WIDE FREQUENCY BAND POWER SYSTEM LINEAR AND LINEAR TIME-VARIANT MODEL IDENTIFICATION - SIGNAL PROCESSING PROBLEMS

Zbigniew Staroszczyk

Institute of the Theory of Electrical Engineering and Electrical Measurements, Warsaw University of Technology, Warsaw, Poland
Institute of Fundamentals of Electronics, Military University of Technology, Warsaw, Poland
Phone (48) 22-6607137 Fax (48) 22-6292962 e-mail: stazby@iem.pw.edu.pl

Abstract – *The paper deals with the LTI/LTV power system models and their experimental verification. The frequency dependent system impedance is used for power system harmonics studies. As a voltage/current power system transfer function it explains well harmonics related phenomena observable in real systems. With very accurate impedance measurements power system nonlinearity can be observed. The nonlinearity manifests as a system time-variance for which LTV (linear time varying) model can be used. New model improves the power system description. The problems of such the model identification and verification are discussed in the paper.*

Keywords – powers systems, power system harmonics, transfer function, time-variant, time-varying, LTI, LTV

1. INTRODUCTION

In power system harmonics investigations the linear system model is commonly assumed and used. With the recently developed accurate methods of such the model identification new phenomena became apparent. The power system non-linearity and time variations can be observed and taken into account in the more adequate (accurate) model of the system. As the power system is relatively stiff and distributed, its nonlinear components driving points are weakly affected by consumed currents but depend on sinusoidal shaped system voltage waveforms. That way the nonlinear system components make the power system LTV (linear time variant) with the double fundamental frequency, but not nonlinear in the common sense. Such the LTV model is the extension of the standard LTI (linear time invariant) system model, which better suits to real power system description. The paper discusses LTI/LTV power system model identification and interpretation problems.
The paper does not deal with problems of the linear time invariant (LTI) model identification presented in previous author's publications [1][2]. Some LTI model identification illustrative results are only given to present the reference to LTV power system modeling. The paper is focused on a linear time variant (LTV) system model for which the time-varying impedance, or the time dependent power system impulse response must be identified [3]. Such identification requires more advanced DSP and forms new interpretation problems discussed in the paper.

2. LINEAR TIME INVARIANT POWER SYSTEM MODEL

The linear time invariant (LTI) system model allows for relatively simple power system description with the use of harmonic sources and impedance/admittance frequency dependent vectors (single phase systems) or matrices (three phase systems) [1]. In reality the impedance, or the transfer function in a more general approach, is the frequency domain representation of the fixed impulse response of the system. Frequency domain description, analysis and interpretation of LTI systems is a common practice as it is much easier and meaningful then equivalent time domain analysis [4].
The knowledge of power system impedance is essential for harmonics flow analysis, informs on system sensitivity to distorted customer currents, and allows for polluter/polluted identification of continuously loaded PCC (point of common coupling) [5], [6], [7], [8], [9].
In spite of simplicity there are DSP problems in LTI power system model identification, as the observed power system signals and the system itself is nonstationary and even nonlinear [9], [10], [11]. As far as the accuracy of the real system description is satisfying, any model (the simplest is the best) can be considered good. In many practical situations, where the model is identified basing on system observations, complex modeling is useless as needs too many independent system excitations and very accurate (inaccessible) system observations.
The author's approach to system identification is to test the system with short duration current impulses as in Fig. 1. From the voltage answer to such excitations the system equivalent impedance can be found [2], [3].

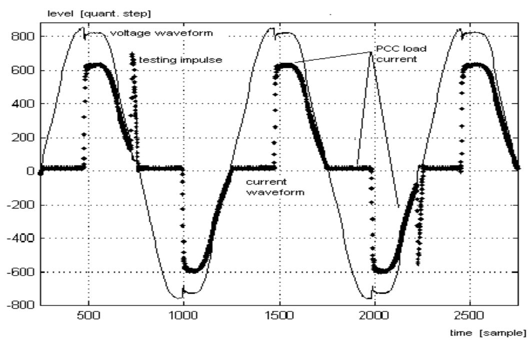

Fig. 1 Testing current and system voltage signals used for impedance identification.

The drawings presented in Fig. 2 illustrate how accurate real system impedance observations are currently accessible. The presented impedance patterns for different states of reactive power compensator helped to explain harmonics amplification observed for compensated state of the system. More experimental data can be found in [11].

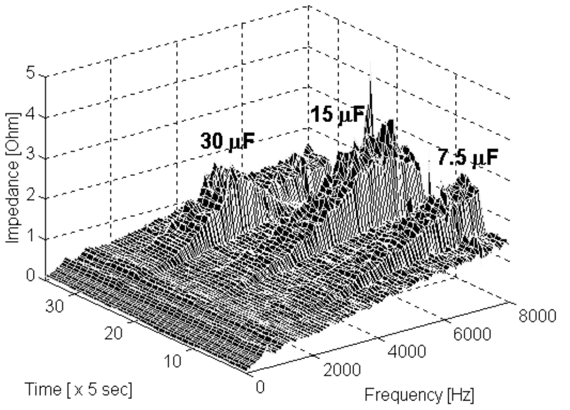

Fig. 2 Observed power system impedance during reactive power compensation process.

For the loaded system, with the known impedance and the PCC currents, the equivalent Thevenin harmonic sources of the system side can be identified. Such identification answers the question to what extend the utility is responsible for voltage distortion in the loaded PCC. As a reference to the identification the unloaded system state voltage observations can serve.

In Fig. 3 and 4 the results of of harmonic side sources identification are presented. With triangle corner stars the observed loaded PCC harmonics voltage phasors are marked. Two other stars present unloadaed PCC voltage harmonics and identification results based on loaded system observtions. It is expected that in ideal situation for each harmonics the triangle is narrow and symmetrical like in Fig. 3. Very good accuracy of identified sources is obtained if the system load consume similar currents to those which test the system. If testing current differs from the PCC distorted current, as in Fig. 1, poorer quality of sources identification is obtained (Fig. 4).

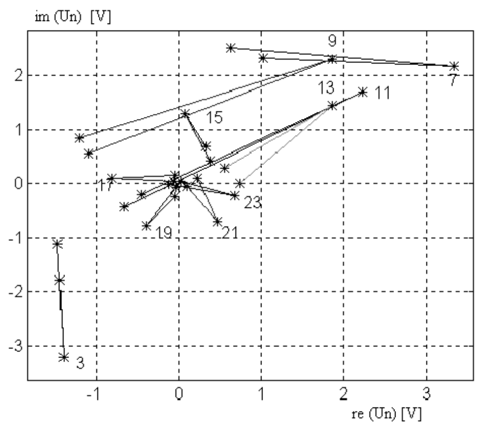

Fig. 3 Good quality of the system side harmonic voltage sources identification.

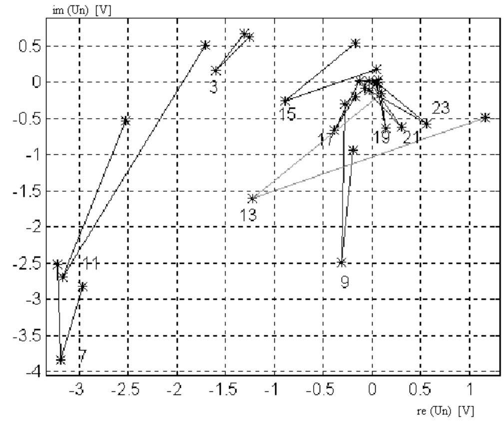

Fig. 4 Poor quality of the system side harmonicvoltage sources identification.

The discrepancy presented in Fig 3 and 4 suggests that the LTI system description does not explain all observable harmonics related phenomena.

3. NONLINEARITY IN POWER SYSTEM OBSERVATIONS

The problem of the correct model of the power system appeared when system impedance information was used for harmonics sources identification. For the erroneous identification the incorrect measured impedance data is responsible [3].

For the fixed shape of the testing pulse there is almost ideal correspondence between independent impedance measurements. Different impedance patterns appear however as the response to different current excitations (Fig 5, 6 and 7).

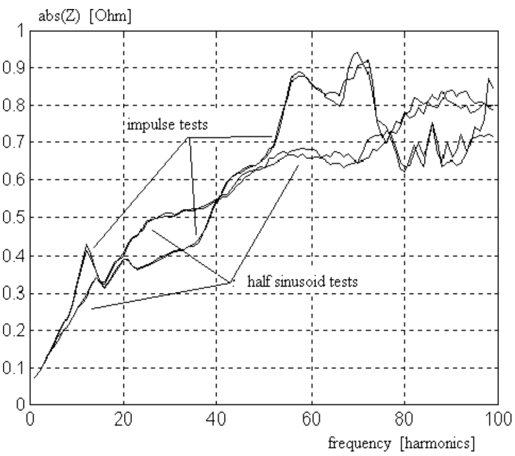

Fig. 5 Impedance contours for impulse and half-sinusoidal power system excitations – four independent measurements.

The complex domain impedance plots, with connected equal frequency points presented in Fig. 6 and 7, show more details of impedance discrepancy. For nonresonant, as well as the resonant frequencies, there is no significant difference in impedance observations for fixed testing pulse shape (see the short lines connecting two equal frequency points in Fig. 6).

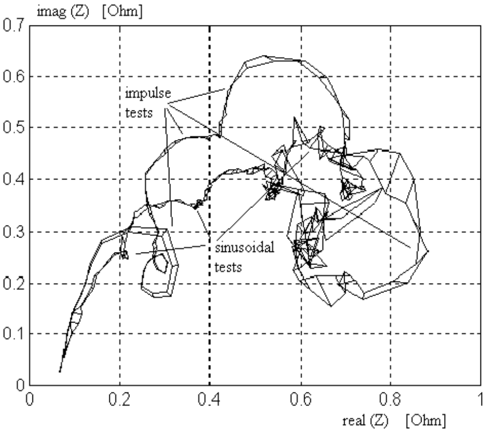

Fig. 6 Complex domain impedance presentation:small differences between two independent observations for the same system testing conditions

The impedance difference for different testing conditions is however significant (Fig. 7).

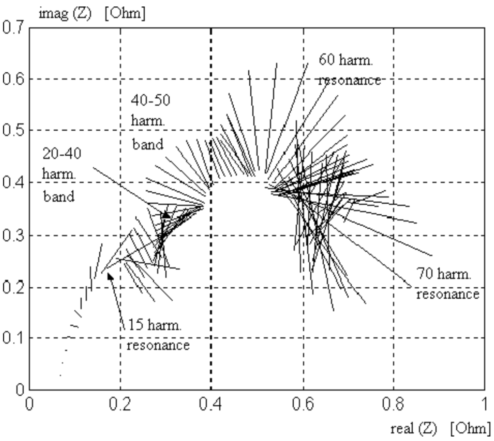

Fig. 7 Observed impedance discrepancy for different system excitations.

The impedance plots in Fig. 5-7 confirm that with high accuracy of power system impedance measurements the nonlinear effects in the power system overcome observation errors and can be taken into account in more adequate system model.

3.1 Problems with LTI/LTV model verification

It was verified that the level of the testing pulse does not influence the impedance patterns, so the time-variance of the system was assumed to be responsible for Fig. 5-7 observations.

The main problem in real power system model investigations is the lack of the known, reference state of the system which is the "living", nonstationary and complex structure. As there is no reference, any impedance pattern from Fig 6 can be treated as valuable for the LTI power system description. There are no random errors in repeated impedance observations, so the obtained impedance may be unjustly considered as very accurate. The Fig. 7 shows that there is up to 30% discrepancy between two such “good” impedance observations.

Fortunately for Thevenin’s model of the system its unloaded state can serve as the reference for sources identification. With no direct reference to impedance observations the good quality of impedance identification can be indirectly verified if good results of sources identification are obtained.

3.2 Instrumentation and methods for LTV model investigations

From the very beginning it was decided to use invasive methods of system identification [2], [3]. It was assumed that power system is LTI so the system impedance was calculated from single voltage and current observations of the power system in its natural and disturbed state. Additional pre and post-DFT signal processing took close form in the time domain and frequency domain methods [11]. Two proposed methods are in reality DFT based and deliver similar quality of impedance data.

Formally any form of system disturbance (excitation) can be used for system identification, however a short time wide band current spikes are recommended [2]. With short time current excitations the instant local impedance of the time varying system can be experimentally investigated.

For LTI systems the testing current pulse is generated near the voltage zero-crossings as in Fig. 1 and has a triangular shape. To allow for LTV model investigations, with a special resonating device, a half sinusoidal current spike with ordered phase is pumped into the system (Fig. 8). Such the way of excitation was used in analog domain simulations of the t-v system presented in the chapter 4. It replaced conception of “virtual current spikes” used in previous LTV system investigations [3].

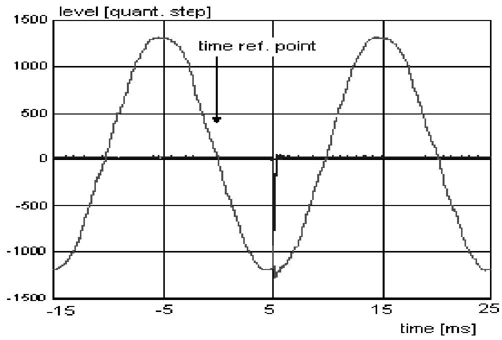

Fig. 8 Arbitrary phase current spike used for LTV model investigations

The current version of the variable phase system exciter is not fully computer controlled which makes very tedious real system time variant observations.

3.3 Current state of research in the field

In plenty of situations linear components of power system are dominating (e.g. for the case of long transmission lines) and the system nonlinearity is hidden to the observer. For such linear systems the LTI model is quite sufficient for a system description. Such the model can be accurately identified with the use of invasive methods [2], [11].

Due to close location of the author accessible PCC to the substation transformer (50m), the nonlinear effects presented in Fig. 5-7 could be observed. With a such PCC the time-varying system identification methods can be verified on the living power system.
Current research concern problems of the LTV system analysis and description. The given solutions are based on simulations of LTV power system model and are discussed in following chapters. They are partly referenced to real system observations.
In the close future the presented methods used for the simulated LTV system analysis will be followed up and verified with real power system measurements.

4. LTV MODEL DSP APPLICATION PROBLEMS AND SIMULATION RESULTS

The aim of the research was to develop the methods which allow to find the time domain voltage response of the LTV system to the given current excitations. The LTV system is described with the set of transfer functions (impedances) describing its frequency behavior for moved position impulse excitations (Fig. 8, Fig. 9).

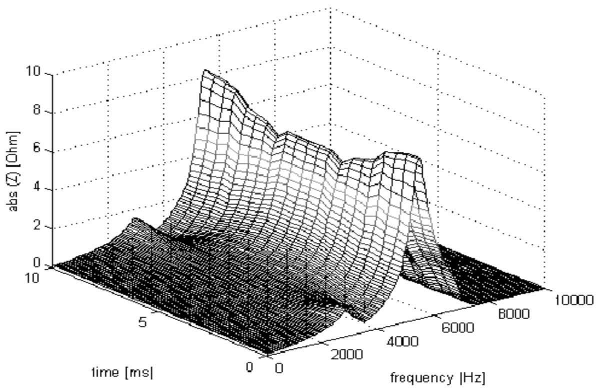

Fig. 9 Time varying impedance of the simulated system – half period observations

The t-v impedance was measured with 1 ms steps giving the set of 20 complex vectors in one period system observations. Ten of them are redundant (symmetrical), so those presented in Fig. 9 are sufficient to the full LTV system description. To find the voltage answer to arbitrary shaped current excitations the time varying digital filer must be used. Frequency domain methods, adequate for LTI systems analysis fail for LTV systems, as no fixed impedance of the system exists.
The filter can not be a linear phase, as impedance phase relations are of importance (Fig 7). To allow for time domain filtering the time dependent impulse response of the t-v filter should be found from measured t-v impedances.
To keep to short impulse response of t-v filters the impedance was windowed by damping its high frequency components. That damping was achieved with the zero-phase LP digital filtering of the voltage signal prior to impedance calculations. That way edited impedance data were symmetrically extended to negative frequencies, and with the use of IDFT the real, time varying impulse responses have been found. With that direct (noninterpolated) approach the t-v filter switches to new response each 1 milisecond.
As the sampling rate was set to 50 kHz, the filter can be tuned 50 times quicker. Such a tuning was assured with the use of linear interpolation on the complex domain impedance data. The time domain grid for the new interpolated impedance set is changed from 1ms to 20 us. With that interpolated method there is 500 different impulse responses who describe the t-v power system.
The results of t-v analysis of the simulated system are given in Fig. 10 - 12.

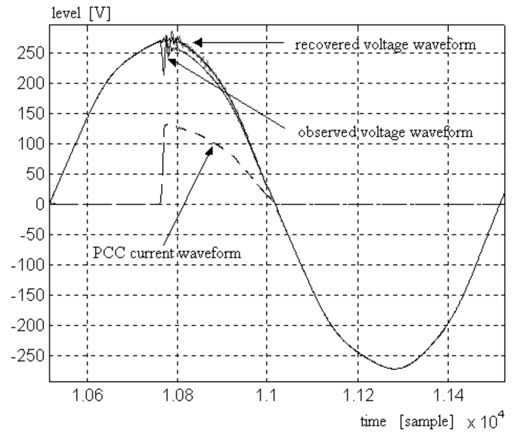

Fig. 10 Current excitation and voltage answer in simulated power system

The simulated LTV system with the t-v impedance as in Fig. 9 was loaded with the current as drawn in Fig. 10. Time domain processing (filtering) was used to reconstruct unloaded system voltage answer from the loaded state voltage and current observations. The unloaded part of period can here serve as the reference.

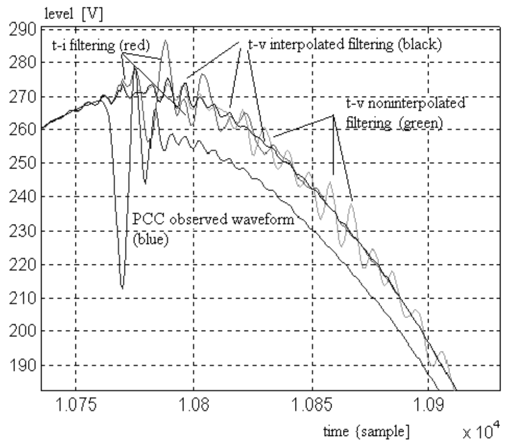

Fig. 11 Quality of the voltage signal reconstruction with different DSP methods.

The time and frequency domain details of voltage signal reconstruction are shown in self-explaining Fig. 11 and 12. There is growing accuracy of the unloaded voltage waveform reconstruction if the t-i was replaced with t-v signal processing.

The frequency domain presentation of Fig. 11 time domain data is given in Fig. 12.

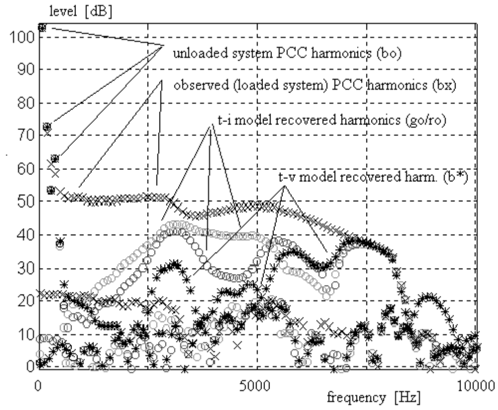

Fig.12 Frequency domain comparison of LTI and LTV power system models.

For interpolating t-v model there is almost excellent signal reconstruction in the whole freqency range with a small degradation in system resonant regions.

4.1 Real system time variant observations

In real system t-v experiments the set of two (not ten as in simulations presented in chapter 4) impedances was used for system description. With the use of noninterpolated time-variant filtering the similar quality of voltage signal reconstruction is observed as reported for the simulated system (Fig 13, 14).

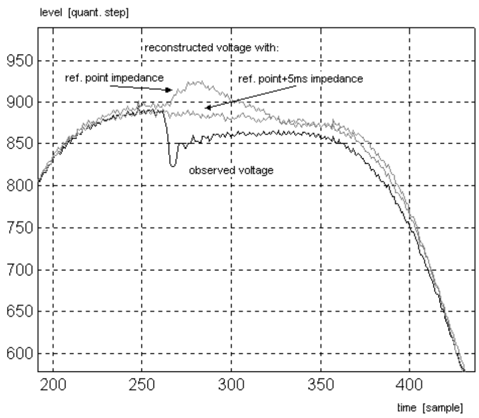

Fig. 13 The details of voltage reconstruction in a real power system

5. CONCLUSIONS

In the paper the LTV extension of the commonly used in harmonics studies LTI power system model is proposed. It was shown that for some system configurations the LTI model is inadequate for accurate system description.

For a new model more deep knowledge of the system is required. Multiple instant system transfer functions have to be determined, instead of one used for LTI systems. The signal processing should be moved to time domain, so time varying impedance must be replaced with time varying impulse responses, which describe the system.

The methods of such conversion have been proposed and verified on simulated LTV system. With a new model the essential improvement of the power system description was obtained.As much complicated, the LTV system model should be used if necessary, in situations where the accuracy assured with the classical linear model of the system is not satisfying.

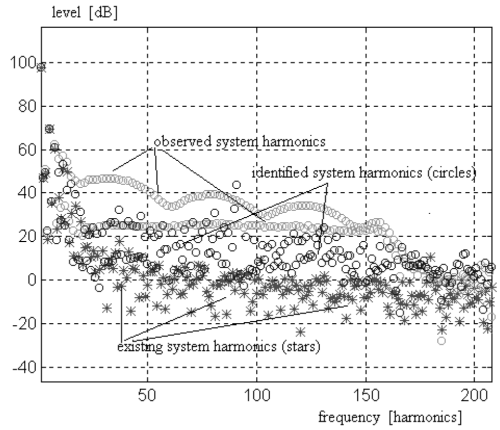

Fig. 14 Frequency domain presentation of signal reconstruction errors.

REFERENCES

[1] Czarnecki L. S., Staroszczyk Z.: "On-line measurement of equivalent parameters of distribution system and its loads for harmonic frequencies", *IEEE Trans. on Instrumentation and Measurements*, vol. 45, No. 2, April 1996.

[2] Staroszczyk Z., Mikołajuk K.: "New invasive method for localisation of harmonic distortion sources in power systems*", European Transactions on Electrical Power*, vol.8 no.5 Sept./Oct. 1998, pp. 321-328.

[3] Staroszczyk Z., Mikołajuk K.: "Time-dependent power system impedance - interpretation and measuring problems", *Proceedings of the 16th IEEE IMTC99*, vol. 2, pp. 795-800, Venice, Italy May 24-26, 1999.

[4] Krishnaswamy Srinivasan: "On separating customer and supply side harmonic contributions*", IEEE Trans. on Power Delivery*, vol. 11, No. 2, April 1996.

[5] Rhode J.P., Kelley A.W., Baran M.E.: "Complete characterization of utilization-voltage power system impedance using wideband measurement", *IEEE Transactions on Industry Applications*, vol.33, no.6, Nov.-Dec. 1997, pp.1472-9.

[6] Mattavelli P., Tenti P.: "Load- and line identification in multi-phase systems: a compensation-oriented approach", *European Transactions on Electrical Power*, vol.6, no.6, Nov.-Dec. 1996, pp.373-80.

[7] Gretsch R., Neubauer M.: "System impedances and background noise in the frequency range 2 kHz to 9 kHz public LV power systems", *European Transactions on Electrical Power*, vol.8, no.5, Sept.-Oct. 1998, pp.369-74.

[8] Swart P.H., van Wyk J.D., Case M.J.: "On techniques for localization of sources producing distortion in three-phase networks", *European Transactions on Electrical Power*, vol.6, no.6, Nov.-Dec. 1996, pp.391-6.

[9] Du Z.P., Arrillaga J., Watson N.R., Chen S.*:* „Identification of harmonic sources of power systems using state estimation*", IEE Proceedings. Generation, Transmission & Distribution*, vol.146, no.1, Jan. 1999, pp.7-12.

[10] Baghzouz Y. and all: "Time-varying harmonics. I. Characterizing measured data"*, IEEE Transactions on Power Delivery*, vol.13, no.3, July 1998, pp.938-44.

[11] Staroszczyk Z., "Problems in real-time wide band identification of power systems", *Proceedings of the IEEE Instrumentation and Measurement Technology Conference, IMTC/98*, 18-21 May, 1998, St. Paul, Minnesota, USA, pp. 779-784.