A New Circuit Envelope Simulation Technique for Analysis of Microwave Circuits

K. Berenji, A. Abdipour, and A. Mohammadi

***Abstract*—This paper proposes to use variable time steps in circuit envelope simulation. The circuit envelope is a general-purpose simulation technique for the transient and steady state analysis of microwave communication systems and circuits. When a microwave circuit is excited with a time variant envelope signal as digital modulated signal, circuit envelope simulation method may be used. In this paper a new technique is proposed to improve the efficiency of the circuit envelope simulation. Using this technique, a millimeter wave power amplifier is simulated and its results are presented. The evaluation of the results with the existing literature proves the accuracy and efficiency of the new technique.**

***Index Terms*—Circuit envelope, nonlinear circuit, harmonic balance, millimeter wave.**

I. Introduction

THE MODERN communication systems employ sophisticated digital modulations, such as QPSK, GMSK, and QAM, and to improve the spectral efficiency [1]. These modulated signals are wideband and time variant. The simulation results obtained by the frequency domain techniques are not sufficient to present all characteristics of these modulated signals and it is required to employ time domain methods [1], [2]. In the absence of the effective and general-purpose techniques that can conveniently handle transient and steady state analysis of nonlinear circuits for modulated carrier excitation, the circuit envelope (CE) provides reduction in simulation time, and the memory usage [3]-[5].

The circuit envelope method can be efficiently used to study a wide range of microwave and millimeter wave circuits, such as power amplifiers, PLLs, and oscillators. We try to increase the efficiency of CE method by using variable time-steps.

In this paper after presenting the circuit envelope method, we develop the idea of the variable time-steps method. Finally, we design and simulate a typical Ka band power amplifier based on this approach.

II. The Circuit Envelope Method

The CE method provides a middle solution between time and frequency domain methods [1], [2]. This method, which is developed on the basis of time dependent Fourier transforms, generally uses time domain techniques over frequency domain analysis [3], [6], [7].

Using complex variable concept, the fundamental signals and their envelopes are assumed complex and the time domain signals can be obtained from their real part.

If we consider a modulated signal, then the signal $x(t)$ in the circuit may be written as

$$x(t) = \mathrm{Re}\left(\sum_{k=0}^{k=K} \hat{x}_k(t) \cdot e^{jk\omega_0 t} \right) = X^T(t) \cdot \omega(t) \tag{1}$$

where

$$\hat{x}_k(t) = \frac{1}{2\pi} \int_{-BW/2}^{BW/2} \hat{x}_k(\Omega) \cdot e^{j\Omega t} d\Omega \tag{2}$$

$\hat{x}_k(t)$ is time variant complex envelope of the k-th harmonic of carrier frequency ω_0, BW is the largest bandwidth of the carrier frequency envelopes [5]-[8], and

$$\omega(t) = \begin{bmatrix} 1 & e^{j\omega_0 t} & \cdots & e^{jK\omega_0 t} \end{bmatrix}^T \tag{3}$$

where $\omega(t)$ is the Fourier basis vector and $\hat{x}_k(t)$ is the vector slow varying Fourier coefficients or the envelope components

$$X(t) = \begin{bmatrix} \hat{x}_0(t) & \ldots & \hat{x}_{K-1}(t) & \hat{x}_K(t) \end{bmatrix}. \tag{4}$$

Using a circuit consisting of sources, nonlinear RC, and linear RLC elements, the modified nodal analysis in a node, e.g., node m, leads to a nonlinear differential equations of the form

$$\frac{d}{dt} q_m(v(t)) + i_m(v(t)) + i_{m,L}(v(t)) + i_{s,m}(t) = 0 \tag{5}$$

where $v(t)$ is the vector of node voltages; $i_{s,m}$ is the vector of the source contributions; $i_{m,L}$ is the current vector of the linear part of the circuit i_m, and q_m define the contributions of nonlinear reactive and conductive elements, respectively.

A solution as $v(t) = V^T(t).\omega(t)$ is desirable, and it is assumed that all the signals in the circuit have the same form as $x_m(t) = X_m^T(V(t)).\omega(t)$.

When (5) is applied to each node, it forms a system of nonlinear differential equations, which is shown in the following matrix notation

$$\frac{d}{dt} Q(V(t)) + j\Omega_{new}^T \cdot Q + I(V(t)) + I_S(t) + I_L(V(t)) = 0 \tag{6}$$

where the dimension of current vector is $N(K+1)\times 1$ and Ω_{new} is defined as $diag(diag([0 \quad \omega \quad \cdots \quad K\omega]))$.

After sampling (6) at t_i moments, we have

$$\left. \frac{d}{dt} Q(V(t)) \right|_{t=t_i} + j\Omega_{new}^T \cdot Q + I(V_i) + I_S(t_i) + I_L(V_i) = 0 \tag{7}$$

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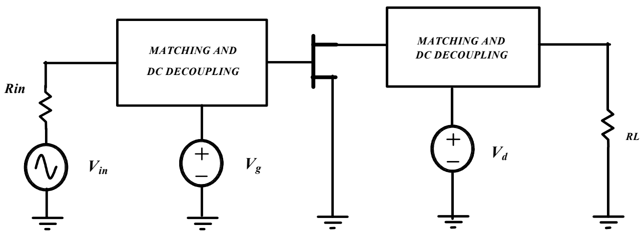

Fig. 1. Schematic of power amplifier.

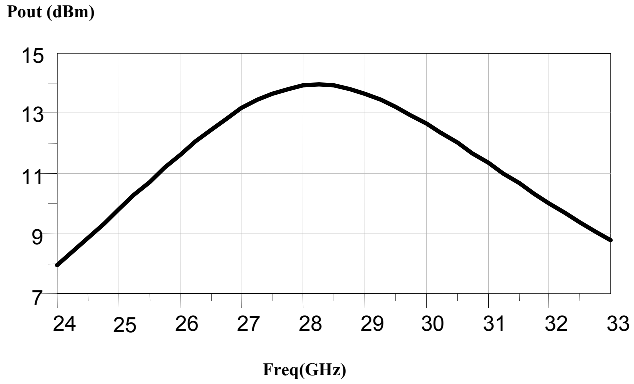

Fig. 2 Output power curve for one dBm single tone input in different frequencies traced by ADS2002.

where $V_i = V(i) = V(t_i) = V(i \cdot \Delta t)$.

Assuming that envelope variation is changing slowly, we may assume $Y(k\omega_0) \approx Y(k\omega_0 + \omega)$. Accordingly $I_L(V_i)$ term can be replaced from frequency domain relations [3], [4], [7]

$$I_L(V_i) = Y \cdot V_i \quad . \tag{8}$$

It is assumed for each t_i, the following approximation is valid [3]

$$\left.\frac{d}{dt}Q(V(t))\right|_{t=t_i} = \alpha_i Q(V(t_i)) + \beta_i \tag{9}$$

Using these assumptions, (8) is changed as follows

$$I(V_i) + \alpha_i Q(V_i) + j\Omega_{new} \cdot Q(V_i) + \beta_i + I_S(t_i) + Y \cdot V_i = 0 \tag{10}$$

Above vector equation is a system of harmonic balance equations, which can be solved for V_i at every time step t_i. In each envelope time step, a HB analysis must be carried out [2]. Using inherent advantage of the envelope approach, the time step spacing needs only to be small enough to resolve the envelopes around each.

III. Variable Time Steps

The idea of variable time steps is based on finding and removing unnecessary time-steps.

The idea may be presented as follow by recalling (6), (9)

$$\begin{aligned}\left.\frac{d}{dt}Q(V(t))\right|_{t=t_i} &= j\Omega^T_{new}Q(V(t_i)) + I(V_i) + \\ &I_S(t_i) + I_L(V_i) = 0\end{aligned} \tag{11}$$

$$\left.\frac{d}{dt}Q(V(t))\right|_{t=t_i} = \alpha_i Q(V(t_i)) + \beta_i \ . \tag{12}$$

Equation (12) can be revaluate as follow

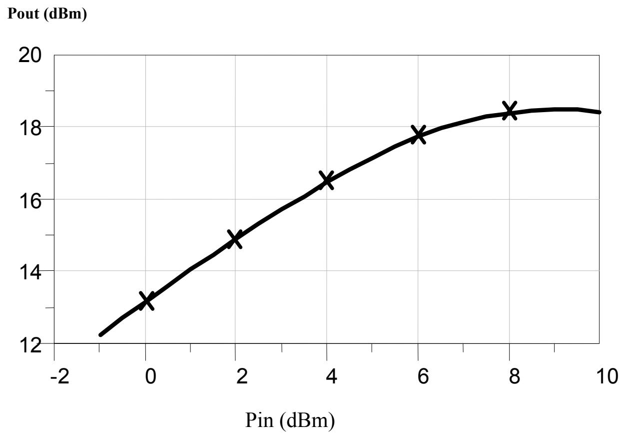

Fig. 3. Comparing compression gain curves obtained by authors' software (x) and ADS2002 simulation result (-).

$$\begin{aligned}&\left.\frac{d}{dt}Q(V(t))\right|_{t=t_i} = \frac{Q(t_i) - Q(t_{i-1})}{\Delta t}, \\ &\alpha_i = \frac{1}{\Delta t}, \ \beta_i = \frac{-Q(t_{i-1})}{\Delta t} \ .\end{aligned} \tag{13}$$

It can be seen that if $Q(t_i) = Q(t_{i-1})$ and $I_S(t_i) = I_S(t_{i-1})$ then (11) converts to a common Harmonic Balance (HB) equation.

In this case it is not required to solve the equation for i+1 step if $I_S(t_i) = I_S(t_{i+1})$. This means that we can assume Δt small enough to follow the input transient effects precisely and after ending transient effects, we can use a HB instead of many CE routines. The improvement in efficiency may be observed in some circuits more clear than others, e.g., PLLs transient responses can be efficiently observed using this technique.

IV. Power Amplifier Design

In this section a Ka band class A power amplifier with 13 dB gain, 18 dBm output power and bandwidth of 2 GHz is designed at 28 GHz center frequency. A Pseudomorphic InGaAs/AlGaAS/GaAs HEMT technology is selected due to its high cutoff frequency and high current density [8].

The schematic of power amplifier is illustrated in Fig. 1. In Fig. 2 the output curve is presented for the input of 0 dBm in different frequencies using ADS2002. The Fig. 3 compares the ADS2002 simulation results with the results of the authors' software.

V. Simulation Results

The circuit has been examined when excited by $\pi/4$ QPSK modulated signal at 28 GHz center frequency and 1 GHz bandwidth. For this purpose, we perform CE method for single transistor circuits. The circuit envelope simulation has been implemented for this scenario.

In the first step, the ADS2002 simulation results are compared with the results of the authors' software in Fig. 4. The results show that accuracy of authors' classical circuit envelope simulation routine.

In Fig. 5 the output envelope signals using classic CE and variable time-step CE are traced. As it is demonstrated, the these two methods result the same output envelope signals.

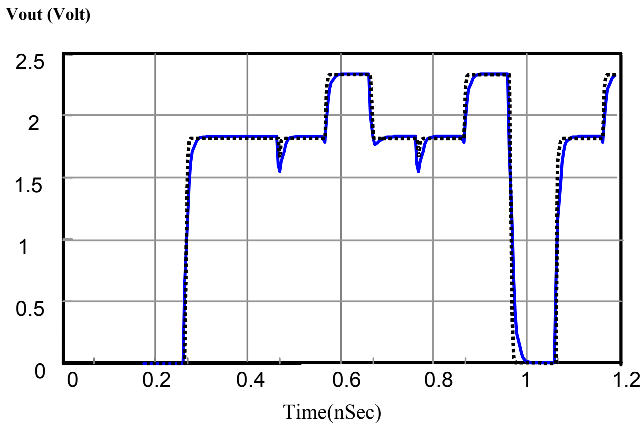

Fig. 4. Output envelope signals obtained by ADS2002 (-) and current software (…) using ordinary CE.

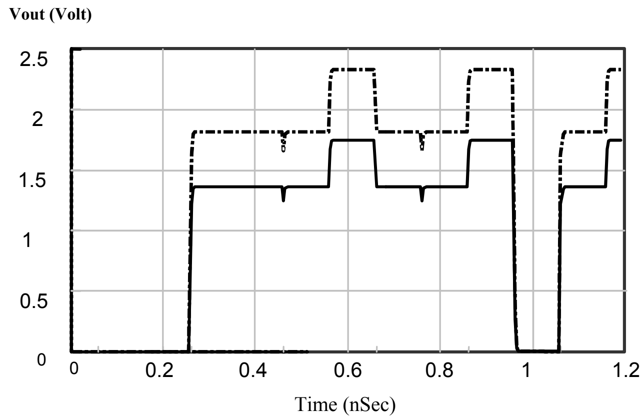

Fig. 5. Output envelope signals obtained by current software using ordinary CE (- and scaled 0.75) and improved CE (-.-).

TABLE I
SIMULATION TIME AND STEPS OF CE AND VARIABLE TIME-STEP CE

Simulation time		Main Calculation Accomplished	
CE	Improved CE	CE	Improved CE
269.28sec	42.3 sec	34909	4941

Comparing the simulation time and steps, it can be seen that employing variable time steps improve the simulation time. It should be noted that this improvement depends on the input signal. Table I presents the simulation time and steps of these two.

VI. CONCLUSIONS

A new CE method, using variable time steps, has been presented. This method can improve the simulation efficiency by eliminating unnecessary time steps. As mentioned, the improvement depends on how the time step has been selected, and the kind of input signal that applied. From the simulation results, it can be seen that the presented method can be effectively used in simulating circuits and systems in which small duration transient response is important but most of the time the circuit or the system are working in their steady state conditions.

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REFERENCES

[1] H. S. Yap, *Designing to Digital Wireless Specifications Using Circuit Envelope Simulation*, HP EEsof Division, Hewlett-Packard, 1996.

[2] K. Kundert and A. Sangiovanni-Vincentelli, "Simulation of nonlinear circuits in the frequency domain," *IEEE Trans. on Computer-Aided Design*, vol. 5, no. 10, pp. 521-535, Oct. 1986.

[3] D. Sharrit, "New method of analysis of communication systems," *MTTS'96 WMFA: Nonlinear CAD Workshop*, Jun. 1996.

[4] E. Ngoya and R. Larcheveque, "Envelop transient analysis: a new method for the transient and steady state analysis of microwave communication circuit and system," *IEEE MTT Symposium Digest*, vol. 3, pp. 1365-1368, 1996.

[5] P. Feldmann and J. Roychowdhury, "Computation of circuit waveform envelopes using an efficient, matrix-decomposed harmonic balance algorithm," in *Proc. ICCAD,* pp. 295-300, Nov. 1996,

[6] M. K. Siddiqui, A. K. Sharma, L. G. Callejo, and R. Lai, " A High-power and high-efficiency monolithic power amplifier at 28 GHz for LMDS applications," *IEEE Trans. Microwave Theory and Techniques*, vol. 46, no. 12, pp. 2226-2232, 1998.

[7] S. A. Maas, *Nonlinear Microwave and RF Circuits*, Norwood, M. A: Artech House, 2003.

[8] V. Borich, J. East, and G. Haddad, "Computer-Aided optimization of adjacent channel power in nonlinear communications amplifiers," in *International Microwave Symposium Digest,* vol. 1, pp. 441-444, 2000.

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