INTEGRATED INSTRUMENTATION SYSTEM FOR CHARACTERIZATION AND PARAMETER EXTRACTION OF ELECTRONIC COMPONENTS

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Abstract--Implementation of an integrated instrumentation system for characterizing and extracting parameters of discrete and integrated electronic components is presented. The experimental data for the devices tested is obtained using high sensitivity HP measuring equipment. The technique used consists of acquiring large sets of data from static I-V characteristics, C-V profiles and impedance measurements performed automatically by a computer. Software routines have been implemented under Matlab environment to extract Spice model parameters for a large set of passive devices. A good agreement between measured and calculated device parameters has been obtained.

1. Introduction

As the electronic components industry continues to grow and overcome many barriers, the characterization tools used to access its various products' behaviour need to advance at a similar trend. Within semiconductor devices field, many measuring instrument manufacturers have developed new sophisticated products and improved their equipments to get high measurement resolution and hence, allow precise semiconductor device parameters to be extracted [1-4]. Furthermore, most of these instruments are provided with interface buses to be remotely controlled by computers [5]. This is to automate measurement and analysis operations. The Parallel and USB interface buses for instance, are carefully designed instrumentation interfacing means that simplify the integration of measuring instruments and a computer into one system. This work presents an integrated PC-based system that takes full advantage of the advanced features of current measuring instruments that operates remotely via interface bus in order to characterize accurately a wide set of passive and active electronic components. These instruments are widely encountered in electronic industry as well as in research. The flow of data through the interface bus is completely monitored using a developed integrated software. In addition to this, and in order to make the system full featured, a set of graphical based routines for Matlab environment have been implemented. These routines allow extraction of SPICE model parameters for a large number of electronic components.

2. Parameter extraction methods

Two different well known approaches have been used so far for electronic device parameter extraction. The local methods where the parameters are generally determined from the slope and/or from the intercept of a regression line of a given parameter [6] and the other methods known as global optimization techniques [7]. For these last methods, all parameters or their subsets are extracted simultaneously and in some cases need to use data from several devices with different sizes. They usually

show good agreement between measured and simulated data in spite of their need to use heavily the CPU and require a relatively large number of data points [1]. As an alternative to these two approaches, least square fitting techniques on linearized model equations have been proposed [8]. Another alternative is the so-called direct parameter extraction technique which requires a small number of data points. This approach was first in fact introduced by Hamer [9] and further developed by several research groups [2], [10].

The parameter extraction methods that have been developed in this work are based on both local methods and optimization approaches. The algorithm selected to build parameters' extraction programs using optimization methods is based on the gradient following approach and more precisely on the Levenberg-Marquardt algorithm [1].

The technique adopted to extract the model parameters of the passive components is summarized in the flowchart shown in figure 1. As it is shown on this figure, a graphical method related to the device type is first used for a set of DC and/or AC measurement data. This step is in fact necessary in case the parameter values extracted are satisfactory enough so that no further refinements are needed.
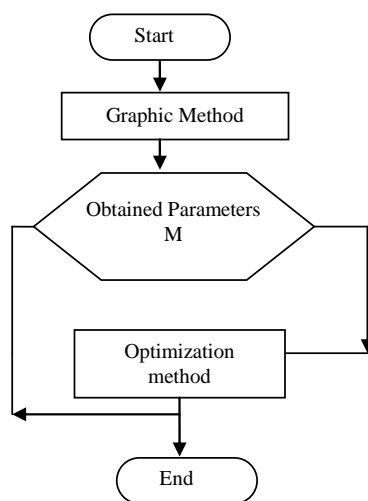

Fig. 1 Technique of extraction of model parameters for passive devices.

Otherwise, the extracted values are input as initial guess into an optimization method, which is in general more sophisticated and gives more accurate results.

2.1 Extraction of Resistor Model Parameters

From the resistor equivalent circuit of figure 2a, one can write an expression for the admittance of the circuit as

$$Y(\omega) = G(\omega) + jB(\omega) \qquad (1)$$

Where

$$G(\omega) = R_P / (R_P^2 + (L\omega)^2) \qquad (2)$$

and

$$B(\omega) = C\omega - L\omega / (R_P^2 + (L\omega)^2) \qquad (3)$$

If a variable operating frequency f is used, then it can be shown that

$$1/G(f) = R_P + (2\pi L)^2 f^2 / R_P \qquad (4)$$

Based on these expressions, one might suggest two different methods for parameter extraction.

The first method consists of the following steps:

a) Obtain the resistance R_p from DC measurements.

b) Then, obtain the inductance L by averaging the values calculated using equations above at different frequencies. The expression of L is given by

$$L = \frac{R_P}{2\pi f} \sqrt{\frac{1}{G(f)R_P} - 1} \qquad (5)$$

From the values of L, the capacitance C can also be extracted by averaging the values calculated at different frequencies using the following expression

$$C = \frac{B(f)}{2\pi f} + \frac{G(f)L}{R_P} \qquad (6)$$

The second method consists of the following:

If we let $a_2 = R_P$ and $a_1 = (2\pi L)^2 / R_P$ in the expressions (4), then

$$1/G(f) = a_1 f^2 + a_2 \qquad (7)$$

becomes a linear function of f^2. Fitting $1/G(f)$ with respect to f^2 by a polynomial of first degree, gives the coefficients a_1 and a_2 and hence, the values of R_p and L which are given by $R_P = a_2$ and $L = \frac{1}{2\pi} \sqrt{a_1 a_2}$.

Note that the set of measurement points does not ensure that the values of $1/G(f)$ are perfectly correlated with f^2.
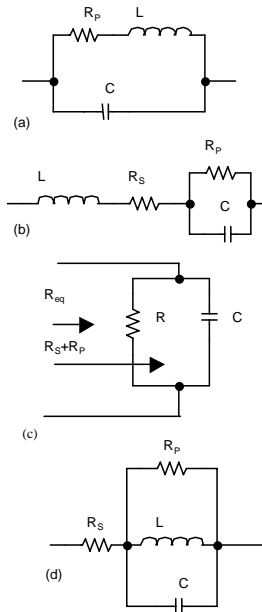

Fig. 2: Equivalent circuits for (a) Resistor, (b) capacitor, (d) Inductor. (c) Circuit used for the measurement of R_S+R_p for a capacitor.

In this case, a suitable choice of the frequency range is to be made to maximize the accuracy of L and R_P and a plot of $1/G(f)$ versus f^2 for different frequency intervals is recommended as a decision criteria. The value of C may then be extracted using the same approach as done previously in the first method.

It appears from the above that the second method is preferred for the following reasons:

a) No DC measurements are required to obtain the value of R_P. In fact, such measurements are sometimes difficult to achieve, especially when R_P has small values.

b) The extraction of the inductance L using the first method requires that the condition $1/G(f)R_P \geq 1$ needs always to be satisfied. Therefore, some measurement points may be missing in the calculation of L and so the accuracy will be reduced.

Note also that a similar inconvenience exists in both methods for the extraction of the capacitance C because for each frequency value, the calculated $C(f)$ given above has to be positive.

2.2 Extraction of Capacitor Model Parameters

The capacitor equivalent circuit considered is shown in figure 2b. The impedance of the equivalent circuit element can be expressed as

$$Z(\omega) = R(\omega) + jX(\omega) \qquad (8)$$

Where

$$R(\omega) = R_S + R_P /((CR_P)^2\omega^2 + 1) \qquad (9)$$

and

$$X(\omega) = \left(L - CR_P^2/((CR_P)^2\omega^2 + 1)\right)\omega \qquad (10)$$

It is simple to proof using the above three expressions that

$$X(f)/f = -2\pi CR_P R(f) + 2\pi(L + R_S R_p C) \qquad (11)$$

The method of extraction of the capacitance is as follows:

a) From DC measurements one can obtain the value of $R_{eq} = R_S + R_P$. it can assumed that $R_{eq} = R_P$ since in almost all situations R_P is much greater than R_S. Due to the large values of R_P required to achieve such measurements, a known resistor R is to be connected in parallel with the device under test as shown in figure 2c. R_P may then be obtained from the expression

$$R_p = 1/(1/R_{eq} - 1/R) \qquad (12)$$

b) To extract the remaining parameters, one can suggest to let $a_1 = -2\pi CR_P$ and $a_2 = 2\pi(L + R_S R_P C)$ then,

$$X(f)/f = a_1 R(f) + a_2 \qquad (13)$$

In which $X(f)/f$ is a linear function of $R(f)$.

The coefficients a_1 and a_2 are obtained from fitting $X(f)/f$ with respect to $R(f)$. Hence,

$$C = -\frac{a_1}{2\pi R_P} \qquad (14)$$

and

$$L = \frac{1}{2\pi}(a_2 + R_S a_1) \qquad (15)$$

As it has been shown earlier, to obtain the value of L, R_S should be known. Its value can be obtained by averaging the calculated values at different frequencies. This implies that

$$R_S = R(f) - R_P /(a_1^2 f^2 + 1) \qquad (16)$$

2.3 Extraction of Inductor Model Parameters

The impedance of inductor model given in figure 2d can be expressed as:

$$Z(\omega) = R(\omega) + jX(\omega) \qquad (17)$$

where,

$$R(\omega) = R_S + G_P / \left[G_P^2 + \left(C\omega - \frac{1}{L\omega} \right)^2 \right] \qquad (18)$$

and

$$X(\omega) = (\frac{1}{L\omega} - C\omega) / \left[G_P^2 + \left(C\omega - \frac{1}{L\omega} \right)^2 \right] \qquad (19)$$

using the above expressions, one can write

$$\frac{1}{R(f) - R_S} = G_P + \frac{R_P}{(2\pi L)^2} \left(\alpha f + \frac{1}{f} \right)^2 \qquad (20)$$

Where,

$$\alpha = -(2\pi)^2 LC \qquad (21)$$

On the other hand, it can be shown that

$$\frac{fX(f)}{R(f) - R_S} = \frac{R_P}{2\pi C}(1 + \alpha f)^2 \qquad (22)$$

The steps involved in extracting the inductor model parameters are as follows:

- R_S is obtained from DC measurements.
- Letting $a_1 = \alpha R_P / 2\pi C$ and $a_2 = R_P / 2\pi C$, then

$$fX(f)/[R(f) - R_S] = a_1 f^2 + a_2 \qquad (23)$$

Therefore, a fitting polynomial of the form

$$X(f)/[R(f) - R_S] \qquad (24)$$

with respect to f^2 gives the value of a_1 and a_2. Note that $\alpha = a_1 / a_2$

- Also, using a polynomial fitting approach, the coefficients of the expression

$$1/(R(f) - R_S) = b_1(\alpha f + 1/f)^2 + b_2 \qquad (25)$$

can be obtained.

If $b_1 = R_p /(2\pi L)^2$ and $b_2 = G_P$, Then R_P, L and C can be deduced using the following expressions:

$$R_P = 1/b_2 \qquad (26.a)$$

$$L = 1/(2\pi \sqrt{b_1 b_2}) \qquad (26.b)$$

$$C = -(\alpha / 2\pi)\sqrt{b_1 b_2} \qquad (26.c)$$

3. Results and Discussion

The methods of extraction of three passive component model parameters described above have been implemented within a Matlab graphical user interface environment. It is worth noting that the developed program offers a user-friendly interface and all calculated parameters are displayed on the same window frame (refer to figure 3). This figure shows a typical function to plot for a device under test, which is in this case X(f) versus frequency in the range 1MHz to 10MHz. The results extracted for the considered component are: R_p=100.7237Ω, L=2.2792$\times$10^{-7} H, C=2.0098$\times$10^{-11} F with an error coefficient of 0.99988. Note that the solid curve on the figure shows the simulated X(f) using extracted parameters. Other software routines were also implemented to be used for comparing the calculated impedance magnitude and phase values with respect to the measured ones.
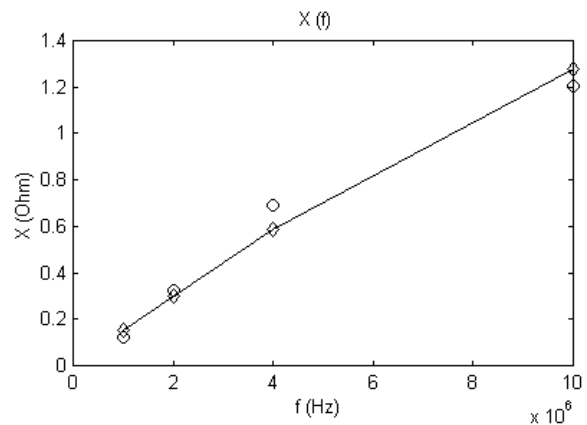

Fig. 3: Typical results of the implemented software routine for extraction of passive components' model parameters.

Different types of resistors, capacitors and inductors have been tested and characterized. For instance, the resistor circuit parameters

are obtained easily even with graphical methods and the use of optimization methods does not give any significant improvement in accuracy. As an example, results obtained for a thick film silicon resistor type of 10Ω are shown in figure 4. Note the good agreement between the calculated and the measured values.

As for the capacitor and inductor circuit parameters, the use of graphical methods comes out to be not enough and the use of optimization methods is necessary. For instance, many trials for initial condition values need to be done before obtaining satisfactory results.
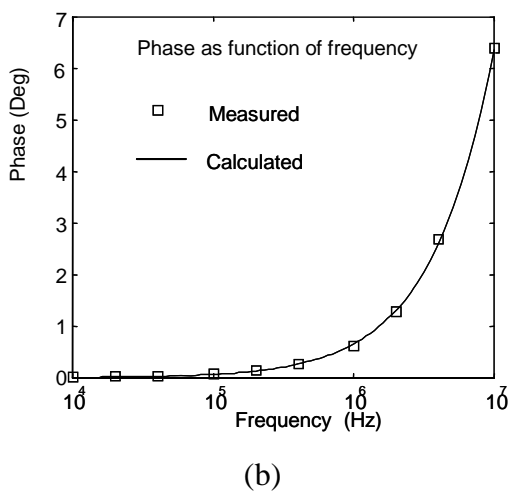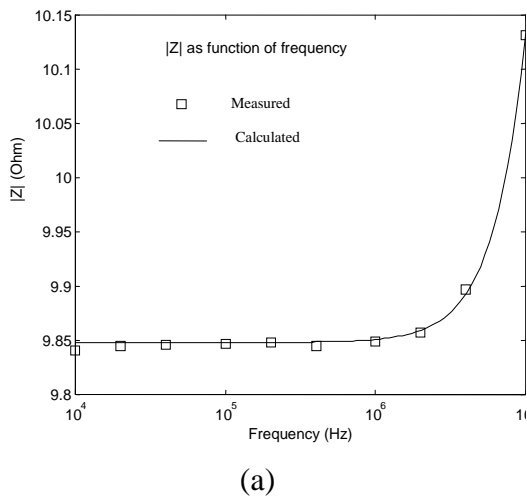
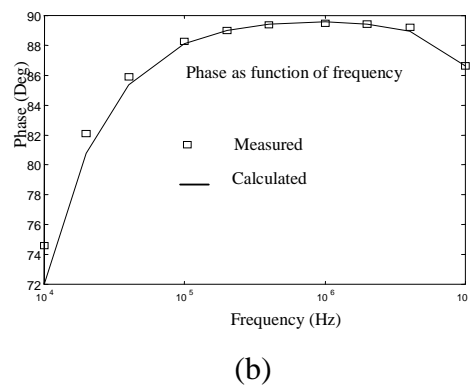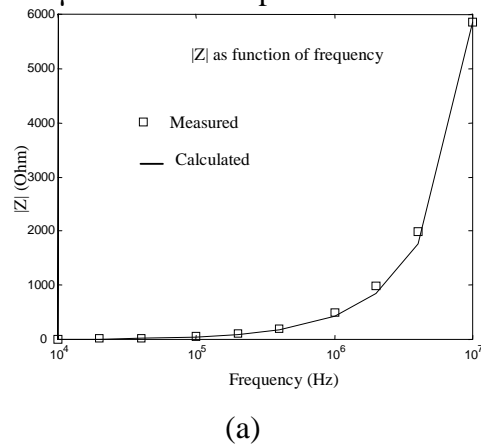this device are: R_s=1.36Ω, R_p=100KΩ, L=66.67µH and C=1.09pF.

(a)

(b)

Fig. 5: Calculated impedance magnitude (a) and phase (b) from extracted parameters of a 70µH inductor. Obtained parameters for this case are: R_S=1.36Ω, R_P=100KΩ, L=66.67µH and C=1.09pF

(a)

(b)

Fig. 4: Calculated impedance magnitude (a) and phase (b) from extracted parameters of a 10 ohm thick film silicon resistor.

Figure 5 shows the calculated and extracted magnitude and phase of the impedance of a 70µH inductor. The obtained parameters for

As for a capacitor, the measurement of leakage currents through the dielectric is made possible using either the HP 4140B or the HP 4145B model, since current values which are as small as 1fA (10^{-15} A) can be measured.

This allows characterization of the dielectric material of a capacitor and hence determines any degradation by ageing or after a misleading connection.

Figure 6 shows the calculated and extracted magnitude and phase of the impedance of a 1µF electrolytic capacitor. The extracted parameters for this device are: R_S=1.29Ω, R_P=330.58Ω, L=14.27nH and C=0.867µF. Note again the very good agreement between the calculated and the measured values.
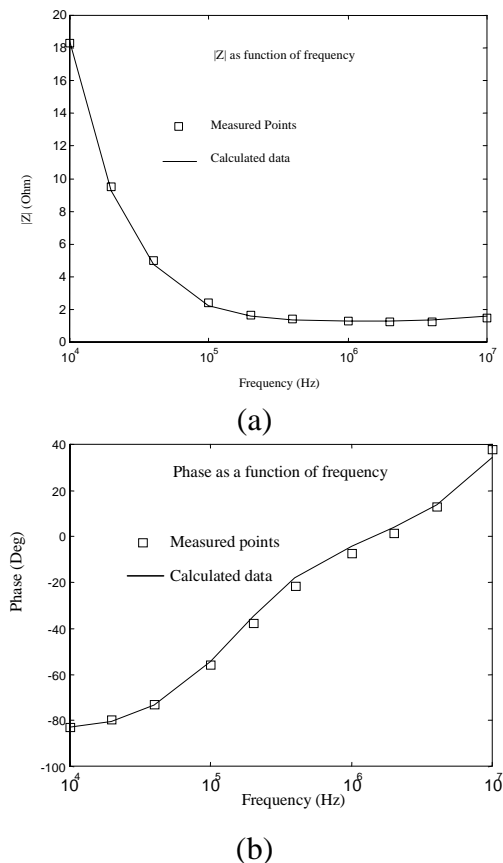
(a)

(b)

Fig. 6: Calculated impedance magnitude (a) and phase (b) from extracted parameters of a 1µF electrolytic capacitor. Obtained parameters for this case are: $R_S=1.29\Omega$, $R_P=330.58\Omega$, $L=14.27nH$ and $C=0.867µF$.

4. Conclusion

In this work, an integrated PC-based system for the characterization of integrated and discrete electronic devices has been implemented and tested. The system can acquire experimental data from electronic devices through the PC interface bus using a set of high precision test instruments. A set of graphical interface routines developed in MATLAB environment was implemented for extraction of SPICE model parameters for different types of commercial electronic components. The results obtained from theoretical calculation and experimental characterization of some simple passive components (resistor, capacitor and inductor) are in very good agreement. This has been done for the frequency range 10 KHz to 10 MHz. The developed product is useful in industrial environments as well as in research labs for electronic device characterization.

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