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A LECCS Model Parameter Optimization Algorithm for EMC Designs of IC/LSI Systems

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***Abstract*— In this paper, we propose a parameter optimization algorithm for EMC macro-modeling of IC/LSI power currents called the *LECCS (Linear Equivalent Circuit and Current Source)* model. The unnecessary electro-magnetic wave from a digital electronics device may cause the electromagnetic interference (EMI) to other apparatus. Thus, its reduction has been regarded as one of the highest priority issues in digital electronics device designs. In order to accurately simulate high-frequency currents from power-supply sources that are the primary sources of EMI, the LECCS model has been proposed as a linear macro-model of a power-supply circuit. A LECCS model consists of multiple RLC-series circuits in parallel to represent the equivalent circuit between the voltage source and the ground. Given a set of measured impedances at various frequencies, our proposed algorithm first finds the number of RLC-series circuits corresponding to the number of valleys. Then, it searches optimal values of RLC parameters by a local search method. The effectiveness of our algorithm is verified through applications to a real system, where the accuracy and the required processing time by our algorithm are compared with the conventional method.**

I. Introduction

The unnecessary electromagnetic wave from an IC/LSI system is not only the source of the electromagnetic interference (EMI) to other apparatus, but also may cause the functional interference between system components including a printed circuit board (PCB) and modules on a PCB. To reduce this unnecessary electromagnetic wave, the circuit implementation method for IC/LSI systems to realize the isolation of high-frequency currents while keeping high-speed functions has become the critical issue in the digital system design society. For this purpose, the *EMC (electro-magnetic compatibility)* design theory treating digital circuits as high-frequency circuits must be established through the fusion of the electric circuit theory and the electromagnetic wave theory.

Conventionally, the simulation-based technology including SPICE has been used for the circuit layout design of digital systems. Likewise, the simulation technology should also be adopted for the EMC design of them. In the EMC design, the estimation of EMI levels and the modification of circuit designs at early design stages are very important, because the design modifications at final stages can sometimes be impossible. Actually, when the layout design including module placements and routings is completed, the EMI simulation should be applied using the estimated currents and voltages at that stage. Then, when the implementation design on a PCB is finalized, the unnecessary electromagnetic wave should be estimated as precisely as possible.

One of the primary sources for EMI from a PCB is the high-frequency current between the voltage source and the ground in an IC/LSI system. To evaluate EMI accurately, the precise estimation of this high-frequency current is indispensable. This estimation must also be finished within short time so that the result can be reflected in the design process. Therefore, the *LECCS (Linear Equivalent Circuit and Current Source)* model has been proposed for the EMC macro-modeling of IC/LSI power currents [1]-[4]. As shown in Figure 1, a LECCS model consists of multiple RLC-series circuits in parallel with a current source, to represent the equivalent linear circuit between the voltage source and the ground for the fast and precise estimation of the high-frequency current between them. Although several models for EMI estimations have been proposed [5]-[7], there is no all-purpose model to satisfy every requirement such as the calculation time, the estimation accuracy, and the versatility.

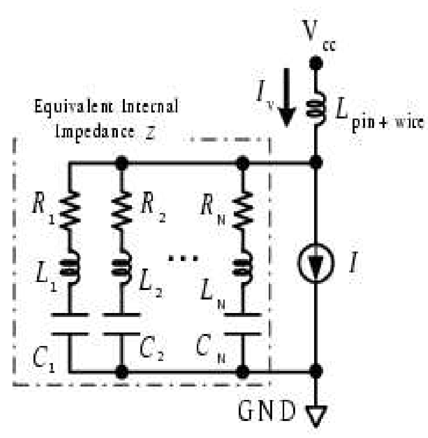

Fig. 1. A LECCS model.

In order to obtain the accurate LECCS model for a given IC/LSI system, the number of RLC-series circuits and RLC parameter values in each series circuit should be optimized. Conventionally, these parameters are adjusted manually through a number of trials by experienced users. This manual adjustment does not only require a lot of time but also requires the training experience for fine adjustments. As a result, the LECCS model has become hard for conventional users. To reduce this burden, this paper proposes a parameter optimization problem for a LECCS model based on a local search technique [8], after formulating the *LECCS model parameter optimization problem*. We note that $L_{pin+wire}$ in a LECCS model is removed from the measured impedances for simplicity.

The rest of this paper is organized as follows: Section II formulates the LECCS model parameter optimization problem. Section III presents our algorithm for this problem. Section IV verifies the effectiveness of our algorithm using a real LSI system. Section V concludes this paper.

II. LECCS Model Parameter Optimization Problem

A. Problem Formulation

In the LECCS model parameter optimization problem, measured impedances between the voltage source and the ground in an IC/LSI system are given as the input, and the number of RLC-series circuits and RLC parameter values to approximate the given impedances are requested as the output. Actually, the measured impedances are given as a set of amplitudes and phases at measured frequencies. As in Eq. (1), the quality of the LECCS model as the output is evaluated by the sum of the differences between amplitudes of measured impedances and those of calculated impedances at all the measured frequencies.

< LECCS model parameter optimization problem >

Input:

- amplitude $|input\_Z(\omega)|$ and phase $\theta(\omega)$ at each measured frequency ω.

Output:

- the number of RLC-series circuits N
- RLC parameter values ($1 \leq i \leq N$) R_i: resistance at i-th circuit
  L_i: inductance at i-th circuit
  C_i: capacitance at i-th circuit

Objective:

- to minimize the error function E:

$$E = \sum_{i=1}^{N} \sum_{\omega_k \in \Omega_i} \left| |input\_Z(\omega_k)| - |model\_Z(\omega_k)| \right| \quad (1)$$

B. Definitions of Symbols

In this subsection, we define the terms and the corresponding symbols used in this paper.

- (angular) frequency: ω
- the set of measured frequencies at i-th valley: Ω_i
- measured impedance at ω: $input\_Z(\omega)$
  - real part: $input\_ReZ(\omega)$
  - imaginary part: $input\_ImZ(\omega)$
- calculated impedance in LECCS model at ω: $model\_Z(\omega)$
  - real part: $model\_ReZ(\omega)$
  - imaginary part: $model\_ImZ(\omega)$
- calculated admittance in LECCS model at ω: $model\_Y(\omega)$
  - real part: $model\_ReY(\omega)$
  - imaginary part: $model\_ImY(\omega)$
- frequency with maximal real part of admittance at i-th valley: ω_i^R
- frequency with maximal imaginary part of admittance at i-th valley: ω_i^I
- algorithm constant parameters; α, β, γ
- impedance amplitude of i-th circuit in LECSS model at ω: $|Z_i(\omega)|$

III. Algorithm for LECCS Model Parameter Optimization

A. Valley Detection

Measured impedances between a voltage source and a ground in an IC/LSI system may have several valleys because of resonances as shown in Figure 2. The frequency with the minimal amplitude in a valley, which is called the *minimal frequency* in this paper for convenience, can be regarded as the resonance frequency for the corresponding RLC-series circuit in a LECCS model. Thus, the number of valleys is equal to the number of RLC-series circuits.

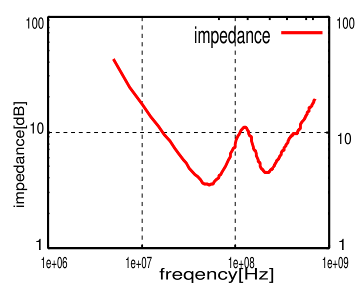

Fig. 2. Measured impedance amplitudes between a voltage source and a ground in H8S/2623.

The frequency range in each valley is defined as the range between two neighboring frequencies with maximal amplitudes, which are called *maximal frequencies*. Note that the lower limit of the first valley is given by the smallest measured frequency, and the upper limit of the last valley is by the largest measured frequency.

In our algorithm, the minimal and maximal frequencies are alternately found in sequence by scanning the impedance amplitudes from the smallest frequency to the largest one.

Here, to avoid noises in measured data from the frequency range of a valley, any maximal frequency whose amplitude does not exceed the one at the closest minimal frequency by α dB, is ignored in our algorithm. Similarly, the minimal frequency whose amplitude does not exceed the one at the closest maximal frequency by β dB, is also ignored.

B. Initial Values for RLC

The initial values for RLC parameters are calculated by using admittances that are given by taking the inverse numbers of the measured impedances. From the measured admittances, we first find a frequency with the maximal real part, ω_i^R, a frequency with the maximal imaginary part, ω_i^I, and the real part value, Y_i^R, at ω_i^R in the i-th valley for $i = 1, ..., N$, respectively. In a LECCS model, the admittance between the voltage source and the ground is described by:

$$model\_Y(\omega) = \sum_{i=1}^{N} \left(R_i + \frac{1}{j\omega C_i} + j\omega L_i \right). \quad (2)$$

Thus, the real part and the imaginary part of the admittance are respectively given by:

$$model\_ReY(\omega) = \sum_{i=1}^{N} \frac{R_i}{R_i^2 + (\omega L_i - \frac{1}{\omega C_i})^2} \quad (3)$$

$$model\_ImY(\omega) = -\sum_{i=1}^{N} \frac{\omega L_i - \frac{1}{\omega C_i}}{R_i^2 + (\omega L_i - \frac{1}{\omega C_i})^2} \quad (4)$$

Here, we assume that the frequency with the maximal real part in the i-th valley is equal to the i-th resonance frequency in Eq. (3). Then, we can obtain:

$$\omega_i^R = \frac{1}{\sqrt{L_i C_i}}. \quad (5)$$

$$Y_i^R = \frac{1}{R_i}. \quad (6)$$

Similarly, we assume that the imaginary part in Eq. (4) takes the maximal value at the frequency with the maximal imaginary part in the i-th valley. Then, we can obtain:

$$\begin{aligned} \omega_i^I &= \frac{R_i C_i + \sqrt{R_i^2 C_i^2 + 4 L_i C_i}}{2 L_i C_i} \\ &\approx \frac{R_i}{2L_i} + \frac{R_i}{2L_i}\sqrt{\frac{4 L_i C_i}{R_i^2 C_i^2}} = \frac{R_i}{2L_i} + \frac{1}{\sqrt{L_i C_i}} = \frac{R_i}{2L_i} + \omega_i^R \end{aligned} \quad (7)$$

where we use $R_i^2 C_i^2 \ll 4 L_i C_i$. As a result, we can obtain:

$$\omega_i^I - \omega_i^R = \frac{R_i}{2L_i}. \quad (8)$$

Therefore, for each valley, we can obtain R_i, L_i, and C_i using Eqs. (5), (6), and (8) from measured admittances.

C. Variation Unit for Local Search

The initial RLC parameter values in III-B are further optimized by a local search method [8] in our algorithm. The variation unit for each parameter variable is calculated for this local search. Actually, the variation unit for R_i is calculated by the sum of differences between the measured impedance amplitudes and the calculated impedance amplitudes at all measured frequencies:

$$\Delta R_i = \left| \frac{\sum_{\omega_k \in \Omega_i} (|input\_Z(\omega_k)| - |model\_Z(\omega_k)|)}{\gamma \sum_{\omega_k \in \Omega_i} \frac{\partial}{\partial R_i} |Z_i(\omega_k)|} \right| \quad (9)$$

where the denominator of the right-hand side is necessary for the normalization, and γ is the constant coefficient in the algorithm. The variation units for L_i and C_i are also calculated in the same manner.

D. Local Search Procedure

The RLC parameters of each circuit for each valley are gradually refined by repeating the following procedure. Here, to consider the effects from neighboring valleys, we apply this procedure for circuits $1-2-1-2-3-2-3-4-3-4-....-(N-2)-(N-1)-N$ in this order, where circuit 1 represents the one corresponding to the first valley with the least frequency range, and circuit N represents the one corresponding to the last valley with the largest frequency.

1) randomly select one parameter among R_i, L_i, and C_i.
2) add and subtract the variation unit in III-C to/from this selected parameter.
3) calculate E within the frequency range in valley i in Eq. (1) by using each new parameter value, and select the best one among three including the one by the original parameter.
4) accept the parameter update with the selected one.

IV. Evaluation in Real System

In this section, we verify the effectiveness of the proposed LECCS model parameter optimization algorithm by using the measured impedances between a voltage source and a ground in the H8S/2623 16-bit micro-controller. The estimation error and the required time are compared between two results by our algorithm and by the conventional manual adjustment. Figure 3 shows the measured impedances (amplitudes, phases) used here, where the estimated PCB inductance ($3.6nH$) is removed to avoid its influence. The impedance amplitudes actually have three valleys as shown there. Thus, the corresponding LECCS model also has three RLC-series circuits in parallel, where the second valley is manually detected because the depth is too small to be detected by our algorithm.

Tables I and II show the RLC parameter values of three RLC-series circuits in the LECCS model found by the manual adjustment and by our algorithm, respectively. Figures 4 and 5 illustrate amplitudes of the corresponding calculated

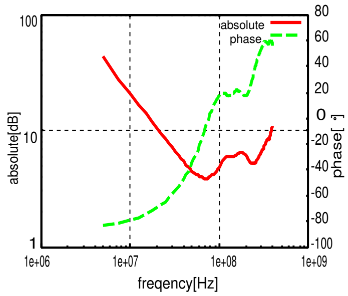

Fig. 3. Measured impedances between a source and a ground in *H8S/2623*.

TABLE I

RLC PARAMETERS BY MANUAL ADJUSTMENT.

circuit	R[]	L[nH]	C[nF]
1st	3.9	9.0	0.63
2nd	8.0	20	0.026
3rd	12	30	0.037

impedances and their errors from the measured ones. The maximum error is 1.37 dB and the required time is about three hours for the manual adjustment, while the error is 0.62 dB and the time is about 16 seconds for the algorithm.

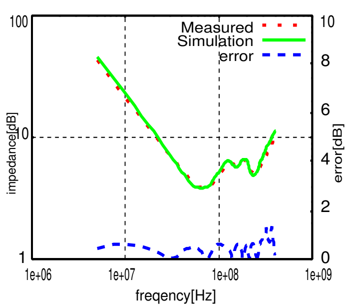

Fig. 4. Calculated impedance by manual adjustment.

These results indicate that the big differences of parameter values at the second and third circuits cause the difference in the accuracy. Because the second valley is very small, the manual adjustment of RLC parameters for this valley is very hard to be refined. This adjustment process also consumes a lot of time. Therefore, this experiment supports the superiority and the effectiveness of our algorithm in generating precise

TABLE II

RLC PARAMETERS BY ALGORITHM.

circuit	R[]	L[nH]	C[nF]
1st	4.1	7.9	0.67
2nd	19	39	0.028
3rd	8.8	17	0.029

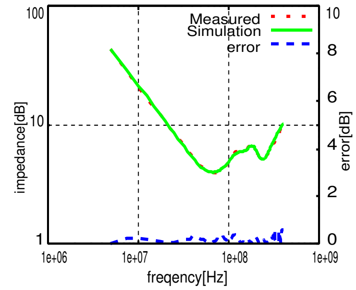

Fig. 5. Calculated impedance by algorithm.

LECCS models for EMC designs of IC/LSI systems in short time.

V. Conclusion

This paper has formulated the LECCS model parameter optimization problem for EMC designs of IC/LSI systems and has presented its algorithm. Our algorithm first finds the number of RLC-series circuits and the initial values of RLC parameters from the measured admittances that are inverse numbers of the measured impedances. The effectiveness of our algorithm is confirmed through applications to the measured impedances in a real IC/LSI system.

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