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A VIRTUAL INSTRUMENT FOR THE CHARACTERIZATION OF NONLINEAR COMPONENTS UNDER NON-SINUSOIDAL CONDITION

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Abstract: In the paper a new method for the measurement of R, L, C parameters under non-sinusoidal condition is proposed. The measurement procedure, starting from the consideration that for a non-linear SISO system the discrete transfer function H(z) functionally depends on the applied input, uses the estimated z parameters to obtain the best estimate of the equivalent circuit R, L, C parameters of first and second order systems. The method is implemented by a virtual instrument based on IEEE-1155 and IEEE-488 measurement systems. The realized instrument is vatidated with reference to many experimental results obtained in both on-line and off-line tests.

Keywords: RLC measurement, non-sinusoidal condition, parameter identification, non-linear systems

1 INTRODUUCTION

More and more power electronic devices, such as either electrical rotating machine drives or static power supplies and converters (AC\DC DC\DC and DC\AC) are today adopted in several fields. Being based on non linear and/or switching circuits they do not allow that sinusoidal conditions be established inside and outside them. As a consequence, both passive components like resistance, inductors and capacitors and active components like IGBT and FET, which are included in or deal with them, work with wide-band voltage and current signals. This means that i.e. parasitic capacitance or inductance in electronic circuits [1], rotor winding impedance of PWM driven induction motors [2]-[4], ceramic varistors [5], other filtering devices such as LISN [6] or power cables [7] should be characterized in non-sinusoidal conditions.

In a rough circuit analysis the most of these components is considered linear, and mainly the real part is analyzed versus frequency. Typically either RGL meters are used to measure imaginary and real part of impedance at several frequency values of the sinusoidal stimulus, or network-impedance analyzers to provide the transfer function of the dipole under measure. In many other cases the R, C and L values at the frequency of 1 kHz together with a tolerance range which holds into account non-sinusoidal conditions it is all the designer can get to drive simulation and realization of devices.

This is enough when the resulting status and output parameters match the design specifications also if characterized by high uncertainty. But in aerospace, telecommunication, biomedical or all those applications where parameters like signal distortion, input and output impedance and output voltage amplitude must be constrained in known and narrow ranges, also the dependence of passive and active components on the signal waveform has to be analyzed.

Unfortunately, if the R, L, C parameters are measured by one of the aforementioned measurement methods for each frequency tone of the input signal, even supposing insignificant the non-linearity, they cannot be analytically composed to obtain a unique value that reproduces the component behavior in the corresponding non sinusoidal conditions.

The authors, starting from previous experiences in parametric identification and impedance measurements [8]-[11], suggest to this aim the adoption of parameter identification techniques to build up a new R, L and C measurement method. They start from the consideration that a Single Input Single Output (SISO) Linear Time Invariant (LTI) system may be characterized by its discrete transfer function H(z), and from H(z), once a system model has been chosen, it is possible to obtain the corresponding R, L and C parameters. Moreover, if the SISO system is non-linear the obtained discrete transfer function is considered as functionally dependent by the applied input H(z)=f(input), thus giving the best estimate of the equivalent R, L, C parameters for that determined operating condition.

On the basis of this considerations a virtual instrument for the characterization of passive electrical components in non-sinusoidal Kondition has been set up. The instrument uses both IEEE1155 and IEFE488 hardware and it is characterized by a user-friendly visual C user-interface. In the paper, after a detailed description of the measurement method, the hardware architecture and the adopted software solutions are then presented. Finally results of numerous experimental tests carried out in both on-line and off-line conditions on different components are reported.

2 THE MEASUREMENT PROCEDURE

Supposing that the component under test (CUT) be plugged in a determined circuit, the proposed measurement procedure is made of the following steps (Figure 1):

(i) theoretical analysis of the circuit;
(ii) acquisition of the CUT input and output signals x(t), y(t);
(iii) identification of the discrete transfer function (H(z);
(iv) determination of R, L and C parameters [12], [13] from H(z).

(i) The component under test and the circuit wherein it is plugged must be analyzed in order to choose both the component equivalent circuit and the input and output Signals. As an example, a capacitor equivalent circuit can be either series or parallel while the current can be chosen as input and the voltage as output or viceversa. The choices are made on the basis of the characteristics of the component (high or low losses) and the circuit operating conditions (signal frequency spectrum and amplitude, floating or grounded measurement points) respectively.

(ii) At first, both sensing (current or voltage probe, differential or single ended input) and acquisition (input range, sampling frequency f_s, acquisition time interval **D**T) parameters must be defined. Then, if the component characterization has not to (or cannot) be made on-line, the input signal must be reproduced by an adequate stimulus generator suitably conditioned to be directly connected to the component under test. Finally the input and output signals can be acquired, memorized and made available to the next step.

(iii) Parametric models are widespread mainly in real-time application tanks to the low number of parameters and calculations they require, respect to other analytical models. On the other hand they give problems for high order systems when a correspondence must be found between model parameters and system physical components. This implies that for low order systems they represent the best compromise between opposite requirements as modeling accuracy and calculation speed. A lot of parametric models have been already presented in literature. The authors propose to use an output error model they experienced in several applications for the parametric identification of SISO linear time invariant systems [8], [10], [15]. In this model:

$$Y(Z) = H(z)X(z)\,Z^{-nk} + E(Z) \tag{1}$$

being: X(z), Y(z) and E(z) the z transforms of x(k), y(k) and e(k) respectively; H(Z) the system transfer function and nk the delay between y(k) and x(k).

Furthermore posing
$$H(z)=\frac{N(z)}{D(z)}=\frac{q_{nf}\,z^{-nk}+...+q_{nf}\,z^{-nk-nb}}{1-q_0 z^{-1}-...-q_{nf-1}z^{-nf}} \tag{2}$$

where nb and nf are the degrees of respectively N(z) and D(z), the system model is completely defined by $\{q_i\}$.

The $\{q_i\}$ estimation is carried out by a least square mean identification algorithm (LSM) [12]-[14].

By the inverse transform of (1) and using (2), the following states:

$$y(k)+q_0 y(k-1)+...+q_{nf-1}y(k-nf)=q_{nf}\,x(k-nk)+...+q_{nf+nb}x(k-nk-nb)+e(k) \tag{3}$$

The LSM algorithm searches for the $\{\hat{q}_i$ which minimizes the square mean of e(k) calculated on the whole set of samples (N_{points}).

Once the best $\{\hat{q}_i$ has been found, the output signal estimate y(k) is obtained for each k.

If this other error function
$$err=\left|\frac{1}{N_{Points}}\sum_{k=1}^{N_{Points}}(y(k)-y(k))\right| \tag{4}$$

comes to be greater than a suitable threshold the parameter estimate is not considered accurate.

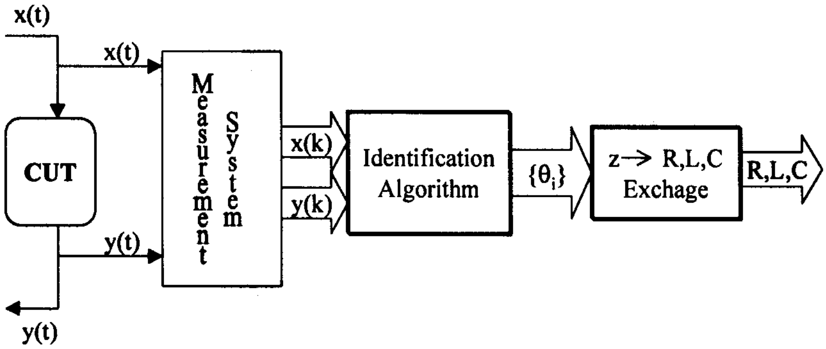

Figure 1. Block diagram of the measurement procedure.

As a consequence a further optimization algorithm is run to refine the parameter estimate by changing each $\hat{q}_i$ in a limited constraint around the value given by LSM, until a new minimum of err is reached. The use of a different error function gives to the optimization algorithm the possibility of finding a different parameter best estimate respect to that of the LSM algorithm. If no improvements are registered it means that a model error occurred and choices made in previous steps should be revised. Finally, if the identified system is linear and the bandwidth of the input signal used for the parameter estimate fully overlaps the system bandwidth, the so estimated H(z) constitutes a system model of general validity. On the contrary, in case of either significant non linearity of the system, or insufficient spectral content of the input signal, the H(z) keeps validity constrained only to the input signal adopted for the parameter estimate.

(iv) For first and second order SISC systems, simple direct relationships can be drawn between $\{q_i\}$ in z domain and the R, L, C parameters of the component equivalent circuit in the time domain. As for an example, considering the parallel equivalent circuit of a capacitor (figure 2) and choosing the current as input and the voltage as output, the H(z) is the following:

$$H(z) = \frac{q_1 z^{-1}}{1 - q_0 z^{-1}};$$

As a consequence for the parallel circuit we have:

$$R_x = \frac{q_1}{1 - q_0}; \; C_x = \frac{T_e(1 - q_0)}{q_1 \ln(q_0)}.$$

The above described procedure can be usefully executed for all the applications where a characterization of low order electrical systems in fixed non sinusoidal conditions is required, whatever the amplitude, the 0 factor and the time constant of the system are.

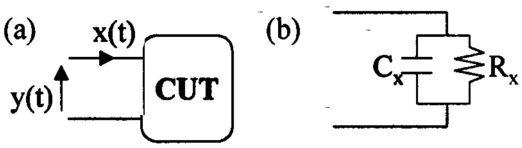

Figure 2. (a) Input and output signal, (b) equivalent circuit of a real capacitor.

3 THE VIRTUAL INSTRUMENT

In order to build up an automatic measurement system able to carry out the procedure for the characterization of components in non-sinusoidal conditions, suitable hardware architecture and software structure must be designed and set up. Some steps of the proposed measurement procedure are conditioned by logic tests on measurements and/or user provided data which drive: i) the definition of the measurement circuit connections, ii) the choice of conditioning and/or sensing devices, iii) changes of measurement parameters, iv) further measurements and/or calculations. Its complexity imposes the use of a measurement system characterized by reconfiguration capabilities typical of virtual instruments, that are sets of measurement, Generation and elaboration devices integrated by suitable software in a unique (in this sense virtual) application dependent instrument.

3.1 Hardware

In figure 3 a block diagram of the measurement system is reported. A powerful Personal Computer, hosting suitable interface boards, controls a measurement system based on IEEE 488 and VXI instruments, while a complete set of current and voltage probes allows all the possible current-voltage, and single-ended differential combinations to be obtained.

Well calibrated input channels, very large size memory, and high maximum sampling frequency are indispensable features for obtaining the best parametric system model identification. These features cannot be found all together in most of PC data acquisition boards, thus VXI and IFFE-488 instruments where chosen, even if they are more expensive and require heavier control software.

In particular, the signal acquisition section is made by:

a) an IEFE-488 controlled Digital Oscilloscope (Tektronix TDS 54OD, 500 MHz bandwidth, 4 input single-ended channels, maximum 1 GS/s sampling frequency for each channel, total record length 8 Msamples, from 8 up to 15 bit resolution in high resolution mode);

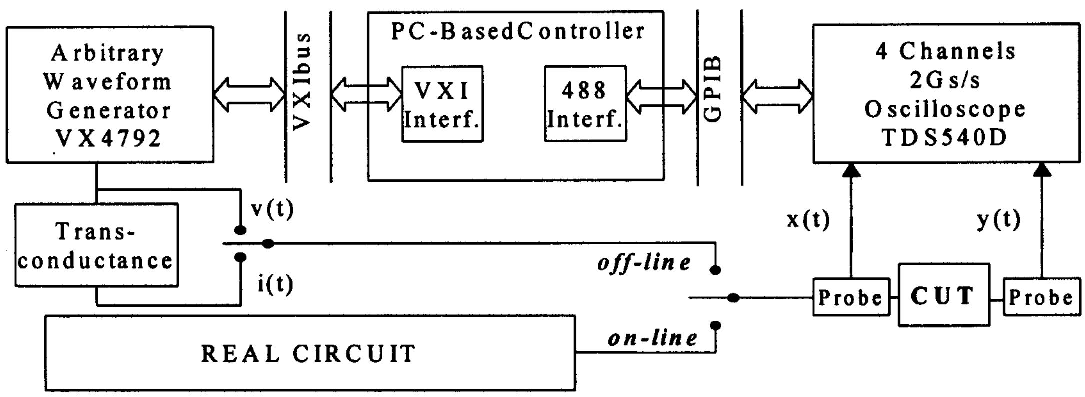

Figure 3. Block diagram of the measurement station.

b) an active current probe (Tektronix A6312 + AM5O3S amplifier, 0-100 MHz bandwidth, up to 20 A in d.c., and 50 A in a.c.);

c) a passive voltage probe pair (Tektronix P6135, 500 MHz bandwidth) for both differential and single- ended voltage measurements.

Then, in order to allow the off-line characterization of components to be carried out, the measurement station is completed by a stimulus section based on a VXI message-based arbitrary waveform Generator (Tektronix VX4792, 200 MHz maximum Generation frequency, 12 bit resolution, 256K waveform points) and on a voltage-to-current amplifier, which allows arbitrary waveform voltages or currents to be generated.

3.2 Software

The instrument software (figure 4) has been written in C++ and organized in: i) user interface ii) acquisition object, iii) identification object, iv) Generation object.

i) The user interface provides the virtual instrument front panels. It is organized in set-up, result and Generation panels-, the last one is made active only if the user press the off-line measurement button in the acquisition page. Before accessing the instrument set-up panel the user is required to make suitable connections among the oscilloscope, the probes (voltage and current) and the measurement circuit, assigning channel 1 (or the couple 1 and 2 for differential measurements) to the voltage probe output, and channel 3 to the current probe amplifier output. Then, the user must also choose and set the proper current amplifier gain. Finally, the user accesses the set -up panel providing the following information: the set current amplifier gain, whether the voltage signal is differential or not, the equivalent circuits chosen in a list shown by the panel itself. The Generation panel, instead, allows the choice of the stimulus signal either among some canonic waveforms (PWM, triangle, square) or among all the files "*.wav" which are found in a suitable PC hard-disk directory. Finally the measured R,L, C values are reported in the output fields of the result panel where, if the continuous mode button of the set-up panel has been pressed by the user, a diagram is periodically updated showing the parameter values versus time.

ii) The acquisition object receives the user inputs from the aforementioned interface and provides the $\{X_k\}$ and $\{Y_k\}$ arrays to the identification object. It controls the oscilloscope via IEEE-488 interface. Depending on the necessity of differential voltage measurements, it activates two or three input channels and makes the oscilloscope perform: a) the acquisition of 100000 waveform points for each channel at 500 Msamples/s, and b) the FFT of the input signal (the equivalent circuit determines whether the current or the voltage signal must be considered the input). On the basis of the maximum frequency tone (F_{max}) resolved in the input signal, the acquired sets of samples are suitably decimated to obtain an equivalent sampling frequency of $10 \cdot F_{max}$ before sending them to the identification object. Only in case of very low frequency components the acquisition has to be repeated with a lower sampling frequency in order to obtain waveform point sets $\{X_k\}$ and $\{y_k\}$ which are large enough (2000 points) for the identification object.

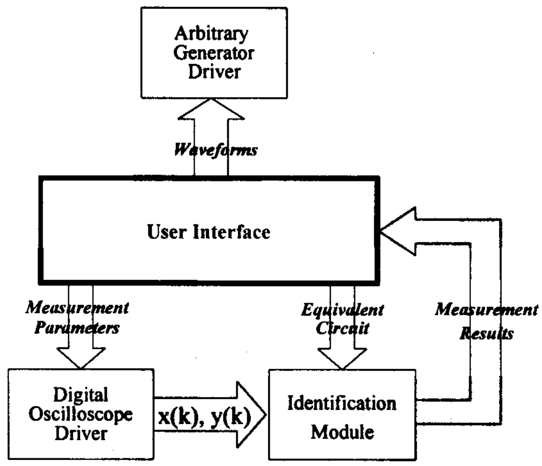

Figure 4. Block diagram of the realized software.

iii) The identification object receives $\{X_k\}$ and $\{Y_k\}$, calculates the R, C, L parameters and send them to the user interface. The input - output signals $\{X_k\}$ and $\{Y_k\}$ are processed by the LSM algorithm as described in paragraph 2 and if the R, L, C parameter estimate shows to be not accurate the equivalent circuit is changed and the identification repeated.

iv) The signal Generation object constitutes the VXI arbitrary waveform generator software driver. It receives the user inputs from the Generation panel, loads the waveform generator memory, and activates the signal output. Only a manual switching of the generator output in the voltage-to-current amplifier is required to the user if a current instead of a voltage is requested.

4 EXPERIMENTAL RESULTS

Once a new measurement method has been defined it must be compared with the methods that are usually adopted. The proposed technique has been compared for the on-line measurements with a HP Impedance/Gain Phase Analyzer 4194A™, while for the off-line measurements with a numerical impedance meter (GenRad DigiBridge™). The Comparison has been made on inductive or capacitive components as follows: i) the R, L, C parameters measured by each instrument are used to determine the transfer function of the component under test; ii) each transfer function obtained is used to simulate the output signal corresponding to the measured input; iii) the obtained signals are compared with the measured output signal. As an example in Figure 5 the three output currents (the two simulated and the measured one) concerning a 470 µH iron core inductance are reported. The inductance is a component of a DC power supply, which in this test is working with a 100 kHz, 50% duty cycle switching signal. The corresponding RL series parameters on-line measured by the virtual instrument and off-line measured by the HP 4194A™ at a frequency of 100 kHz, are reported in Table 1. As it can be noted in Figure 5, the output signal obtained by the virtual instrument parameters (continuous line) is the best estimate of the actual signal (dashed line). Moreover, the differences between the measured values reported in table 1, are always greater than uncertainty. The same conclusions were drawn also at different switching frequencies; in Figure 6 the RL parameters of the same inductive component measured by the both instruments are reported versus switching frequency (taking into account the measurement uncertainty band). These results demonstrate that the virtual instrument allows the best estimate of the component behavior in no sinusoidal conditions. Furthermore, the changes registered in both the inductive and the resistive parameter by the virtual instrument outline that the dependence of the parameter values on the signal waveform rnust be considered significant.

Table 1. The measured R and L parameters

	HP 4149	Virtual Instr.
Lx	(423±3) µF	(506±3) µF
Rx	(15.10±0.02) Ω	(20.21±0.08) Ω

Finally, in Table 2 are reported results of some capacitance measurements. They deal with off-line tests made to analyze the sensitivity of different dielectric Materials to the stimulus waveform. In particular, the RC parallel circuit parameters of three capacitors, characterized by the same nominal value (2.2 µF) but by different dielectric Materials (plastic, ceramic and electrolytic), were measured by the virtual instrument in three different stimulus conditions (square wave, triangle and sine), and by DigiBridge™ (in sinusoidal conditions), at the same frequency of 10 kHz. Analyzing the results the following considerations can be made: i) all the measured differences are meaningful (greater than uncertainty); ii) the three dielectric materials are sensitive to the stimulus waveform with a maximum in the electrolytic capacitor; iii) as expected, measurements made by the two instruments in the same sinusoidal conditions are fully compatible.

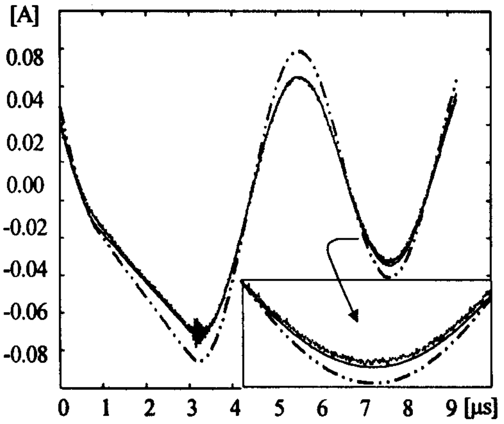

Figure 5. Measured output (┈┈┈), HP output (—··—), virtual instrument (——).

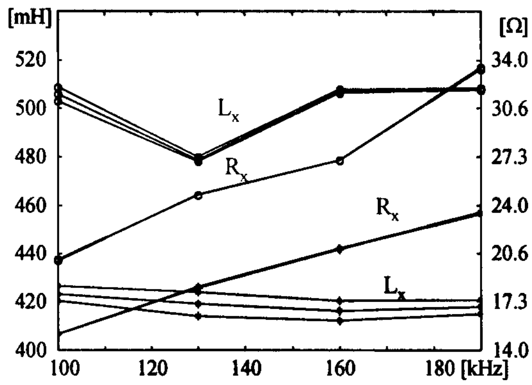

Figure 6. R and L parameters measured by the virtual instrument (o), the HP (*) versus switching frequency.

Table 2. Results of off-line measurements carried out by the virtual instrument and by the DigiBridge™ on the 2.2 µF capacitors.

		Virtual instrument values		Digibridge™ values	
Dielectric	Waveform	C [µF]	R [Ω]	C [µF]	R [Ω]
Plastic		2.172±0.002	113±4	2.0423±0.0002	3279±2
		2.0927±0.0003	216±15		
		2.0560±0.0003	2813±70		
Ceramic "		2.242±0.002	111±4	2.1191±0.0002	1412±2
		2.1817±0.0003	159±27		
		2.1579±0.0003	1495±16		
Electrolytic		1.729±0.002	22.70±0.05	1.6194±0.0002	33.73±0.02
		1.6572±0.0004	26.824±0.002		
		1.609±0.001	29.1±0.2		

5 CONCLUSIONS

A novel virtual instrument for the R, L, C parameter evaluation in non-sinusoidal conditions has been presented. It allows either an on- line characterization of the component in its real working conditions, or a traditional off-line measurement by reproducing any non-sinusoidal condition with a suitable stimulus Generator In numerous experimental tests, carried out in different non sinusoidal conditions, the R, G, L parameter estimate made by the proposed instrument showed to be more accurate than measurements provided by traditional methods, and allowed to notice meaningful parameter changes in inductive and capacitive components. This first implementation of the proposed technique is constrained to system with model order not higher than two. Future developments will concern the extension to both higher order and the MIMO systems.

REFERENCES

[1] Jia-Tzer Hsu and Khai D.T. Ngo, Behavioral Modeling of the IGBT Using the Hammerstein Configuration, *IEEE Transactions on power Electronics* 11 (6) (1996) 746-753.

[2] F. Marino, V. Mungiguerra. F. Russo, F. Vasca, Parameter and State Estimation for Induction Motors via Interlaced Least Squares Algorithm and Kalman Filter, *Proceedings of Power Electronics Specialists Conference, 1996. PESC '96 Record., 27th Annual IEEE* pp 1235-1241 vol.2 23-27 June 1996.

[3] H. Rasmussen, M. Knudsen, M. Tonnes, Parameter Estimation of Inverter and Motor Model at Standstill Using Measured Currents only *Proceedings of the IEEE International Symposium on Industrial Electronics, 1996. ISIE'96* pp 331 - 336 vol.1 17-20 June 1996 Vol. 1

[4] R.J.A. Gorter, A. Veltman, P.P.J. Van der Bosch, Skin effect impact on induction motor parameters estimation using an output-error identification method *Proceedings. of Power Electronics Specialists Conference, PESC '94 Record.,25th Annual IEEE,* pp 763 - 768 vol.1 20-25 June 1994

[5] Masafumi Suzuki, *Analysis of Ceramic Varistor, Proceedings of the 3rd International Proc. of 3rd Conference on Properties and applications of Dielectric materials.* 1991, Tokyo- Japan, 655-658.

[6] Fu-Yuan Shih, Dan Y. Chen, *A Procedure for Designing EMI Filters for AC Line Applications, IEEE Transactions on power Electronics* ***2*** **(1)** (1996).

[7] Vladimir Szekely, Identification of RC Networks by Deconvolution: Chances and Limits, *IEEE Transactions on Circuits and Systems - 1: Fundamental Theory and applications.* **45** (3) (1998).

[8] Bernieri, G. Betta, A. Pietrosanto, Optimum Sampling Frequency Choice for Accurate Identification of Electrical Systems, in *Proceedings IX IEEE Instrumentation/Measurement Technology Conference - IMTC192,* (New York May 1992), New York, USA, 1992, p. 10-1 3.

[9] L. Angrisani, A. Baccigalupi, A. Pietrosanto, A DSP Based Apparatus for Impedance Measurement, IEEE *Trans. On Instrumentation and Measurement* **45** (6) (1996) 930-934.

[10] Baccigalupi, A. Bernieri, A. Pietrosanto, A Digital-Signal-Based Measurement System for on-line Fault Detection, *IEEE Trans. On Instrumentation and Measurement* **46** (3) (1997) 731-736.

[11] L. Angrisani, A. Baccigalupi, A. Pietrosanto, A VXI Instrument for Real-time Tracking of lmpedances, *Measurement* **20** (4), pagg.277-285, 22 Oct. 1997.

[12] L. Ljung, *System Identification: Theory for the User.* Englewood Cliffs, NJ: Prentice-hall, New York, 1987

[13] L. Ljung, *Modeling and identification for simulation.* Englewood Cliffs, NJ: Prentice-hall.

[14] R. Pintelon, J. Schoukens, Frequency-Domain Identification of Linear Time-Invariant System Under Nonstandard Conditions. *IEEE Trans. On Instrumentation and Measurement* ***46*** **(1)** (1997) 930-934.

[15] Bemieri, G. Betta, M. D'Apuzzo, Measurement Problems Arising from the Use of a Recursive Algorithm for Model Identification of Electrical Systems, *IEEE Trans. On Instrumentation and Measurement* **41** (2) (1992) 240-245.

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