ESTIMATING AND MODELING NONLINEAR LOAD PARAMETERS

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***Abstract* – The paper describes the study and development of a parameterized model of nonlinear loads, which are presented in the most of electronic equipments available in the market. The electronic nonlinear load is represented by a bridge rectifier with an input inductor L modeling the EMI input filter inductance, an output filter capacitor C and an equivalent resistive load R connected on it. The model parameters (L, C and R) are determined from voltage and current data acquisition through a least square algorithm (by applying the concept of singular value decomposition - SVD). From the knowledge of the linear and the nonlinear electrical system parameters, the network can be friendly analyzed employing time domain simulators, such as ATP, PSIM©, Matlab/Simulink©, PSPICE©, and so on. Consequently, many aspects of the influence of these electronic loads over the electrical installation can be studied such as power factor, displacement factor and harmonic distortion, allowing a power quality analysis.**

***Keywords* – Discrete model, harmonics, least square method, nonlinear load, power electronics, power quality.**

I. INTRODUCTION

This work describes a method that allows the modeling in time domain of the main types of electronic loads typically found in academic and commercial environments. Most of electronic devices are conceived to be supplied into DC current and, hence, in order to convert the available AC line voltage into the necessary DC output voltage, an off-line switch mode power supplies (SMPS) is required. The off-line SMPS consists of a full-bridge rectifier directly connected to the mains in association with a bulky capacitor in a way to convert the AC voltage into DC voltage. The adequate DC voltage level is obtained connecting a DC-DC converter to the output capacitor of the bridge rectifier. These devices are categorized as nonlinear loads in view of the fact that off-line SMPS drains nonlinear current from the mains. This fact leads to the need for developing a specific research concerning the modeling of these loads and, toward this end, commercial simulators can be applied to analyze the impact of nonlinear loads in electrical installations. According to the available bibliography, there is no a complete and satisfactory solution to the problem of determining the parameters of a nonlinear load in the time domain.

Koval and *Carter* in [1] have only described the behavior of nonlinear loads, and presented in [2] a model of these loads based on the harmonic spectrum of the current. However, they do not describe the behavior of the loads in the presence of voltage harmonic distortions. *Reformat et al.* in [3] have presented a mathematical modeling not easily applicable in commercial simulators. *Karlsson* and *Hill* in [4] follow the same path. Nevertheless, *Karimi* and *Mong* in [5] have performed a study that resembles to the one to be presented here. However, the study performed in [5] does not address the question about the identification of the parameters of the load equivalent circuit. *Dos Reis et al.* in [6] have presented a way to identify the equivalent model parameters of an off-line SMPS using a complex set of equations and a graphical way to determine the relevant information from the input voltage and current data of the equipment under test (EUT).

In this context, the methodology presented in this paper represents a proposal of solution in the time domain for parameters estimation in single-phase electronic nonlinear loads and, hence, it does not comprise the analysis of nonlinearities present in other types of loads like three-phase ones, saturated magnetic cores, etc.

Nevertheless, this proposal aims to contribute for consolidating and systematizing a time domain solution and, toward this end, a complementary proposal of modeling is being developed in order to extend this analysis to loads with other features of nonlinearity.

The main purpose of this work is to describe a methodology that allows the identification of the different components of the off-line SMPS using an automated process based on digital oscilloscope data acquisition and a least square based algorithm to estimate the nonlinear load parameters, where these parameters are obtained by means of singular value decomposition (SVD) technique. Thus, the data obtained through the mapping of several available nonlinear loads will be used to validate the proposed identification process.

II. BASIC TOPOLOGIES OF NONLINEAR LOADS

Nowadays most electronic loads are nonlinear, since they represent, mostly, electronic equipments as audio and video devices, industrial and personal computers, video monitors, printers, and electronic ballasts for discharge lamps. These equipments generally work with a DC voltage power source. Since the energy distribution system is performed in AC voltage, a primary stage to convert the AC voltage to DC voltage becomes necessary. In low power applications, the rectification is normally performed by means of a single-phase bridge rectifier associated with a bulky capacitor as output filter. This structure or topology frequently composes the input stage of SMPS, as shown in Figure 1, where the inductor L represents the parasitic inductance of the circuit or an input EMI filter and the capacitor C_{DC} is the filtering capacitor of the rectifier.

Input rectifiers usually employ capacitors with high capacitance and, in this case, the main disadvantage of this topology is the presence of electrical current only during the capacitor charging stage. This fact results in a significant harmonic distortion of the input current, which flowing through the source voltage impedance leads to harmonic distortion in the input voltage.

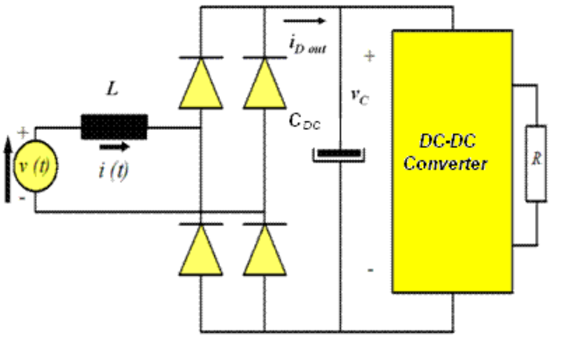

Fig. 1. Typical SMPS topology used in electronic loads.

The output structure of the rectifier, which is composed by a DC-DC converter and an electronic load, can be represented in a simplified way through an equivalent resistive load R.

In order to illustrate the resulting distortion, Figure 2 presents typical waveforms of the nonlinear load shown in Figure 1. It is remarkable that the concept of nonlinearity of the load is based on the existence of a nonlinear relationship between the current and voltage waveforms at the load supply connectors. In some degree, the parasitic inductance L is advantageous, since it increases the time interval of the current in the converter input.

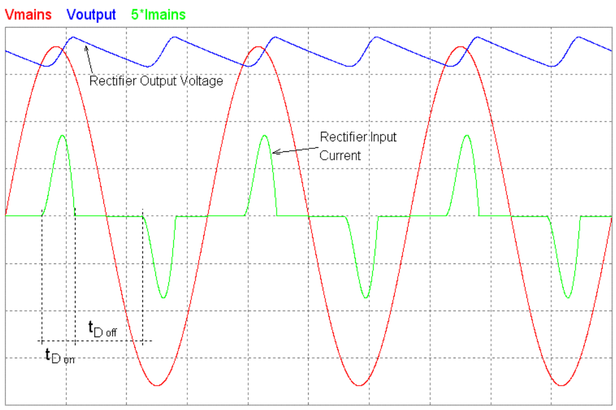

Fig. 2. Input voltage, input current and output voltage waveforms in the rectifier considering an input inductance.

From Figure 2, it is possible to verify that the input current has a high growth rate and this feature is in general responsible for the increase in the level of electromagnetic interferences (EMI) generated by the circuit. Moreover, a significant increase in the value of the maximum input current is observed supposing a hypothetical sinusoidal current for the same power.

III. PARAMETERS ESTIMATION: AN APPROACH BASED ON DISCRETIZATION

A. An Overview

An approach for modeling of nonlinear loads is proposed in this work and consists of an estimation process based on time domain analysis to determine, from sampled time domain data, the parameters of the equivalent model of the circuit in Figure 1. The input circuit is modeled by means of a time-invariant discrete-time linear system whose dynamics is represented through a set of difference equations obtained from a discretization method, and the data for the set of equations is generated from the voltage and input current waveforms. In a similar way, Choi, Cho and Van Landingham in [7] proposed a discrete-time small-signal linear equivalent system as a process for a general class of converters modeling.

In order to perform the estimation technique proposed in this work, the input rectifier is represented through a second-order linear equivalent model applicable during the time interval in which it behaves as a linear system. Hence, during this time interval in which the capacitor is in the charging state, the rectifier can be modeled as an RLC circuit, as shown in Figure 3. The voltage and input current waveforms associated with the linear behavior are considered in the composition of the difference equations, whose parameters will be determined as a step of the estimation process.

B. Mathematical Description

It is essential to take into account the fact that the topology under analysis (the one illustrated in Figure 1) is not a linear circuit and therefore must be analyzed as a piece-wise linear circuit. Hence, it is necessary to describe correctly the moment in which the voltage and current behaves linearly. The linear stage begins when the C_{DC} capacitor voltage reaches the source voltage after the time interval t_{Doff} since, in this stage, the voltage is applied directly to the circuit via the conduction of the diodes, and concludes when the input current reaches zero (i(t)=0). That is, the circuit of Figure 1 is linear in the time interval t_{Don}, such as it is illustrated in Figure 2.

Thus, the circuit in Figure 1 can be represented in conformity with Figure 3 illustrating the equivalent model for the rectifier during its charging stage.

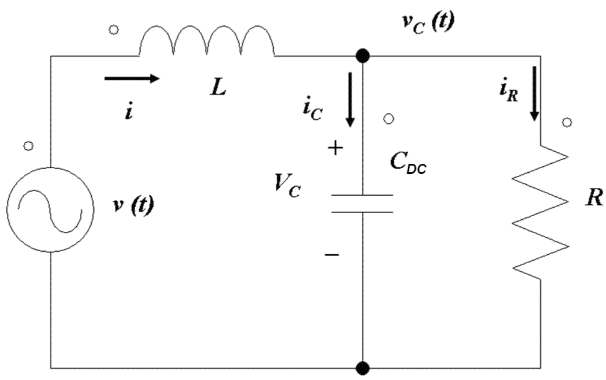

Fig. 3. Equivalent circuit of the C_{DC} charging stage.

Hence, during this time interval, the rectifier can be described through the following linear second-order differential equation in (1). As it can be verified, this equation expresses the linear relationship involving the mains voltage v(t) and the input current i(t).

$$\frac{d}{dt}v(t)+\frac{1}{RC}v(t)=L\frac{d^2}{dt^2}i(t)+\frac{L}{RC}\frac{d}{dt}i(t)+\frac{1}{C}i(t) \qquad (1)$$

A second-order transfer function can be extracted from the differential equation described in (1) by applying the Laplace Transform, such as it is represented in (2). Hence, this transfer function also establishes (in the frequency domain) the relationship between the input current i(t) and the mains voltage v(t), and its coefficients are a function of the parameters R, L and C to be estimated.

$$G(s)=\frac{I(s)}{V(s)}=\frac{\frac{1}{L}\left(s+\frac{1}{RC}\right)}{s^2+\frac{s}{RC}+\frac{1}{LC}} \qquad (2)$$

Where:

I(s) - Input current in frequency domain.
V(s) - Mains voltage in frequency domain.

The next stage of the process consists of obtaining a discrete model of the system which is derived through a discretization method. In this work, the Backward approximation technique is employed by applying the expression below.

$$s=\frac{z-1}{T_s z} \qquad (3)$$

Where:

T_s - Sampling time (s).

By substituting (3) into (2), the following discrete second-order transfer function is obtained from the original system yielding the form expressed in (4).

$$G(z)=\frac{I(z)}{V(z)}=\frac{\alpha_1 z^2+\alpha_2 z}{z^2+\beta_1 z+\beta_2} \qquad (4)$$

The set of coefficients α_1, α_2, β_1 and β_2 of the discrete transfer function are described as a function of the parameters R, L, C and the sampling time T_s, according to the expressions represented below.

$$\alpha_1=\frac{T_s RC+T_s^2}{RLC+T_s L+T_s^2 L} \qquad (5)$$

$$\alpha_2=\frac{-T_s RC}{RLC+T_s L+T_s^2 L} \qquad (6)$$

$$\beta_1=\frac{-(T_s L+2RLC)}{RLC+T_s L+T_s^2 L} \qquad (7)$$

$$\beta_2=\frac{RLC}{RLC+T_s L+T_s^2 L} \qquad (8)$$

Hence, the above set of equations represents the relationship between the coefficients of the discrete transfer function and the parameters R, L and C to be estimated. It can be verified that these equations have a common denominator due to the algebraic simplification applied to the discrete transfer function to normalize the coefficients with respect to the highest order coefficient.

These equations compose a nonlinear algebraic equation system that leads to expressions for R, L and C as a function of the sampling time and the coefficients of the discrete transfer function. Thus, (9), (10) and (11) represent the approximations for the values of L, C and R taking into account the discrete system obtained through the Backward approximation technique with a sampling time T_s. According to (11), R is expressed additionally as a function of L and C.

$$L=\frac{-T_s\alpha_1}{\beta_1} \qquad (9)$$

$$C=\frac{-T_s\beta_1}{\alpha_1-\alpha_2-1} \qquad (10)$$

$$R=\frac{T_s^2\alpha_1}{\beta_2 LC} \qquad (11)$$

Applying the inverse Z-transform into (4), the resulting equation is a linear difference equation with the following form:

$$I(n)=-\alpha_1 I(n-1)-\alpha_2 I(n-2)+\beta_1 V(n)+\beta_2 V(n-1) \qquad (12)$$

Where:

I(n) - Input current sample (system output).
V(n) - Mains voltage sample (system input).

The difference equation in (12) represents the discrete-time equivalent linear model of the original continuous-time system.

A set of data points of the input voltage and input current waveforms in the EUT (input rectifier) could be obtained, for example, using the oscilloscope data acquisition function (corresponding to the linear behavior stage). This data points set composes two vectors with N samples, which will be the data source for the estimation process. Through N values extracted from the mentioned waveforms, a system of linear equations formed by N-2 equations and four variables can be expressed in the following matrix representation.

$$\begin{bmatrix} I(3) \\ I(4) \\ . \\ I(N) \end{bmatrix}=\begin{bmatrix} 2I(2)-I(1) & -I(2) & V(2)-V(3) & V(3) \\ 2I(3)-I(2) & -I(3) & V(3)-V(4) & V(4) \\ . & . & . & . \\ 2I(N-1)-I(N-2) & -I(N-1) & V(N-1)-V(N) & V(N) \end{bmatrix}.\begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \beta_1 \\ \beta_2 \end{bmatrix} \qquad (13)$$

Thus, the above system can be represented in the following compact form:

$$I=\Psi\;\theta \qquad (14)$$

Where:

I - (N-2 x 1) output current samples vector.
Ψ - (N-2 x 4) regression matrix.
θ - (4 x 1) parameter vector to be determined.

Consequently, the number of equations is determined from the number of data points (values) taken from the waveforms (which is controlled by the adopted sampling time T_s) and the variables correspond to the parameters (R, L and C) to be estimated. According to this methodology, the estimation of the desired parameters can be performed through the relationship involving the α_1, α_2, β_1 and β_2 coefficients. In other words, from the solution associated to (14) and consisting of a (4 x 1) vector with the coefficients α_1, α_2, β_1 and β_2, the values of R, L and C are obtained through (9), (10) and (11).

C. System of Linear Equations: method of solution

The solution of the system of linear equations shown in (14), requires any process that comprises the inequality between the number of equations and the number of variables, since the number of equations is equal or higher than the number of variables. For instance, the equation (14) may be solved through the following equality:

$$\theta = (\Psi^T \Psi)^{-1} \Psi^T I \qquad (15)$$

Where the superscript *T* stands for the transpose matrix operation. However, it turns out that the conditioning of the matrix $\Psi^T\Psi$ depends on the period of time in which the voltage and current are sampled, since the order and the proximity between the values in the same column may be lead to almost linear dependent columns. As a consequence, the accuracy on computing the matrix inverse of $\Psi^T\Psi$ (the accuracy of the estimated parameters) is highly dependent on T_s. In order to overcome the possibility of bad conditioning, a solution for the linear system equations is determined employing singular value decomposition method (SVD).

This method is widely applied in linear algebra to solve matrix inversion problems and is one of the most accurate techniques to handle least square based methods. The SVD consists in obtaining two orthonormal bases. Thus, the regression matrix Ψ is decomposed into three matrices, as given below.

$$\Psi = USV^T \qquad (16)$$

Where:

U - (N x N) orthogonal unitary matrix.
S - (N x 4) diagonal matrix.
V - (4 x 4) orthogonal unitary matrix.

The solution is then obtained from the following expression involving the matrices derived from the decomposition.

$$\theta = (VS^{-1}U^T)I \qquad (17)$$

D. The sampling time

As detailed previously, an important issue, which determines the accuracy of the solution, is the value of the sampling time T_s to be employed to build the regression matrix Ψ. The criterion to be applied should take into account the time response of the system under analysis and the available computational power. A large sampling time does not preserve the dynamic features of the system and, according to Nyquist–Shannon sampling theorem, a signal without frequency components above $(2T_s)^{-1}$ can be represented and determined through a set of samples spaced by T_s (where $1/T_s$ is the Nyquist's frequency) in a way to characterize completely the dynamic behavior of the system. Hence, this feature is a physical limitation of the process. On the other hand, a very short sampling time may generate an ill-conditioned regression matrix, which in conformity with (13) is composed by elements involving sampled values from input and output in consecutive time instants. Hence, this feature is a mathematical limitation of the process.

In view of these facts, the criterion to be employed to determine the sampling time takes into consideration the statistical features of the set of current and voltage data points collected to perform the estimation. However, when the system under analysis involves only simulation, and since the parameters to be estimated are previously known, the suitable choice of T_s is easily obtained from the time constants of the system. Since the RLC circuit has a capacitive time constant (τ_c = RC) and an inductive time constant (τ_L = L/R), the value of T_s is derived from the magnitude of the minor time constant. In this case, typically the sampling time satisfies the following relationship: $T_S \leq 0.1 \min\{\tau_C, \tau_L\}$.

Although the above criterion based on the time constants of the system can be applied in situations involving simulation, in practical situations involving waveforms from an unknown system, the time constants, that are functions of the parameters under estimation, cannot be determined a priori.

For the application described in this work, the value of T_s was established taking into consideration the presence of harmonics in the input current. Aiming to comprise a range of frequencies until the 50th harmonic component of the input current resulting in a bandwidth B = 50 x 60 Hz = 3 kHz, the maximum sampling time to be employed was established according to the Nyquist–Shannon sampling theorem. In this case, since the bandwidth is B = 3 kHz, the maximum sampling time to be applied through the collection of the experimental data is $T_{s\ max} = (2 \times B)^{-1} = 166.67\ \mu s$. In the present work, the used sampling time was T_s = 100 μs due to the oscilloscope characteristics. Since this value is smaller than maximum sampling time $T_{s\ max}$, the accuracy of the process increases.

E. The implementation

The code to estimate the parameters was built over the software MATLAB©, which is employed for processing data from simulation and from EUT using a data acquisition process. In the first case, the simulation which was conceived as an intermediate step in the development of the proposed method, is activated via code and the resulting waveforms, mains voltage v(t) and input current i(t), are collected in two data point vectors with the same length. In the second case, involving an oscilloscope for experimental data acquisition, the data are collected and stored in the same vectors. Finally, from these vectors, the mathematical process is performed according to the following sequence:

- extraction of an intermediary set of data points from each vector corresponding to a limited part of the stage of linear behavior of the system; thus, it will be composed two new vectors with N data points;
- generation of shifting vectors to characterize the required difference in the levels of delay expressed in (12);
- composition of the matrices according it is represented in (13) to compose the equation system;
- resolution of the equations system by SVD method;
- determination of the parameters R, L and C as a function of the sampling time T_s and of the coefficients of the discrete transfer function by applying (9), (10) and (11).

F. The Estimation Process: an experimental data example

Aiming to exemplify the parameters estimation of the equivalent discrete linear model for a nonlinear load in conformity with the procedure described above, the waveforms were obtained through experimental data acquisition. Toward this end, the acquisition was performed from an oscilloscope connected to a single-phase bridge rectifier supplied by the mains (127 VRMS), as shown in Figure 1. The utilized components values are: R = 53.2 Ω, L = 1.2 mH and C_{DC} = 616 μF.

Figure 4 illustrates an initial data acquisition trial representing a complete cycle of input current and mains voltage waveforms. This acquisition comprises a set of 2000 data points for each parameter (oscilloscope characteristic).

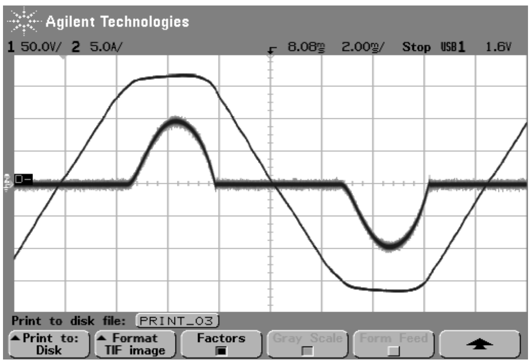

Fig. 4. A complete cycle of mains voltage and input current.

From Figure 4, it is possible to verify a significant presence of high frequency noise in the current waveform as well as the presence of harmonic distortion in the mains. Probably, because of this high frequency noise, it was not obtained a satisfactory accuracy of the estimated parameters.

In a subsequent acquisition performed for the same rectifier (using the same oscilloscope), it were collected again a set of 2000 data points for both waveforms, but this time corresponding about to 12 cycles of the mains, resulting in a set of 166 points by cycle approximately. Additionally, it was activated in the oscilloscope the resources for noise reduction and for acquiring only the average values of the waveforms, allowing a strong high frequency noise reduction, such as it is represented in Figure 5. The sampling time for this data acquisition is T_s = 200 ms / 2000 = 100 μs (using the same oscilloscope).

Figure 6 illustrates an intermediary set of 30 data points approximately selected from the vectors in a given data points acquisition (corresponding, as already mentioned, to the capacitive charging stage) and plotted via software (where the current is multiplied by 10) to represent the linear operation interval from which it will be performed the estimation. Although the presence of harmonic distortion can be verified in the voltage waveform, the extraction of a minor set of data points from the same range of linear behavior results in a filtering effect under the experimental data in a way to improve the accuracy of the results.

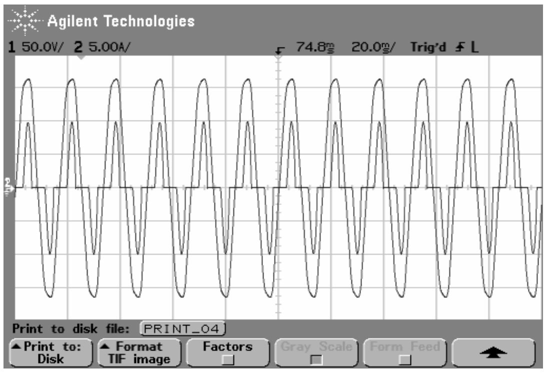

Fig. 5. Current and Voltage waveforms: several cycles.

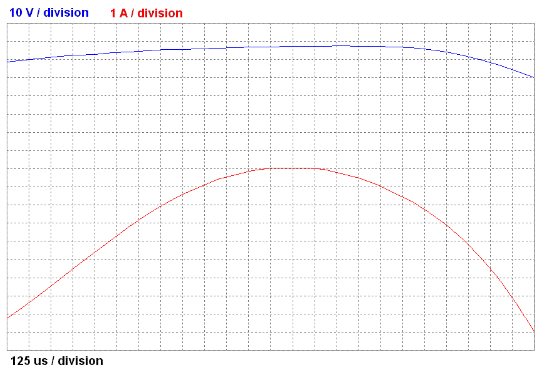

Fig. 6. Zoom of the capacitive charging stage used to estimation.

In order to validate statistically the proposed method, a group of 10 set of experimental data acquisitions (similar to those shown in Figure 6), was used for processing through the implemented software for estimation. The presence of residuary noise in the data (collected under the same conditions) is the factor responsible for the differences verified in the obtained estimation results. However, the selected Ts describes suitably the dynamic features of the system since it acts as a high frequency noise filter and, besides, does not lead to an ill-conditioned regression matrix. Table I compares the results obtained from the estimation process (the best results and the average estimated values) with the real values by presenting the percentage error.

TABLE I
Experimental Data

The Real Parameters	The Best Results	Error (%)	The Average Results	Error (%)
R = 53.2 Ω	R = 54.5 Ω	2.0	R = 50.7 Ω	3.0
C_{DC} = 616μF	C_{DC} =602.5 μF	2.0	C_{DC}=550.7μF	9.0
L = 1.2 mH	L = 1.3 mH	8.38	L = 1.3 mH	14.4

In order to investigate the efficiency of the proposed method, without any high frequency noise, the rectifier shown in Figure 1 was simulated using the parameters shown in Table I. In consequence, the mains voltage v(t) and the input current i(t) were obtained and stored in two new data point vectors with the same length and the corresponding waveforms were presented graphically in Figure7. Finally, the proposed estimation process was performed again, but now, using the results obtained from simulation.

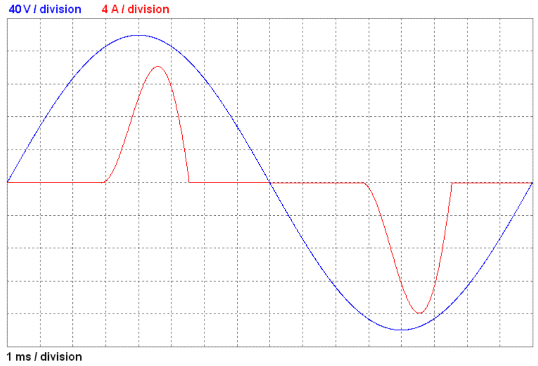

Fig. 7. Capacitive charging stage considered to estimation.

The obtained results, summarized in Table II, demonstrate the accuracy of the proposed methodology to estimate the nonlinear load parameters since the obtained values are close to the rectifier parameters. In this case, without any high frequency noise, it is possible to increase the sampling time and therefore to improve the exactitude of the results.

TABLE II
Data from simulation

Real Values	Ts = 100 μs		Ts = 10 μs	
	Estimated Values	Error (%)	Estimated Values	Error (%)
R = 53.2 Ω	R = 43.5 Ω	18.12	R = 52.5 Ω	0.04
C_{DC} = 616μF	C_{DC} =613.7 μF	0.37	C_{DC}=615.6 μF	0.07
L = 1.2 mH	L = 1.2 mH	0.55	L = 1.2 mH	1.28

IV. CONCLUSION

This paper studies the modeling and identification of electronic single-phase loads, as personal computers, electronics ballasts, SMPS, audio, and video equipments. The proposed model of the nonlinear load can be used for performing simulations, in the time domain, of any electrical installation including these nonlinear loads, allowing the determination of any electrical parameters (like current, voltage, power factor, displacement factor, apparent power, total harmonic distortion (THD), etcetera) in any point of the circuit. Hence, from the information obtained from the simulation of the system under analysis it is possible, for example: to determine the neutral currents including the add effect of the harmonic components in all phases; to verify over voltages generated by harmonic resonances; to perform a complete power quality study of the electrical system under analysis. This study can be easily performed in time-domain simulators such as ATP, PSIM©, MATLAB/SIMULINK©, PSPICE©.

A significant contribution to the error observed in the proposed method is addressed to the adopted model since it considers all components as ideal ones. A very accurate model must include the components non-idealities like, for example, parasitic resistance and inductance in the bridge filter rectifier capacitor C_{DC}. For most applications, the proposed method presents effective results.

The proposed process is an original approach to address the power quality analysis. A more extensive proposal of modeling is in development with the objective to comprise the analysis of other types of nonlinear loads like magnetic cores and three-phase loads.

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