le n \le M-1 \\ 0 \quad , & \text{otherwise} \end{cases}. \qquad (4)$$

In practice, convolution from Fig. 2 is computed with three FFTs (Fast Fourier Transforms). If CZT parameters are fixed during filtering the spectrum of $h[n]$ is computed only once and the filtration is realized by two FFTs.

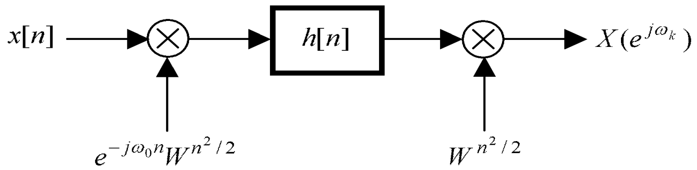

Fig. 2. Computation of CZT by convolution in the time domain.

Fig. 4a-b shows the spectra of the voltage signal acquired in laboratory experiment computed by FT, DFT and CZT. The fundamental frequency equals 49.6 Hz. The frequency step in DFT equals 5 Hz [6] and for CZT the frequency step is set to 0.005 Hz. The presented example illustrates how the lack of sampling synchronization influences the amplitude spectrum of the DFT. On the other hand, computation of the spectrum from the same samples with CZT is robust against non-synchronous sampling, in the sense that one can always compute amplitude and phase values for the frequencies of interest (49.6 Hz in the example). The spectra presented in Fig. 4c, d show that frequency bins computed by CZT are very accurate, whereas DFT bins computed with a fixed 5 Hz step, may contain significant errors, as in the case depicted in Fig. 4d for the 7-th harmonic.

4. Computation of harmonic impedance

The proposed method for harmonic impedance computation is based on load variability. The algorithm detects significant voltage and current changes in order to select fragments of signals comprising a sufficient level of information about the estimated impedance. The algorithm simultaneously estimates the fundamental frequency, in order to establish CZT parameters for higher harmonics analysis as well as to ensure a constant fundamental frequency during load changes. A block diagram of the proposed computation method is presented in Fig. 3.

Digital voltage and current signals $u[n]$ and $i[n]$ are inputs to the CZT 1. Parameters of CZT 1 are fixed, *i.e.* starting frequency f_{1s} = 47.5 Hz, frequency step Δf = 0.005 Hz and number of bins M = 1024. The outputs of CZT 1 are estimated frequencies and amplitudes of fundamental components of voltage and current signals computed as mean values for applied time window length, which has the duration of 0.2 s. In each iteration, the time window is shifted by half of its length along the signal. We used the Hanning time window [25]. Voltage and current amplitude estimates A_1 are used for automatic detection of power system state changes. Frequencies and amplitudes of voltage and current signals for higher harmonics are estimated by CZT 2. Frequency step in CZT 2 equals f_1 as estimated by CZT 1. CZT 1 and CZT 2 are computed sequentially; first CZT1 with the objective of estimation of the actual fundamental frequency and then CZT 2 for computing frequency bins for higher harmonics. CZT2 - was set to compute M = 25 frequency bins (only for harmonic frequencies) with the step Δf equal to the actual value of the fundamental frequency and starting frequency f_{2s} also equal to the actual value of the fundamental frequency, thus Δf and f_{2s} depend on the value of the fundamental frequency estimated by CZT1.

Spectra computed by CZT 1 and CZT 2 for signals recorded in a laboratory experiment are presented in Fig. 4. The fundamental frequency is estimated by CZT 1 as 49.6 Hz, next frequency bins for harmonics are computed by CZT 2 for frequencies $49.6 \cdot h$, $h = 2, 3, 4, \ldots 25$, (*e.g.*, the frequency of 7-th harmonic equals $7 \cdot 49.6 = 347.2$ Hz, and not $7 \cdot 50 = 350$ Hz as it would be assumed in DFT computations). For comparison, Fig. 4 depicts spectra computed by FT and DFT. The frequency step in DFT is fixed and equals 5 Hz [25], thus the value of the 7-th harmonic is not even checked.

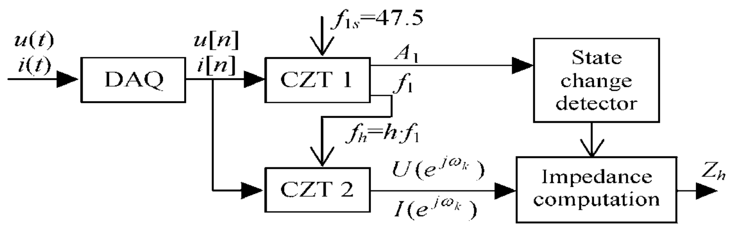

Fig. 3. Block diagram for computation of harmonic impedance.

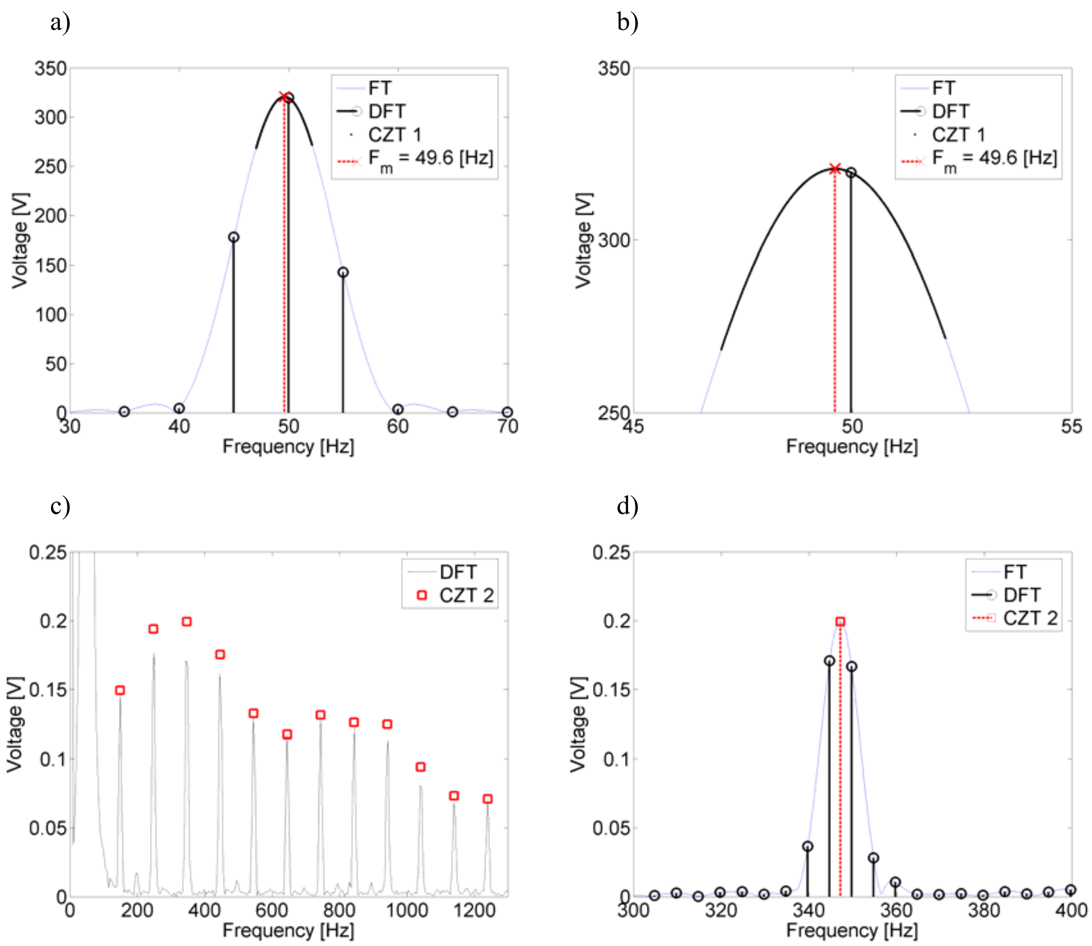

Fig. 4. Exemplary results: a) estimation of fundamental frequency by CZT 1, b) zoomed view on fundamental frequency, c) frequency bins for higher harmonics from 2 to 25 (only odd harmonics are present), d) zoomed view on 7-th harmonic.

A sliding time window may select fragments of signal with different phase before and after power system state change. Proper alignment of those phases is obtained in the frequency domain by using the time shifting property of the Fourier Transform and the phase difference φ between U_{h1} and U_{h2} is taken into account in computation of harmonic impedance as follows

$$Z_h = \frac{\Delta U_h}{\Delta I_h} = \frac{U_{h2}(e^{j\omega_h}) \cdot e^{j\varphi} - U_{h1}(e^{j\omega_h})}{I_{h1}(e^{j\omega_h}) - I_{h2}(e^{j\omega_h}) \cdot e^{j\varphi}} . \tag{5}$$

5. Laboratory experiment

A laboratory model of the power system was built in order to verify the correctness of the proposed method for harmonic impedance computation in case of non-synchronous sampling. The model, shown in Fig. 5, consisted of a programmable voltage source, the measurement system and a variable load. The programmable Agilent 6812B voltage source allowed us to adjust its internal resistance, inductance, fundamental frequency, RMS voltage and harmonics. The measurement system consisted of a PC equipped with a 16-bit DAQ card PCI-6036E from National Instruments working with a sampling rate of 12796 Hz connected to a first-order antialiasing RC filter. A laboratory current transformer of class 0.5 with a class 0.1 shunt resistor and voltage transformer of class 0.5 were used. The load part consisted of a bulb, a current-limiting reactor (choke), a fluorescent lamp and an autotransformer loaded with a resistance. The internal impedance $Z_h = R + j\omega_h L$ (R = 1 Ω and L = 1 mH) of the voltage source was estimated. Load variation was controlled manually, *i.e.* the autotransformer ratio was adjusted and the fluorescent lamp was turned on and off at random moments. The fundamental frequency of the source was also manually adjusted during the experiments.

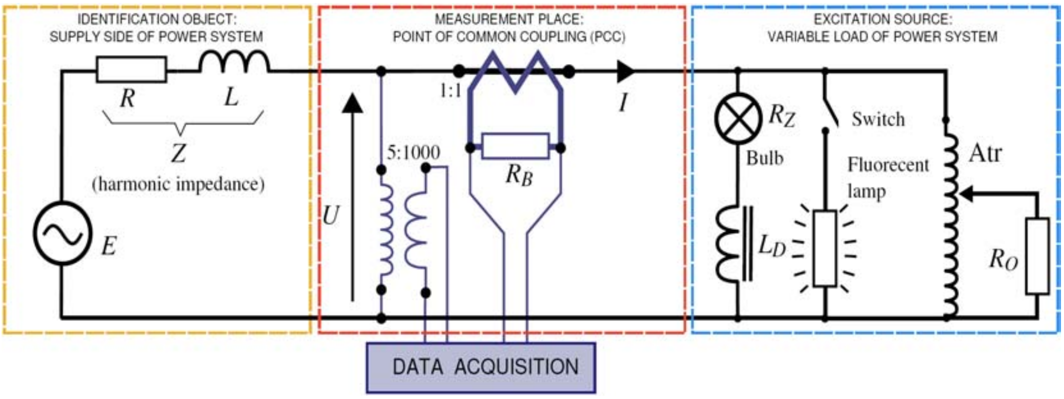

Fig. 5. Laboratory model of the power system.

6. Results

The known harmonic impedance of the laboratory power system model (Fig. 5) was estimated using voltage and current signals acquired during a 1-minute-long experiment. The measurement point was placed between the identified part of the model and the load. The analysis was performed off-line in an Matlab environment. Fig. 6 shows the results computed by CZT 1 from the block diagram in Fig. 3. Fig. 6a depicts changes of fundamental component amplitudes of voltage and current signals acquired during the experiment. Fig. 6b shows fundamental frequency values of voltage and current.

Power system state changes that are necessary for harmonic impedance estimation result from load changes. Therefore signal fragments, used in (5), describing two different power system states, should be located before and after significant load change. For detection of power system state changes, a simple algorithm based on the difference of two successive values of the voltage amplitude computed by CZT 1 was used. For clear presentation of the proposed method the fragment of the signal presented in Fig. 7 was selected. Fig. 7 shows state changes, marked by circles and described by numbers 1 to 6, used for impedance computation according to (5). The same plot shows the value of the fundamental frequency as (5) is only valid for constant fundamental frequency. For the analyzed load changes, the fundamental frequency was equal to 50 Hz (change 1-2), 50.2 Hz (change 3-4) and 50.4 (change 5-6).

Harmonic impedance estimates for CZT- and DFT- based computations as well as actual impedance values are presented in Fig. 8. Reference impedance values denoted in plots as Z_{ref} were computed from known parameters of the load. Fig. 8a, c show results obtained for CZT and DFT respectively for odd harmonics from 1 to 25, as only odd harmonics had significant presence in the signal. Fig. 8b, d and Tables 1-2 present estimation errors computed as

$$err = \frac{abs(Z_{ref}) - abs(Z_h)}{abs(Z_{ref})} 100\% . \tag{6}$$

Numbers in the legends in Fig. 8 denote power system state changes used for harmonic impedance computation depicted in Fig. 7. The constant fundamental frequency during the state change was an additional constraint for impedance estimation.

The fundamental frequency during state change denoted in Fig. 7 as 1-2 equals 50 Hz, which means that signals are synchronously sampled. In this case the fixed 5 Hz frequency step in DFT ensures correct results of impedance computation. The impedance estimation errors for CZT and DFT methods are practically the same.

For 3-4 load change the fundamental frequency equals 50.2 Hz. This is the case of non-synchronous sampling. CZT results are still correct. As seen from Tab.1 the impedance is estimated for multiplies of the actual (measured) fundamental frequency and not for multiplies of the nominal 50 Hz frequency like in the DFT case. Results obtained from DFT computations are difficult for physical interpretation because the impedance is estimated for frequencies at which the excitation (current harmonics) does not exist. For example the impedance is calculated for 150 Hz instead of the actual harmonic frequency equal to 150.6 Hz. Analog voltage and current signals do not contain components of such frequency, so the impedance for this frequency should not be calculated. The nonzero numerical results obtained with the DFT for such frequency are the effect of the convolution of the signal spectrum with the spectrum of the time window. This is also the reason why frequency lobes have a width of a few Hz, (as seen in Fig. 4) and this ensures reasonably-looking results (small impedance errors).

For 5-6 load change the fundamental frequency equals 50.4 Hz. CZT results are still correct and for DFT significant errors appear for higher harmonics. DFT errors are caused by misinterpretation of harmonic frequencies *e.g.*, DFT incorrectly interprets the 19-th harmonic as 950 Hz whereas the actual value equals 957.6 Hz. This case illustrates the advantage of using CZT instead of DFT for impedance computation. In real-world power systems the fundamental frequency deviates slightly around a nominal value, thus hardware or software synchronization is a must. The proposed software solution is an alternative for synchronous sampling; it can be as well used for off-line analysis.

a)

b)

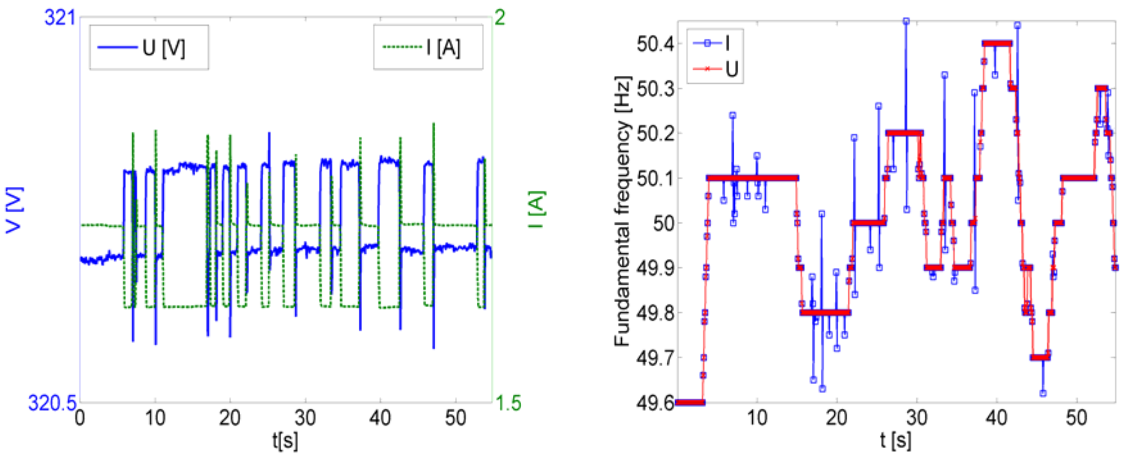

Fig. 6. Computation results for signals acquired in laboratory experiment, obtained from CZT 1 (see Fig. 3): a) voltage and current amplitudes of fundamental frequency components, b) voltage and current fundamental frequency. The fundamental frequency was manually adjusted in the power source during the experiment, thus its values show rapid changes which are not the result of variable power demand.

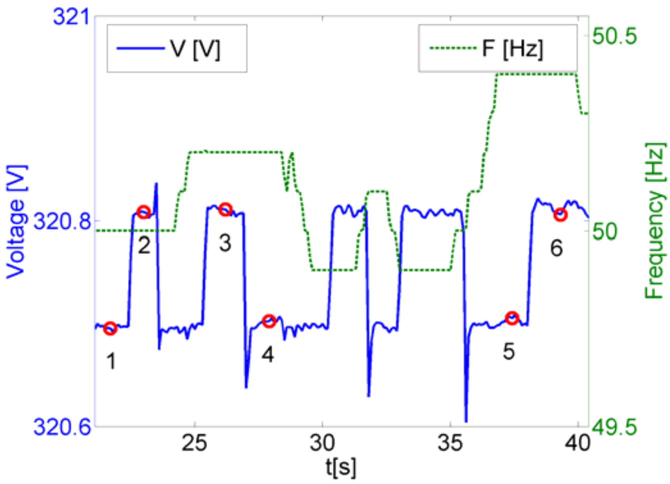

Fig. 7. Power system state changes; numbered circles stand for measurements taken for impedance computation.

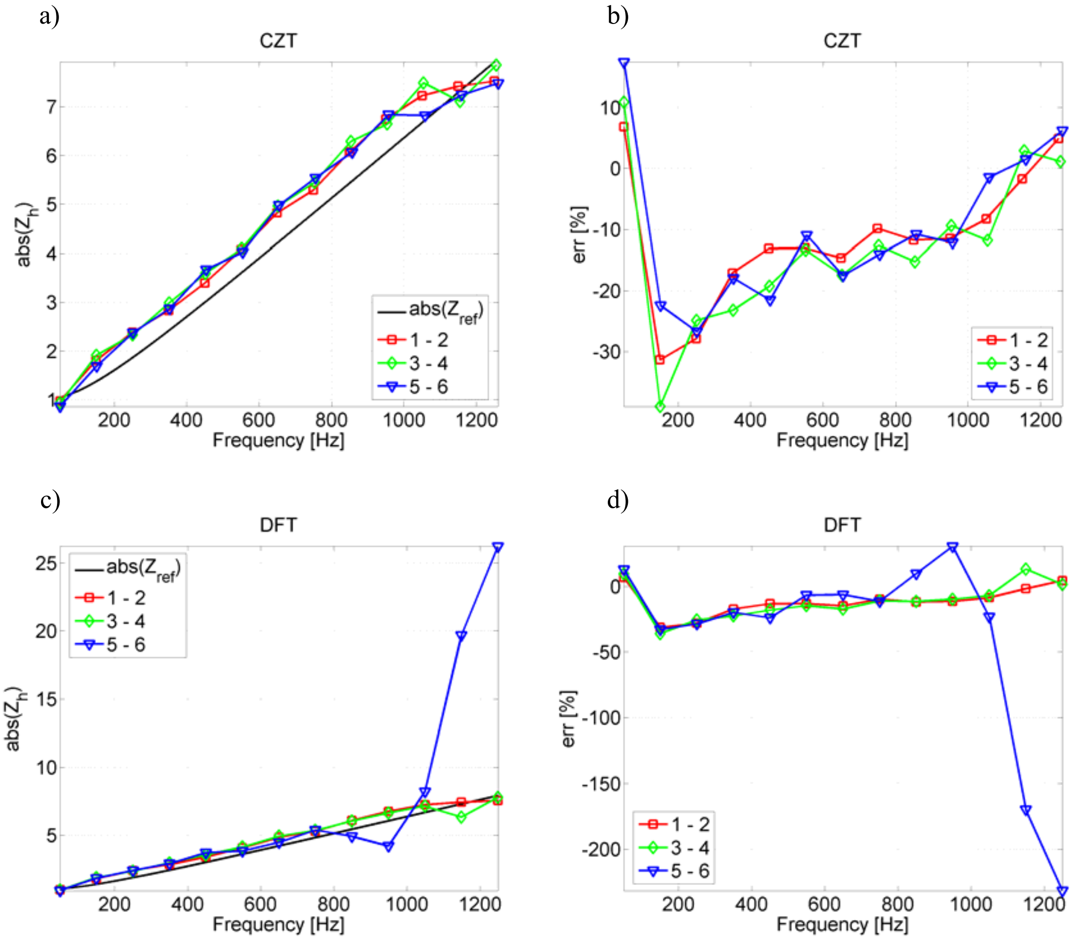

Fig. 8. Harmonic impedance estimates: a), b) proposed method and estimation errors, c), d) DFT method and estimation errors. Denotations: Z_{ref} - reference impedance values computed from parameters of the load, numbers stand for state changes depicted in Fig. 7.

7. Conclusions

The paper presents a new method for harmonic spectral impedance computation dedicated to digital signals sampled at a fixed frequency. The novelty of our approach relies on using CZT instead of DFT for computing voltage and current spectra. CZT is used for fundamental frequency estimation and then higher harmonic estimation. Higher harmonic spectra are computed at exact harmonic frequencies even in the case when the fundamental frequency slightly differs from its nominal value. This feature is not available in the standard DFT method because of its fixed frequency step.

The proposed method was tested in laboratory experiments with satisfactory results. It can be noticed from the results that the method may be especially useful for harmonic impedance measurements in case of lack of hardware sampling synchronization or for off-line analysis of signals already acquired with a fixed sampling frequency.

The obtained results show that the proposed method offers better accuracy of harmonic impedance estimation than DFT-based computations especially for higher harmonics (an example of a well-suited application may be the estimation of power network harmonic impedance for power line communications) in the case when the fundamental frequency differs from its nominal value. An additional advantage of the proposed CZT-based method is monitoring of power system fundamental frequency.

The computational cost of the proposed method can be roughly evaluated by the number of FFTs executed during computations. The standard method based on synchronous sampling needs one FFT for computing the whole spectrum of the signal, while the proposed method requires two FFTs for the first CZT with fixed parameters and three FFTs for the second CZT with the frequency step dependent on fundamental frequency that varies in the power system. Both CZT are computed for the same discrete signal, thus overall computations require 4 FFTs.

Table 1. Harmonic impedance estimation errors for CZT.

1-2		3-4		5-6	
f_h [Hz]	*err* [%]	f_h [Hz]	*err* [%]	f_h [Hz]	*err* [%]
50	6.8	50.2	10.9	50.4	17.5
150	-31.4	150.6	-39	151.2	-22.4
250	-27.9	251	-24.9	252	-26.8
350	-17.1	351.4	-23.2	352.8	-18
450	-13.1	451.8	-19.3	453.6	-21.6
550	-13	552.2	-13.4	554.4	-11
650	-14.7	652.6	-17.5	655.2	-17.6
750	-9.8	753	-12.6	756	-14.1
850	-11.7	853.4	-15.3	856.8	-10.8
950	-11.5	953.8	-9.4	957.6	-12.2
1050	-8.3	1054.2	-11.8	1058.4	-1.4
1150	-1.7	1154.6	2.9	1159.2	1.5
1250	4.9	1255	1.1	1260	6.2

Table 2. Harmonic impedance estimation errors for DFT.

1-2		3-4		5-6	
f_h [Hz]	*err* [%]	f_h [Hz]	*err* [%]	f_h [Hz]	*err* [%]
50	6.8	50	9.6	50	13.1
150	-31.2	150	-36	150	-32.8
250	-27.9	250	-25.5	250	-28.6
350	-17.1	350	-22.5	350	-19.8
450	-13.2	450	-18	450	-23.9
550	-13.1	550	-14.7	550	-6.5
650	-14.8	650	-17.2	650	-6.2
750	-9.7	750	-10.9	750	-11.4
850	-11.8	850	-11.3	850	9.9
950	-11.3	950	-9.7	950	**30.7**
1050	-8.5	1050	-6.9	1050	**-23.1**
1150	-1.7	1150	13.2	1150	**-170**
1250	4.6	1250	1.6	1250	**-232**

References

[1] A. Robert, T. Deflandre, Joint CIGRE/CIRED Working Group CC02: "A guide for assessing the network harmonic impedance". *Int. Conf. Electricity Distribution (CIRED'97),* June 2–5, 1997, Paper 2.3.

[2] O. Gonbeau, L. Berthet, J.L. Javerzac, D. Boudou: "Method to determine contribution of the customer and the power system to the harmonic disturbance". *Proc. of XVII International Conference on Electricity Distribution CIRED'2003*, Barcelona, 2003.

[3] F. Zhenyu, E. Johan: "Harmonic Impedance Analysis in the Presence of Static Var Compensator (SVC)". *Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES*, Octo., Novemb., 2006, pp. 1485 – 1492

[4] B. Palethorpe, M. Sumner, D.W.P. Thomas: "System impedance measurement for use with active filter control". *Power Electronics and Variable Speed Drives, 2000. Eighth International Conference on, IEE Conf. Publ*., no. 475, 2000.

[5] C. Li, W. Xu, T. Tayjasanant: "A 'Critical Impedance'--based method for identyfying harmonic sources". *IEEE Trans. Power Delivery*, 19(2), April 2004.

[6] A. Girgis, R. McManis: "Frequency domain techniques for modeling distribution or transmission networks using capacitor switching induced transients", *IEEE Trans. Power Delivery*, 4(3), July 1989.

[7] A. Menchetti, R. Sasdelli: "Measurement Problems in Power Quality Improvement", *European Trans. on Electric Power*, no. 4(5), 1994.

[8] M. Nagpal, W. Xu, J. Sawada: "Harmonic impedance measurement using three-phase transients". *IEEE Trans. Power Delivery*, 13(1), January 1998.

[9] W. Xu, E. Ahmed, X. Zhang, X. Liu: "Measurement of network harmonic impedances: practical implementation issues and their solutions". *IEEE Trans. on Power Delivery*, no. 17(1), January 2002.

[10] Z. Staroszczyk: "A Method for Real-Time, Wide-Band Identification of the Source Impedance in Power Systems". *IEEE Trans. Instrum. Meas*., vol. 54, no. 1, Feb. 2005, pp. 377 - 385.

[11] R. Langella, A. Testa: "A New Method for Statistical Assessment of the System Harmonic Impedance and of the Background Voltage Distortion". *9th International Conference on Probabilistic Methods Applied to Power Systems*, KTH, Stockholm, Sweden - June 11-15, 2006.

[12] D. Borkowski: *Estimation of power system spectral parameters with coherent resampling.* Ph.D. dissertation, Measurement Department, AGH University of Science and Technology, Kraków, Poland, 2007.

[13] J. Arrilaga, N. R. Watson*: Power system harmonics.* Chichester: John Wiley & Sons, Ltd, 2003.

[14] W. Wiechowski: "Validation techniques of network harmonic models based on switching of a series linear component and measuring resultant harmonic increments". *9th International Conference on Electrical Power Quality and Utilisation*, 2007, Barcelona, Spain.

[15] P. Bettini, A. De Lorenzi: "400-kV-Network Harmonic Impedance Evaluation from Harmonic Distortion Measurements at RFX Site". *European Trans. on Electric Power*, 8 (1), February 1998.

[16] A. Bień, D. Borkowski, A. Wetula: "Estimation of power system parameters based on load variance observations - laboratory studies". *9th International Conference on Electrical Power Quality and Utilisation, 2007*, Barcelona, Spain.

[17] D. Borkowski, A. Bien: "Improvement of accuracy of power system frequency analysis by coherent resampling". Accepted to appear in *IEEE Trans. Power Delivery*, vol. 24, issue 2.

[18] A. Girgis, W. H. Quaintance III, J. Qui, E.B. Makram: "A time-domain three-phase power system impedance modeling approach for harmonic filter analysis". *IEEE Trans. Power Delivery*, vol. 8, no. 2, April 1993.

[19] T. Lobos, J. Rezmer: "Wavelet transform for realtime estimation of transmission line impedance under transient conditions". *IEEE Instrumentation and Measurement Technology Conference*, Brussels, Belgium, pp. 756-760, June 1996.

[20] A. Ferrero, R. Ottoboni: "A low-cost frequency multiplier for synchronous sampling of periodic signals". *IEEE Trans. Instrum. Meas*., vol. 41, no. 2, pp 203 - 207, April 1992.

[21] H. Karimi, M. Karimi-Ghartemani, M. R. Iravani: "Estimation of frequency and its rate of change for applications in power system". *IEEE Trans. Power Delivery*, vol. 19, no. 2, April 2004, pp. 472–480.

[22] J. Borkowski: "LIDFT - The DFT Linear Interpolation Method". *IEEE Trans. Instrumentation and Measurement*, no. 49(4), 2000.

[23] M. Sedlacek, M. Titera: "Interpolations in frequency and time domains used in FFT spectrum analysis", *Measurement*, no. 23, July 1999.

[24] D. Borkowski: “Numerical aspects of power system modelling targeted at simulation study of non-invasive power system impedance measurement method”. *8th Int. Conf. on Electrical Power Quality and Utilisation, Cracow*, Poland, September 2005.

[25] *Testing and Measurement Techniques—Section 7: General Guide on Harmonics and Interharmonics Measurement and Instrumentation for Power Supply Systems and Equipment Connected Thereto*, Standard IEC 61000-4-7 Ed.2002.

[26] L. R. Rabiner, R. W. Shafer, and C. M. Rader: “The chirp-z transform algorithm”. *IEEE Trans. Audio Electroacoust.*, vol. 17, no. 2, Jun. 1969, pp. 86–92.

[27] M. Aiello, A. Cataliotti, V. Cosentino, S. Nuccio: “Synchronization Techniques for Power Quality Instruments”. *IEEE Trans. Instrum. Meas.*, vol. 56, no. 5, Oct. 2007, pp. 1511–1519.

[28] M. Aiello, A. Cataliotti, S. Nuccio: “A chirp-z transform-based synchronizer for power system measurements”. *IEEE Trans. Instrum. Meas.*, vol. 54, no. 3, Jun. 2005, pp. 1025–1032.

[29] M. Aiello, A. Cataliotti, S. Nuccio: “An induction motor speed measurement method based on current harmonic analysis with the chirp-z transform”. *IEEE Trans. Instrum. Meas.*, vol. 54, no. 5, Oct. 2005, pp. 1811-19.