PRACTICAL, HIGH SPEED GRADIENT COMPUTATION FOR HARMONIC BALANCE SIMULATORS

J.W. Bandler*, Q.J. Zhang and R.M. Biernacki*

Optimization Systems Associates Inc.
P.O. Box 8083
Dundas, Ontario, Canada L9H 5E7

ABSTRACT

We introduce a powerful computational concept which we name the future adjoint sensitivity technique (FAST). FAST combines the efficiency of the exact adjoint sensitivity technique with the simplicity of the conventional perturbation technique. The same concept carries over to a practically implementable Jacobian for fast harmonic balance simulation. Our result promises high speed gradient evaluation essential for yield optimization of nonlinear MMIC circuits by general purpose software.

INTRODUCTION

Recent years have witnessed a resurgence of interest in harmonic balance (HB) simulation methods in the microwave industry. A growing number of microwave engineers are using HB simulators to design nonlinear circuits. Extensive number crunching currently required by available HB simulators have inhibited fast optimization of nonlinear circuits and its extension to yield driven design. Another significant drawback of current implementations is due to inaccurate sensitivity and gradient calculations.

For researchers in the HB area, improving HB efficiency and robustness has always been a serious task. Kundert and Sangiovanni-Vincentelli [1] and Rizzoli et al. [2, 3] have already suggested an exact Jacobian approach. Rizzoli et al. [4] combined both optimization and solving nonlinear equations at a single level, affording certain advantages. Its most serious disadvantage is its incompatibility with established yield optimization formulations.

Recently Bandler, Zhang and Biernacki developed the exact adjoint sensitivity technique (EAST) for the HB technique [5, 6]. The EAST has been tested in a nonlinear HB-based parameter extraction program and demonstrated to be extremely powerful [7].

Motivated by the potential impact of the adjoint sensitivity approach on general purpose CAD programs we have studied its implementation aspects. We have discovered a practically implementable technique which we name FAST (future adjoint sensitivity technique). It retains most of the efficiency and accuracy of the EAST while accommodating the simplicity of the conventional perturbation method, which we name PAST (perturbation approximate sensitivity technique).

FAST is directly applicable not only to the node/port formulation of the HB equations [1, 5, 6] but also to the state variable formulation [2-4], both within the framework of general purpose software.

The FAST concept has also been implemented in computation of Jacobians for high speed HB simulation. By avoiding the analytical differentiation of device equations, our approach easily accommodates complicated and piecewise device descriptions.

The features of FAST and its Jacobian extensions are exposed by a mixer example and a frequency doubler example, respectively.

NOTATION AND DEFINITIONS

We follow the notation of [5]. The overall nonlinear circuit is divided into linear and nonlinear parts. The voltage and the current waveforms at the linear-nonlinear connection ports are represented by real vectors $\mathbf{v}(t)$ and $\mathbf{i}(t)$, respectively. The kth harmonic of these voltage and current spectrums are represented by capital letters $V(k)$ or $I(k)$, respectively. $Y(k)$ is the port (linear-nonlinear connection ports) admittance matrix of the linear part. A bar denotes the split real and imaginary parts of a complex quantity. The hat distinguishes quantities of the adjoint system. In particular, $\bar{V}$ or $\bar{I}$ are real vectors containing the real and the imaginary parts of $V(k)$ or $I(k)$ for all harmonics k, $k = 0, 1, ..., H$. $\bar{Y}$ is a real matrix containing the real and the imaginary parts of $Y(k)$ for all harmonics k, $k = 0, 1, ..., H$.

BASICS OF THE HB TECHNIQUE

Let $\bar{I}_{LN}$ and $\bar{I}_{NL}$ represent the current into the linear and the nonlinear parts, respectively. The harmonic balance equation is

$$\bar{F}(\bar{V}) = \bar{I}_{LN} + \bar{I}_{NL} = 0 \tag{1}$$

A simple Newton's update for solving (1) is

$$\bar{V}_{new} = \bar{V}_{old} - \bar{J}^{-1}\bar{F}(\bar{V}_{old}) \tag{2}$$

where $\bar{J}$ is the Jacobian matrix.

GRADIENT ANALYSIS USING FAST

Suppose the output voltage $\bar{V}_{out}$ can be computed from $\bar{V}$ as

$$\bar{V}_{out} = \bar{e}^T\bar{V}. \tag{3}$$

The adjoint voltage $\hat{\bar{V}}$ is the solution of the linear equation

* J.W. Bandler and R.M. Biernacki are also with the Simulation Optimization Systems Research Laboratory and the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario, Canada L8S 4L7.

$$\overline{J}^T\hat{V} = \tilde{e}. \quad (4)$$

Suppose ϕ is a generic circuit design variable. For a given value of ϕ, we first solve the harmonic balance equation (1) to obtain the solution $\overline{V}_{solution}$, i.e.,

$$\overline{F}(\phi, \overline{V}_{solution}) = 0. \quad (5)$$

Then the approximate sensitivity of output voltage $\overline{V}_{out}$ w.r.t. variable ϕ can be computed as

$$\partial\overline{V}_{out}/\partial\phi = - \hat{\overline{V}}^T\overline{F}(\phi+\Delta\phi, \overline{V}_{solution})/\Delta\phi. \quad (6)$$

This formula is much easier to implement than our previously published EAST [5, 6]. The function $\overline{F}$ in (6) is evaluated by perturbation and can be readily implemented. The effort for solving the linear equations (4) is small since the LU factors of the Jacobian matrix are available from the final iteration of (2).

COMPARISON OF FAST WITH PAST

Suppose there are 10 design variables in the nonlinear circuit. Using PAST to calculate circuit sensitivities, one needs to perturb all design variables and to solve the entire nonlinear circuit for each perturbation, i.e., 10 times. The best possible situation for this approach is that all 10 simulations use the same Jacobian and all converge in one iteration.

Using FAST, we also need to perturb all variables. But instead of completely solving 10 nonlinear circuits, we only evaluate 10 error functions in the form of (1). The solution of adjoint equation (4) is accomplished in 2 forward/backward substitutions.

A detailed comparison reveals that FAST always requires less computation than that of the best possible situation of PAST. In our numerical experiment, FAST is 23 times faster than PAST.

Accuracy is a particularly important feature of FAST. In our numerical experiment, gradients from FAST are about 100 times more accurate than those from PAST. This means that HB optimization will be more robust by using FAST.

COMPARISON OF FAST WITH EAST

The generic EAST is accepted by all circuit theoreticians as the most powerful tool. However, to implement it, we have to keep track of all arbitrary locations of variables and to compute branch voltages at all these locations. This requirement, in general, is so involved that microwave software engineers virtually abandoned hope of generally implementing the EAST.

In FAST, we completely eliminate the need to track variable locations. We only need to identify the output port, which is the simplest step in adjoint sensitivity theory.

DISCUSSION ON STEP LENGTH

Like any numerical techniques, the performance of the FAST can be enhanced to deal with ill-conditioned or large scale problems. The choice of the step length $\Delta\phi$ may have a significant effect on accuracy. Suppose δ is the machine precision. The optimal step length should be approximately equal to the product of ϕ and the square root of δ.

FAST ANALYSIS OF A FET MIXER

Consider the mixer example used in [5, 6, 8]. Figs. 1 and 2 show the large-signal MESFET model and the DC characteristics of the device. The frequencies are f_{LO} = 11 GHz, f_{RF} = 12 GHz and f_{IF} = 1 GHz. The DC bias voltages are V_{GS} = -0.9 V and V_{DS} = 3.0 V. With LO power P_{LO} = 8 dBm and RF power P_{RF} = -15 dBm, the conversion gain is 6.9 dB. 26 variables are considered including all parameters in the linear as well as in the nonlinear part, DC bias, LO power, RF power, IF, LO and RF terminations. We use FAST theory to compute the sensitivities of the conversion gain w.r.t. all variables. The same sensitivities were also evaluated by the EAST and PAST. Excellent agreement between the three approaches is shown in Table I.

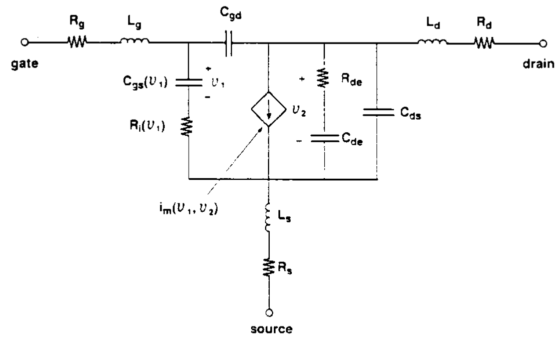

Fig. 1 A large-signal MESFET model used for the mixer example. All parameter values are consistent with [8].

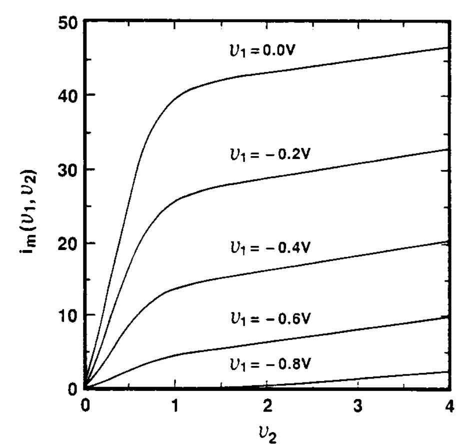

Fig. 2 The DC characteristics of the MESFET model in Fig. 1.

TABLE I

NUMERICAL VERIFICATION OF FAST FOR THE MIXER EXAMPLE

Var.	Sensitivity from FAST	Sensitivity from EAST	Sensitivity from PAST	Difference between FAST and EAST (%)	Difference between FAST and PAST (%)
linear subnetwork					
C_{ds}	-24.28082	-24.28081	-24.03669	0.00	1.01
C_{gd}	-32.16238	-32.16237	-32.33670	0.00	-0.54
C_{de}	-8.8×10^{-13}	1.7×10^{-13}	0	120.21	100.00
R_g	10.00754	10.00756	9.89609	-0.00	1.11
R_d	11.71325	11.71327	11.71338	-0.00	-0.00
R_s	-4.98829	-4.98827	-4.98861	0.00	-0.01
R_{de}	-0.07171	-0.07171	-0.07115	0.00	0.79
L_g	-0.30238	-0.30238	-0.30054	0.00	0.61
L_d	-0.87824	-0.87824	-0.87247	0.00	0.66
L_s	-0.33527	-0.33527	-0.33191	0.00	1.00
nonlinear subnetwork*					
C_{gs0}	-5.43110	-5.43110	-5.38265	0.00	0.89
τ	1.52983	1.52984	1.56057	-0.00	-2.01
V_ϕ	-20.84224	-20.84223	-20.84308	-0.00	-0.00
V_{p0}	-14.62206	-14.62206	-14.62469	0.00	-0.02
V_{dss}	0.30209	0.30209	0.30210	0.00	-0.00
I_{dsp}	9.39335	9.39335	9.39338	-0.00	-0.00
bias and driving sources					
V_{GS}	-4.94402	-4.94402	-4.94271	-0.00	0.03
V_{DS}	-0.67424	-0.67424	-0.67429	0.00	-0.01
P_{LO}	2.02886	2.02885	2.02882	0.00	0.00
P_{RF}	-0.09073	-0.09072	-0.09077	0.01	-0.05
terminations+					
$R_g(f_{LO})$	8.83598	8.83596	8.76244	0.00	0.83
$X_g(f_{LO})$	2.20500	2.20496	2.16567	0.00	1.78
$R_g(f_{RF})$	0.71282	0.71281	0.70568	0.00	1.00
$X_g(f_{RF})$	0.46410	0.46409	0.45702	0.00	1.53
$R_d(f_{IF})$	0.65950	0.65950	0.65272	-0.00	1.03
$X_d(f_{IF})$	0.09024	0.09024	0.09207	-0.00	-2.02

* Nonlinear elements are characterized by

$$C_{gs}(v_1) = C_{gs0} / \sqrt{1 - v_1/V_\phi} ,$$

$$R_i(v_1) C_{gs}(v_1) = \tau$$

and the function for $i_m(v_1, v_2)$ is shown in Fig. 2, whose mathematical expression is consistent with [8]. V_ϕ, V_{p0}, V_{dss} and I_{dsp} are parameters in the function $i_m(v_1, v_2)$.

\+ R and X represent the real and the imaginary parts of the terminating impedances, respectively. Subscripts g and d represent the gate and the drain terminations, respectively.

From Table I, we notice that the FAST sensitivities are almost identical to the exact sensitivities. But the PAST sensitivities are typically 1 to 2 percent different from their exact values. This fact reveals that the FAST is much more reliable than PAST.

The circuit was solved in 22 seconds on a VAX 8600. The CPU time for the FAST, the EAST and the PAST were 10.7, 3.7 and 240 seconds, respectively. FAST is 3 times slower than EAST but 23 times faster than PAST.

SIMPLE AND EFFICIENT APPROACH TO COMPUTATION OF JACOBIAN

Kundert and Sangiovanni-Vincentelli [1] and Rizzoli et al. [2, 3] have investigated exact Jacobians for accelerating the HB procedure. However, as observed by Rizzoli et al. [3], differentiating complicated or piecewise device equations may be very annoying from a programmer's view point. The perturbation (or incremental) approach is often used in practice.

Such difficulties associated with the exact Jacobians can be eliminated by extending the concept of FAST to the Jacobian calculation. We compute the time domain derivatives $\partial i^T(t)/\partial v(t)$ at the device level using perturbations. These derivatives are then converted to the frequency domain by a Fourier transform. The Jacobian matrix is then assembled from these Fourier coefficients using the formulas in [1, 3].

APPROXIMATE JACOBIAN FOR A FREQUENCY DOUBLER

We have used our Jacobian approach in solving the FET frequency doubler example from Microwave Harmonica [9]. The circuit consists of a common source FET with a lumped input matching network and a microstrip output matching and filtering section. The circuit diagram is shown in Fig. 3. The input frequency is 5GHz. The output is at 10GHz. Four harmonics are considered. We have also used the conventional perturbation approach to compute the Jacobian. The numerical results from the two approaches agree very well. The CPU time for our approach and the perturbation approach is .89 and 5.3 seconds, respectively, on Micro VAX II.

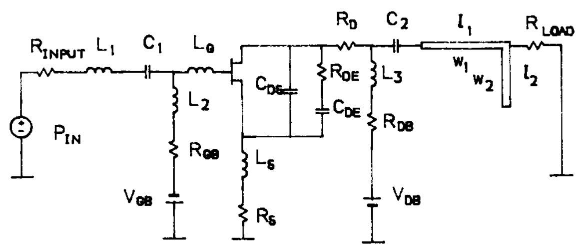

Fig. 3 The frequency doubler example [9] used for testing the Jacobian matrix.

CONCLUSIONS

Our FAST is an expedient tool for gradient calculation in the HB environment. The advantages of FAST over PAST are its unmatched speed and accuracy, and over the EAST is its implementational simplicity. FAST is directly compatible with established formulations of yield optimization. FAST is particularly suitable for implementation in general purpose microwave CAD software. We feel that FAST provides a key to the new generation of yield optimizers for MMICs.

The FAST technique is implemented in a new program called HarPE (Harmonic balance driven model Parameter Extractor) [7].

REFERENCES

[1] K.S. Kundert and A. Sangiovanni-Vincentelli, "Simulation of nonlinear circuits in the frequency domain", *IEEE Trans. Computer-Aided Design*, vol. CAD-5, 1986, pp. 521-535.

[2] V. Rizzoli and A. Neri, "State of the art and present trends in nonlinear microwave CAD techniques", *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-36, 1988, pp. 343-365.

[3] V. Rizzoli, C. Cecchetti, A. Lipparini and A. Neri, "User-oriented software package for the analysis and optimization of nonlinear microwave circuits", *IEE Proc.*, vol. 133, Pt. H, No. 5, 1986, pp. 385-391.

[4] V. Rizzoli, A. Lipparini and E. Marazzi, "A general-purpose program for nonlinear microwave circuit design", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, 1983, pp. 762-769.

[5] J.W. Bandler, Q.J. Zhang and R.M. Biernacki, "A unified framework for harmonic balance simulation and sensitivity analysis", *IEEE Int. Microwave Symp. Digest* (New York, NY), 1988, pp. 1041-1044.

[6] J.W. Bandler, Q.J. Zhang and R.M. Biernacki, "A unified theory for frequency domain simulation and sensitivity analysis of linear and nonlinear circuits", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-36, 1988, pp. 1661-1669.

[7] J.W. Bandler, Q.J. Zhang, S. Ye and S.H. Chen, "Efficient large-signal FET parameter extraction using harmonics", *IEEE Int. Microwave Symp.* (Long Beach, CA), June 1989.

[8] C. Camacho-Penalosa and C.S. Aitchison, "Analysis and design of MESFET gate mixers", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, 1987, pp. 643-652.

[9] *Microwave Harmonica User's Manual*, Compact Software Inc., Paterson, NJ 07504, 1987.