REAL-TIME MEASUREMENT OF TIME VARIANT R, L AND C COMPONENTS IN NON SINUSOIDAL CONDITION

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Abstract: The authors are involved in realizing an innovative measurement instrument for the real-time estimation of Resistance (R), Inductance (L) and Capacitance (C) parameters that models real electrical passive components in non sinusoidal environment. This instrument aims to cover the lack of reference instruments and measurement methods for the assessment of electrical passive components in non sinusoidal conditions. In previous papers the authors proposed a measured method implemented in a FPGA platform. In this paper a further step is proposed optimizing the dynamic behavior of the instrument with respect to fast time-variant passive components. The novelty manly consists on the improved signal processing procedure that implements a "forgetting factor" to promptly respond to changes on monitored devices. A full characterization aiming in find a forgetting factor value able to find the best compromise between accuracy and response time together with tests executed on real signals were also reported.

Key words: *RLC measurement, Equivalent Circuits, System identification, Non-sinusoidal characterization*

1. INTRODUCTION

Design and analysis of electric and electronic devices are realized by means of model described by circuit equations and the corresponding equivalent circuits. In some cases, international standards precisely define system equivalent circuits in which passive Resistance (R), Inductance (L) and Capacitance (C) components are time-invariant parameters. In order to evaluate the values of these parameters, impedance measurement or standard tests made in sinusoidal conditions are commonly used [1], [2].

Nowadays the widely part of electric and electronic devices works with not-sinusoidal signals, and since the most of these components shows non-linear behavior, a parameter estimation based on sinusoidal stimulus may result quite approximate. As a consequence, for some critical applications, both in the design and dimensioning phase of an electric or electronic circuit and in the analysis and characterization phase, it might be very important to know the real behavior of the component under test that can be described by the equivalent circuit in the actual non sinusoidal conditions. Examples of similar critical application can be found, in the design of device like electronic boards for the motor control [3]-[5], active and hybrid filters [6] or power cables for polluted environment, to cite a few.

In order to reaches these goals, the authors have already proposed an innovative measurement method for the estimation of the R, L and C components of devices working in non-sinusoidal conditions, based on parameters estimation techniques [8]-[9]. The method was implemented in a preliminary prototypal FPGA platform that aims in realizing a new real-time instrument for the measurement of the R, L and C components [10].

At this stage the realized instrument shows an intrinsic accuracy lower than 0,1% together with response and settling times respectively lower than 17 ms and 50 ms.

In some cases, passive R, L, and C components exhibit changes characterized by high dynamic and consequently the considered R, L and C parameters have to be real-time upgraded. Examples can be found in sensors, active or hybrid filters, circuits for power factor correction, circuits for the active control of automotive dampers, and so on.

Target of this paper is improving the promptness of the measurement method to make it able to successfully operate with time-variant components or in time-variant applications.

To this aim the measurement procedure, proposed in [10], is modified in order to give different weight to last acquired signal samples respect to the older ones introducing a "forgetting factor". The choice of the optimal value for this parameter is not a trivial task. It is well know that high values of the forgetting factor typically introduce good stabilities in the estimation process but cause latencies and delays in the estimation assessment. On the other hand little values of the forgetting factor reduce response times but causes overshoots and instability of the estimation algorithm. Moreover the optimal values depend on the passive component to be characterized, the model adopted, the parameter variations of the component under test, and the considered stimulus signals [12]. This new feature together with the implementation in cost-effective hardware and firmware platform gives to the realizing instrument the possibility to be directly inserted in the electronic circuits cited above.

In the following, after a theoretical background about the measurement method, the characterization phase in simulation environment is presented. Finally, tests carried out in emulation environment on time-variant R, L and C components are described.

2. THE PROPOSED MEASUREMENT METHOD

The main idea is that a non-linear component can be represented by a linear model that describes its actual behavior only under the considered stimulus and environmental conditions; if these conditions change, a new estimation procedure is required and the model parameters have to be updated. The proposed measurement method gives value to R, L and C parameters of a system equivalent circuit using a linear system model parameter estimation technique [8], [9]. Said y(k) the system output and x(k) the system input at the k instant, we can write:

$$y(k) = h(k) * x(k) + v(k), \quad (1)$$

where h(k) is the impulse response of the system and v(k) is the additive noise of the system output.

Moving from the time discrete domain to the Z-domain, we have: $Y(z) = H(z) \cdot X(z) + V(z)$. The system transfer function, H(z), can be write as:

$$H(z) = \frac{\theta_{nf}\, z^{-nk} + \ldots + \theta_{nf+nb}\, z^{-nk-nb}}{1+\theta_0\, z^{-1} + \ldots + \theta_{nf-1}\, z^{-nf}} \quad (2)$$

The system models in both time and z domains are completely defined by knowledge of the parameter set {θ}.

$$\theta = [-\theta_0, -\theta_1, \ldots, -\theta_{nf-1}, \theta_{nf}, \theta_{nf+1}, \ldots, \theta_{nf+nb}] \quad (3)$$

Finally, the R, L, C parameters of the system equivalent circuit, are calculated from {**θ**} by means of analytical relations [8], [9].

It is possible to estimate the predicted output at the k^{th} time interval as:

$$\hat{y}_{pre}(k) = H(k) * \hat{\theta} \quad (4)$$

$$\text{where: } H(k) = \begin{bmatrix} -y(k-1), -y(k-2), \ldots, -y(k-na), \ldots \\ \ldots u(k-1), \ldots, u(k-nb) \end{bmatrix}^T \quad (5)$$

and $\hat{\theta}$ is the vector of the estimated θ values.

The error function between the estimated and predicted output at the k^{th} interval can be written as

$$e(k) = y(k) - \hat{y}_{pre}(k) \quad (6)$$

It is possible to demonstrate that the mean square error solution to the problem of minimizing (5) can be represented as

$$\hat{\theta}_N(k) = \left(\mathrm{H}^{\mathrm{T}}(k)\mathrm{H}(k)\right)^{-1} \mathrm{H}^{\mathrm{T}}(k)\mathrm{y}(k) = \mathrm{P}(k)\mathrm{H}^{\mathrm{T}}(k)\mathrm{y}(k) \quad (7)$$

$$\text{where } P(k) = \left(\mathrm{H}^{\mathrm{T}}(k)\mathrm{H}(k)\right)^{-1} \quad (8)$$

The estimation of the parameter set $\{\hat{\theta}\}$ is carried out by means of traditional Output Error (OE) parameter estimation technique [8], [11], modified by means of a "forgetting factor", that gives different weight to last acquired signal samples respect to the older ones.

The traditional output error technique estimates {θ} as

$$\hat{\theta}(k) = \hat{\theta}(k-1) + \mathrm{L}(k)\left[\mathrm{y}(k) - \varphi^{\mathrm{T}}(k)\hat{\theta}(k-1)\right] \quad (9)$$

where:

$\{\hat{\theta}\}$ are the estimated $\{\theta\}$ set parameters;

$$\varphi(k) = -y(k-1), \ldots, -y(k-na), \ldots x(k-1), \ldots, x(k-nb) \quad (10)$$

L(k) is the gain matrix defined as:

$$\mathrm{L}(k) = \mathrm{P}(k-1)\varphi(k)\left[\mathrm{I} + \varphi(k)^T \mathrm{P}(k-1)\varphi(k)\right]^{-1} \quad (11)$$

$$\mathrm{P}(k) = \mathrm{P}(k-1) - \frac{\mathrm{P}(k-1)\varphi(k)\varphi^T(k)\mathrm{P}(k-1)}{\mathrm{I} + \varphi^T(k)\mathrm{P}(k-1)\varphi(k)} \quad (12)$$

Introducing the forgetting factor (λ) the equations (11) and (12) became:

$$\mathrm{L}(k) = \mathrm{P}(k-1)\varphi(k)\left[\lambda\, \mathrm{I} + \varphi(k)^T \mathrm{P}(k-1)\varphi(k)\right]^{-1} \quad (13)$$

$$\mathrm{P}(k) = \frac{1}{\lambda}\mathrm{P}(k-1) - \frac{(1/\lambda)\, \mathrm{P}(k-1)\varphi(k)\varphi^T(k)\mathrm{P}(k-1)}{\lambda\, \mathrm{I} + \varphi^T(k)\mathrm{P}(k-1)\varphi(k)} \quad (14)$$

It is possible to highlight as the forgetting factor λ operates in two ways. From one side, it reduces the weight of the older samples respect to newer ones in the L(k) estimation, and from the other side it avoids that the gain factor P(k) goes to zero during the updating.

3. Assessment of the Optimal Forgetting Factor

A characterization phase in simulation environment has been carried out to assess the optimal value of the forgetting factor, able to improve the performance of the measurement method both in terms of estimation accuracy and time response. To this aim a number of numerical tests have been executed in Matlab 7™ environment.

At this stage first order circuit models have been considered. In particular, capacitor with resistance and inductor with resistance, connected on parallel or serial configuration, have been simulated.

Once defined the type of component to be analyzed and its R, L, and C parameters, a voltage or current stimulus signal has been generated and, by the way of a simulation tool, the component response has been calculated. The time variability of the selected component has been caused imposing a casual step variation within the 50-150 % of the initial value of the components.

As far as the stimulus signal is concerned, tests have been arranged considering randomly generated multi-sine signals with a number of tones in the 1 to 50 range, frequency contents in the 50 Hz to 100 kHz range and a 0 to 2π random phase. As for the R, L and C components resistance values in the 1 Ω to 1 MΩ range, inductance values in the 1 μH to 1 mH range and capacitance values ranging from 100 pF to 100 μF have been considered. Multi-sine can be considered as very useful design signals since they are able to represent the most typical harmonic spectrums present in the electric and electronic applications.

In the whole simulation process an observation time of 4 s has been used and a sampling frequency of 1 MHz has been considered. Each test has been arranged choosing a stimulus signal and an initial value of the parameters, then, after an observation time of 2 s, the step variation has been imposed and two further seconds of analysis have been processed.

For each combination of signal stimulus, circuit model, and

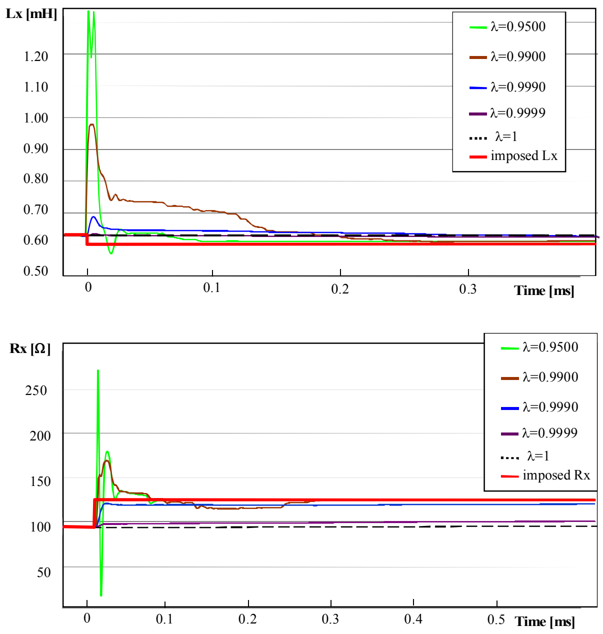

Fig. 1. Evolution of measured RL component for different forgetting factor (λ) when at 0 instant a variation equal to -0.016 mH and 310 Ω occurs.

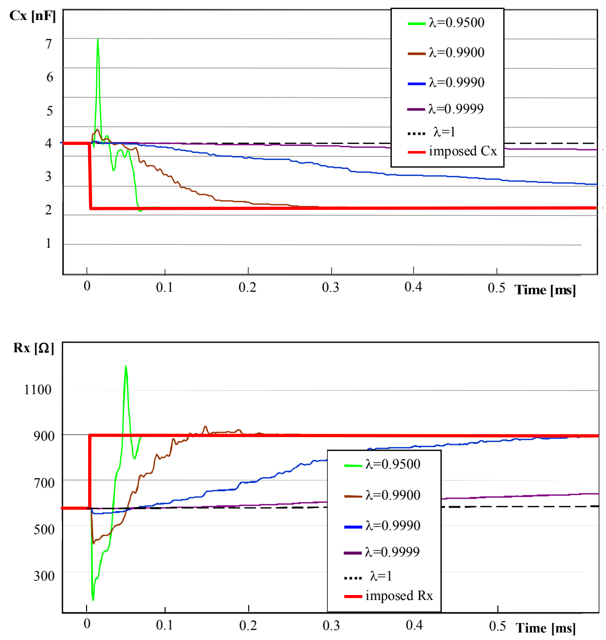

Fig. 2. Evolution of measured RC component for different forgetting factors (λ) when at 0 instant a variation equal to -1.98 nF and 272 Ω occurs.

step variations, 8 different values of forgetting factor ranging from 0,9500 to 0,9999 have been considered. This range of values is that typically adopted in such applications and recommended in literature [11]. Fig. 1 and Fig. 2 show the evolution of the measured RL and RC components, respectively, for different values of the forgetting factor (λ) applying instantaneous variation to RL and RC values.

Table I. Results, in terms of estimation Error, of the forgetting factor characterization for inductor and capacitor.

Component under test : a serial R and L model of an inductor				
Figure of merit	E_L		E_R	
λ	μ [%]	σ [%]	μ [%]	σ [%]
0,9500	0,001	0,0010	-0,0003	0,0002
0,9600	0,0008	0,0007	-0,0001	0,0002
0,9700	0,0008	0,0005	0,0000	0,0013
0,9800	0,0008	0,0005	0,0002	0,0013
0,9900	0,0005	0,0006	0,00020	0,00093
0,9950	0,002	0,002	0,00008	0,00057
0,9990	0,001	0,001	0,00004	0,00024
0,9999	0,0007	0,0005	0,000002	0,000079
Component under test : a parallel R and C model of a capacitor				
Figure of merit	E_C		E_R	
λ	μ [%]	σ [%]	μ [%]	σ [%]
0,9500	-0,42	0,26	0,0001	0,0002
0,9600	-0,45	0,26	0,0001	0,0001
0,9700	-0,45	0,26	0,0000	0,0001
0,9800	-0,40	0,23	-0,0001	0,0001
0,9900	-0,14	0,09	-0,00002	0,00006
0,9950	-0,010	0,006	-0,00006	0,00005
0,9990	-0,010	0,005	-0,00005	0,00002
0,9999	-0,01	0,01	-0,000008	0,000008

For each test, the following figures of merit, able in describing static and dynamic response of the measurement system, were evaluated.

a) The estimation error (E) evaluated by percentage difference between measurement results provided by the algorithm at the steady state and the imposed one. As steady state response the averaged output of the proposed measurement algorithm on the last 50 ms of the observation period has been considered.

b) Absolute percentage overshoot, O, defined as: $O\,[\%] = 100 * \left|\frac{\Delta - d}{d}\right|$. Where Δ is evaluated as the difference between the maximum and minimum values reached by the considered parameters during the transient; and *d* is equal to the imposed step variation.

c) The response time (T_{res}) defined as the time the system reaches a value of 90% of its steady state response.

d) The settling time (T_{sett}) meant as the time the system reaches a threshold of ±5% of its steady state response.

Table I, II and III summarize results of the characterization stage for inductor described by means of LR serial equivalent circuit and for capacitor modeled by RC parallel circuit. For each figure of merit, both mean (μ) and standard deviation (σ) values measured on 1000 test cases are reported.

In particular, Table I reports the results concerning to the static response of the measurement algorithm. Tables II and III

Table II. Results of the forgetting factor characterization (dynamic figure of merits) for a serial R and L model of an inductor.

Component under test:			Inductor			
Considered parameter: L						
Figure of merit	O		T_{res}		T_{sett}	
λ	μ [%]	σ [%]	μ [ms]	σ [ms]	μ [ms]	σ [ms]
0,9500	1694	465	0,0531	0,0054	163	55
0,9600	2123	719	0,0575	0,0061	143	52
0,9700	1482	372	0,0694	0,0075	143	52
0,9800	1299	323	0,105	0,011	143	52
0,9900	1738	733	0,173	0,020	82	40
0,9950	703	287	0,333	0,038	21	20
0,9990	222	66	1,76	0,16	2,86	0,24
0,9999	157	48	17,4	1,6	28,1	2,4
Considered parameter: R						
Figure of merit	O		T_{res}		T_{sett}	
λ	μ [%]	σ [%]	μ [ms]	σ [ms]	μ [ms]	σ [ms]
0,9500	1670	531	0,0381	0,0049	20	20
0,9600	1797	589	0,0402	0,0045	20	20
0,9700	1336	417	0,0482	0,0050	20	20
0,9800	1034	351	0,0633	0,0063	20	20
0,9900	733	322	0,112	0,010	0,263	0,016
0,9950	252	85	0,242	0,017	0,520	0,031
0,9990	59	21	1,307	0,078	2,61	0,15
0,9999	20	10	14,35	0,76	28,5	1,5

Table III. Results of the forgetting factor characterization (dynamic figure of merits) for a Parallel R and C model of a capacitor.

Component under test:			Capacitor			
Considered parameter: C						
Figure of merit	O		T_{res}		T_{sett}	
λ	μ [%]	σ [%]	μ [ms]	σ [ms]	μ [ms]	σ [ms]
0,9500	8104	3631	184	58	367	78
0,9600	11163	6679	184	58	306	72
0,9700	4100	1711	184	58	306	72
0,9800	3127	1203	184	58	286	70
0,9900	1107	290	184	58	245	66
0,9950	438	78	164	55	184	58
0,9990	153	28	165	55	187	58
0,9999	97	23	102	39	192	54
Considered parameter: R						
Figure of merit	O		T_{res}		T_{sett}	
λ	μ [%]	σ [%]	μ [ms]	σ [ms]	μ [ms]	σ [ms]
0,9500	2586	711	0,0463	0,0041	41	28
0,9600	1563	451	0,0533	0,0045	41	28
0,9700	1548	387	0,0632	0,0052	41	28
0,9800	874	212	0,0806	0,0064	20	20
0,9900	592	182	0,137	0,010	0,261	0,016
0,9950	237	69	0,236	0,019	0,502	0,030
0,9990	63	22	1,235	0,075	2,42	0,16
0,9999	29	16	12,41	0,73	24,1	1,6

summarize the dynamic behavior in the inductor and capacitor measurement, respectively. Looking at tables I to III the following consideration can be made:

i) The parameter estimation of the primary C component of the capacitor generally shows worsen performance respect the L inductance of the considered inductor model.

ii) The parasitic components of both inductor and capacitor show similar results. In particular, the overshoot figure of merit shows very similar behavior.

iii) As for the primary parameters the response time and the settling time of the capacitor component are greater than the inductor ones. Looking at the numbers the inductor component is typically estimated after a time lower than 2 ms, while the capacitor takes about 200 ms. This is strictly related to the physical behavior of a capacitor that acts as a signal integrator.

iv) As expected in theory, for each one of the considered components the lower the forgetting factor the higher the overshoot and the settling time and the lower the response time (see also Fig. 1).

v) λ values ranging from 0,9990 to 0,9999 provide acceptable steady state accuracy results in terms of both mean value and its experimental standard deviation.

vi) Results for the inductor component (Table II) shows that values for λ ranging from 0,9950 to 0,9990 give out to a good compromise between the three considered figures of merit in terms of both mean values and experimental standard deviation.

vii) Results for the capacitor component (see Table III and Fig. 2) shows that values for λ ranging from 0,9990 to 0,9999 give out to an acceptable compromise between the three considered figures of merit in terms of both mean values and experimental standard deviation.

Taking into account the simulation results the optimal value of λ equal to 0,9990 has been selected for both components type.

4. TESTS ON REAL SIGNALS

The above proposed measurement method has been suitably implemented on a previous realized FPGA-based hardware and tested on a number of real signals [10]. A measurement station has been set-up. It comprises an arbitrary dual channel waveform generator, a dual channel wide memory digital scope and the FPGA-based meter. A personal computer allows developing the test signals and downloading on the waveform generator.

Many tests have been executed on time-variant R, L, and C components modeled as RL and RC series and parallel circuits. For the sake of brevity two experimental tests are reported in the following. Tests have been selected as representing the worst case in the following of time variant components. In particular the two cases represent situations in which the primary and parasitic parameter change with different periods and cases in which they change with different shapes.

In order to describe the response of the proposed system, Epp evaluated as a point by point percentage difference between measurement results provided by the FPGA instrument and the imposed one, has been considered.

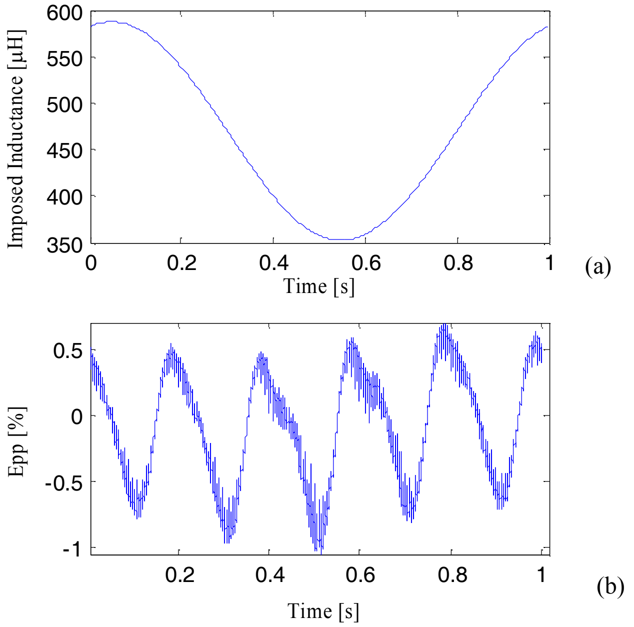

Fig. 3. Tests on real signal: imposed variation of the inductance parameter (a) and behavior of the Epp [%] figure of merit.

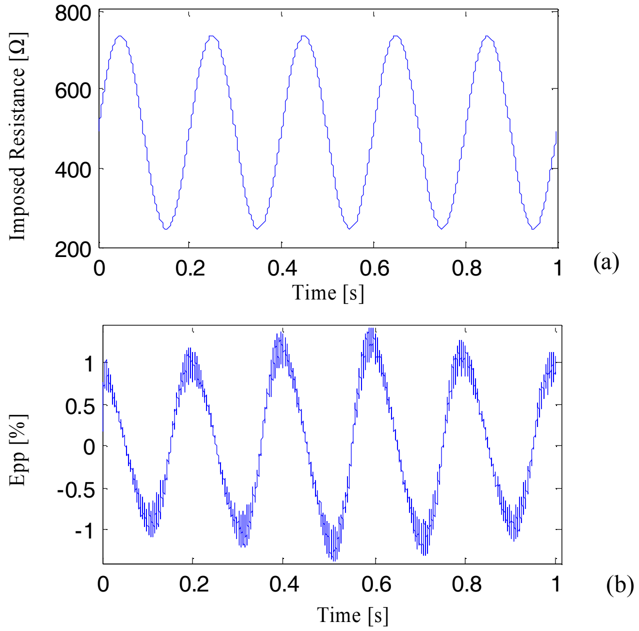

Fig. 4. Tests on the realized instrument: imposed variation of the resistance parameter (a) and behavior of the Epp [%] figure of merit.

The first experiment concerns with an inductor represented by a series RL equivalent circuit. The inductance and resistance values are changed according with sinusoidal shapes. In particular the L parameter follows a sinusoid with a period of 1 s, a mean value of 470 µH, an oscillation amplitude of 58,75 µH; the R parameter changes according to a sinusoid with a period of 0.2 s, a mean value of 491 Ω, an amplitude of 122,75 Ω. An observation period of 1 s is involved. Fig. 3(a) and Fig. 4(a) sketch the imposed values of the resistance and inductance over time respectively, while Fig. 3(b) and Fig. 4(b)show the estimation error . It has to be underline that the two measurements are strictly correlated; consequently, an error on the resistance value estimation determines an error in the inductance measurement and vice-versa. This is evident in Fig. 3(b), where the error on the inductance measurement is plotted versus the time; as you can see the error trend is similar to the evolution resistance variation since it is due to the incorrect estimation of the resistance value.

In the second test the inductance value changes with the time as a sinusoid with a period of 0,5 s with a mean value of 232 µH, an oscillation amplitude of 25 µH. The resistance follows a triangular shape with a period of 1 s, a minimum value of 481 Ω and a maximum value of 721 Ω. An observation time window 1 s is reported. Fig. 5(a) and Fig. 6(a) sketch the imposed values of the inductance and resistance over time. Fig. 5(b) and Fig. 6(b) propose the obtained values of the estimation error. Also in this case the R, and L parameter estimations are strictly related. It is possible to highlight as the imposed variation on the R parameter at the time equal to 0.5 s causes a change in the sign of the Epp of R parameter. On the other end the change in the L parameter causes an underestimation of the R value and a transition of the Epp related to the L parameter.

Analyzing the results of the two presented experiments, it is possible to highlight as the estimation error obtained in dynamic conditions is generally greater than those experienced in steady state cases. This can be due both to dynamic response of the measurement instrument and the intrinsic variability and accuracy of the reference generator adopted. However obtained results are very satisfying for all the considered tests. In addition, the considered value of λ allows the realized instrument following changes in R, L, and C parameters to be estimated with appreciable response time and accuracy. In particular, it is possible to see as a change in the considered R, L and C parameter produces an overshoot in the estimation error that reaches the steady state response in very short time.

5. CONCLUSION

The paper represents a further step in realizing a new measurement instrument for the assessment of R, L, and C components under non sinusoidal conditions. The ability of the instruments to follow time-variant components has been pursued by introducing a forgetting factor in the estimation algorithm. To optimize the time response of the measurement method preserving the metrological performance and the reliability of the measurement a fine tuning of the optimal value of the forgetting factor has been carried out.

The presented tests demonstrate that the chosen forgetting factor value assures very good results both in terms of metrological accuracies and response time for both inductive and capacitive behaviors.. The obtained response and settling time make the measurement method and the proposing measurement instrument suited to be inserted in electrical control and measurement circuit as active or hybrid filter, control of actuator, sensor and circuit diagnostic.

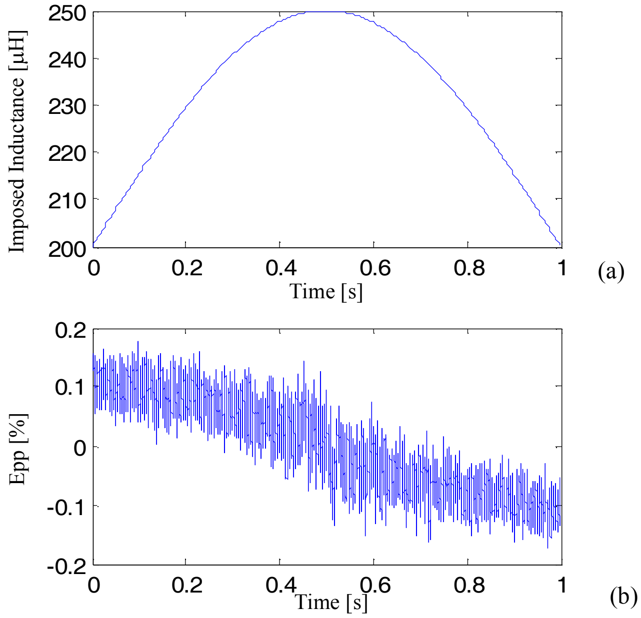

Fig. 5. Tests on real signal: imposed variation of the inductance parameter (a) and behavior of the Epp figure of merit.

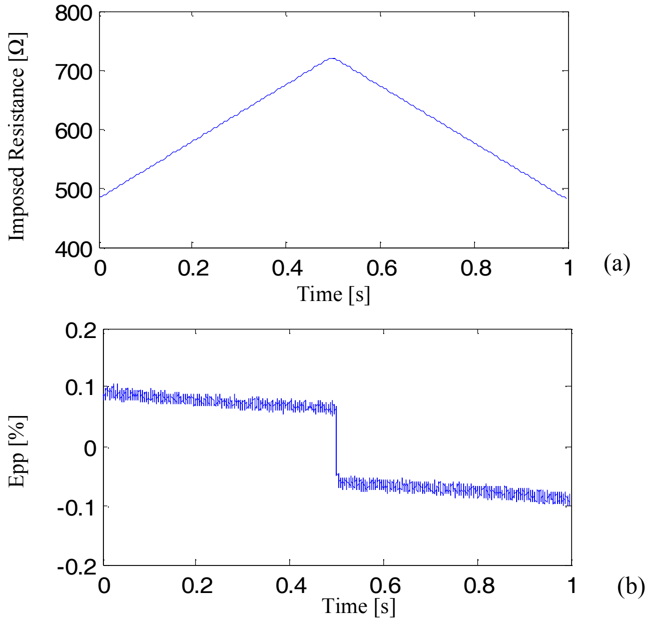

Fig. 6. Tests on the realized instrument: imposed variation of the resistance parameter (a) and behavior of the Epp figure of merit.

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