SIMULATION AND DESIGN OF MICROWAVE CLASS-C AMPLIFIERS THROUGH HARMONIC ANALYSIS +

F. Filicori, V.A. Monaco

Istituto di Elettronica
Università di Bologna
Viale Risorgimento 2
Bologna, Italy

C. Naldi

Istituto di Elettronica e Telecomunicazioni
Politecnico di Torino
Corso Duca degli Abruzzi 24
Torino, Italy

ABSTRACT

Microwave class-C amplifier analysis is performed by solving a non-linear system whose unknowns are the harmonic components of the wave variables at the ports connecting the linear and non-linear parts of the amplifier. An application example is given.

Introduction

In microwave class-C amplifiers the voltage and current waveforms at the transistor terminals and the load have to be determined both to completely characterize the amplifier behaviour and to obtain useful elements for the design. The existing general purpose analysis programs, which operate through time domain integration of the non-linear differential equations throughout the transient interval, require a very great computing effort and they are therefore of no practical use, especially when they must be called as subroutines by optimization programs for CAD. To overcome this drawback two methods have recently been proposed, the shooting method [1,2] and the harmonic balance technique [3], which, even if requiring less computing effort, do not completely satisfy the requirements since they present some difficulties in convergence to the solution and some restrictions on circuit composition.

The method described in this paper satisfies the requirements of a wide application field, and, at the same time, operates with a fast running time and without convergence problems. It is based on the partitioning of the circuit into linear and non-linear subnetworks for which, respectively, frequency domain and time domain equations are written. Then, taking into account that the linear and non-linear subnetworks are interconnected and that the time domain and frequency domain representations are related by the Fourier series, the circuit behaviour can be described by means of a system of non-linear equations whose unknowns are the harmonic components of the incident waves at all the connections.

The periodic steady-state analysis of the non-linear amplifier is thus reduced to the search for the solution of this system of equations from which all the other electrical variables and network functions can easily be determined.

Problems arising in the numerical solution are overcome by a specially designed step-by-step procedure. The results of the analysis of a microwave class-C transistor amplifier are given.

Description of the Method

In microwave class-C amplifiers the non-linearities are confined to the active device while all the remaining elements, such as the case parasitics and the matching network components, are linear and constitute the larger part of the circuit. Therefore, in order to take advantage of the easiness of the frequency domain analysis of linear circuits, the amplifier is partitioned into linear and non-linear subcircuits for which, respectively, frequency domain and time domain equations can be written.

In particular, for the non-linear subnetwork, the voltages and currents at the N connections are assumed as variables and they must satisfy the system of N non-linear equations

$$F_j\left[\mathbf{v}, \frac{d\mathbf{v}}{dt} \ldots \frac{d^s\mathbf{v}}{dt^s}\,;\ \mathbf{i}, \frac{d\mathbf{i}}{dt}, \ldots \frac{d^r\mathbf{i}}{dt^r}\right] = 0 \qquad (1)$$

for $j = 1, 2, \ldots, N$
and $\forall t,\ 0 < t < T$

where T is the period of the circuit response and $\mathbf{v} = \mathbf{v}(t)$, $\mathbf{i} = \mathbf{i}(t)$ are the column vectors of the voltages and currents at the N connections.

The linear subcircuit, on the other hand, is described in terms of wave variables in order to take advantage of the existence property of the scattering matrix for any circuit composition. Thus, for every harmonic k, the linear circuit behaviour is described by the system of linear equations

$$\mathbf{b}_k = \mathbf{S}_k\ \mathbf{a}_k + \boldsymbol{\gamma}_k \qquad \text{for } k = 0, 1, \ldots, M \quad (2)$$

where $\mathbf{S}_k$ is the scattering matrix at the k^{th} harmonic and $\mathbf{a}_k$, $\mathbf{b}_k$ and $\boldsymbol{\gamma}_k$ the column vectors of incident, reflected and impressed waves at the N connections. In terms of these wave variables the voltages and currents at the same connections are given by

$$\begin{aligned} \mathbf{V}_k &= (\mathbf{a}_k + \mathbf{b}_k)\sqrt{R_0}\,, \\ \mathbf{I}_k &= (\mathbf{a}_k - \mathbf{b}_k)/\sqrt{R_0} \end{aligned} \qquad \text{for } k = 0, 1, \ldots, M \quad (3)$$

Moreover, owing to the interconnection of the linear and non-linear subnetworks and the periodicity of the circuit response, the time domain and frequency domain representations are related by the Fourier series

$$\frac{d^\eta}{dt^\eta} v_\lambda(t) = \sum_{k=0}^{M} R_e\left[V_{\lambda k}\left(jk\frac{2\pi}{T}\right)^\eta e^{jk\frac{2\pi}{T}t}\right] \qquad (4)$$

for $\lambda = 1, 2, \ldots N$
$\eta = 0, 1, \ldots s$

$v_\lambda(t)$ being the λ^{th} term of the column vector $\mathbf{v} = \mathbf{v}(t)$, s the maximum order of its time derivatives in eqns. (1) and M the maximum number of harmonics.

Thus, by taking into account eqns. (4) and the analogous relations which hold for the currents, together with eqns. (2) and (3), eqns. (1) can be expressed as the system of equations:

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$$g_i(\mathbf{a}_0, \mathbf{a}_1, \ldots, \mathbf{a}_M, t) = g_i(\mathbf{a}, t) = 0 \quad \text{for } i = 1, 2, \ldots N \text{ and } \forall t,\ 0 \leq t < T \tag{5}$$

whose solution gives the column vector $\mathbf{a}$ of the unknowns, composed of all the vectors $\mathbf{a}_0, \mathbf{a}_1, \mathbf{a}_2, \cdots \mathbf{a}_M$ of the incident wave harmonic components at the N connections.

Since also the functions (5) are periodic with period T, they can be expressed by the Fourier series:

$$g_i(\mathbf{a}, t) = \sum_{k=0}^{M_g} R_e \left[G_{ik}(\mathbf{a})\, e^{jk\frac{2\pi}{T}t} \right] = 0 \quad \text{for } i = 1, 2, \ldots N \text{ and } \forall t,\ 0 \leq t < T \tag{6}$$

whose harmonics $G_{ik}(\mathbf{a})$ can be computed by the fast Fourier transform algorithm, M_g being the maximum order of harmonics necessary to approximate the functions (6). Letting $M_g = M$, i.e. supposing that each function $g_i(\mathbf{a}, t)$ can be approximated by a Fourier series with a number of harmonics equal to that considered for the wave variables at the connections between the linear and non-linear subnetworks, the system of non-linear time-dependent equations (6) can be transformed into the system

$$G_{ik}(\mathbf{a}_0, \mathbf{a}_1, \ldots, \mathbf{a}_M) = 0 \quad \text{for } i = 1, 2, \ldots N \text{ and } k = 0, 1, \ldots M \tag{7}$$

which consists of N(M + 1) non-linear, time-independent equations with an equal number of unknowns, which are the M + 1 harmonics of the incident waves at the N connections. The periodic steady-state analysis of the amplifier is thus reduced to the search for the unknowns in system (7), in terms of which all the electrical variables and network functions can be determined.

In comparison with the harmonic balance technique this method has some advantages. One of these is that it can also deal with non-linear components or subnetworks described only by equations in implicit form and, therefore, does not impose any restrictions on the kind of non-linearities in the circuit to be analyzed, nor does it require an excessive partitioning of the non-linear part of the circuit with consequent reduction in the number of variables. Moreover, the adoption of wave variables as unknowns allows for the description of the linear subnetworks by scattering matrices, whose existence is guaranteed for any circuit composition and whose elements can either be computed by frequency domain linear analysis programs [4] or directly measured using a network analyzer.

Numerical Solution

The solution of the system of equations (7) can be sought by the well-known iterative techniques, such as the Newton-Raphson method, which exhibit fast convergence only if the non-linearities involved are not too strong and the starting point is well-chosen. Therefore, when dealing with junction diodes or bipolar transistors, whose models contain a current vs. voltage exponential dependence, a special strategy is needed to overcome convergence or overflow problems arising from this kind of non-linearities.

To this aim a special step-by-step procedure has been designed. In fact, instead of directly solving the system of non-linear equations (7), whose solution may be rather hard, the problem is transformed into the search for the solution of a sequence of well-conditioned systems corresponding to a sequence of well-chosen circuits obtained from the original one through progressive changes of some parameters. The solution of the last system, corresponding to the last circuit of the sequence which is made identical to the given circuit, represents the required solution.

For the class-C amplifier the parameter changed is the input power in such a way that, starting from zero, it is increased until the nominal value is reached. If, at every step, the input power increment is well-chosen so that the circuit non-linearities are involved gradually, it becomes easy to find the solution of the corresponding system (7). The input power increment is automatically adjusted by an algorithm which reduces it when there is a convergence failure or else increases it when the last few steps show very fast convergence. It should be noted that this strategy, while ensuring a fast and reliable convergence to the solution, also gives a set of useful intermediate results which characterize the amplifier behaviour with respect to the input power variations.

Moreover, since the number of harmonics strongly affects the computing time, it must be kept as small as possible. Thus, this parameter is also adjusted by the analysis algorithm which, starting from a small initial value, increases it whenever in the iterative procedure the approximation accuracy becomes inadequate.

An Application Example

On the basis of the above-described problem formulation and numerical techniques, a computer program performing the steady-state analysis of class-C transistor amplifiers has been written. Using this program the microwave transistor amplifier shown in figure 1, implemented on microstrip and operating with a centre band frequency of 1.6 GHz, has been analyzed. The transistor is of the MSC 3000 type and has been modelled with the equivalent circuit proposed by the Plessey Company[5] and shown in figure 2. The computed waveforms of the voltages and currents at some nodes and branches of the amplifier are shown in figure 3.

The steady-state analysis of the amplifier required 14 steps to increase the input power from 1% to 100% of its nominal value. However, as at every step the search for the solution is very fast (an average of four iterations of the Newton-Raphson algorithm), a total number of only 58 computations of circuit equations (7) were necessary.

The analysis program has also been used to compute the transistor large signal S-parameters and their dependence on the input power[6]. This computation, besides allowing for the transistor model validation through comparison of the measured and computed parameters, is also a useful tool for the amplifier design[7,8]. In fact, a first tentative design, performed by large signal S-parameters, can be a good starting point for an optimization procedure using the periodic steady-state analysis program.

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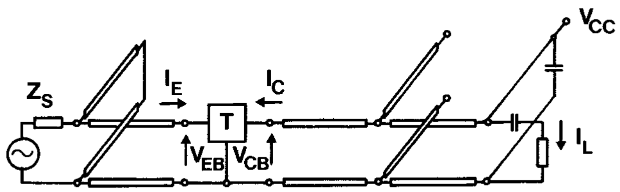

Figure 1: The analyzed microwave class-C transistor amplifier.

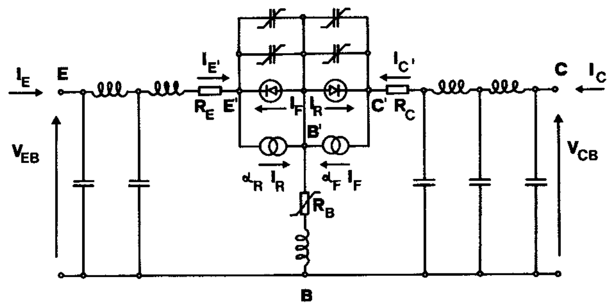

Figure 2: The equivalent circuit of the transistor Type MSC 3000.

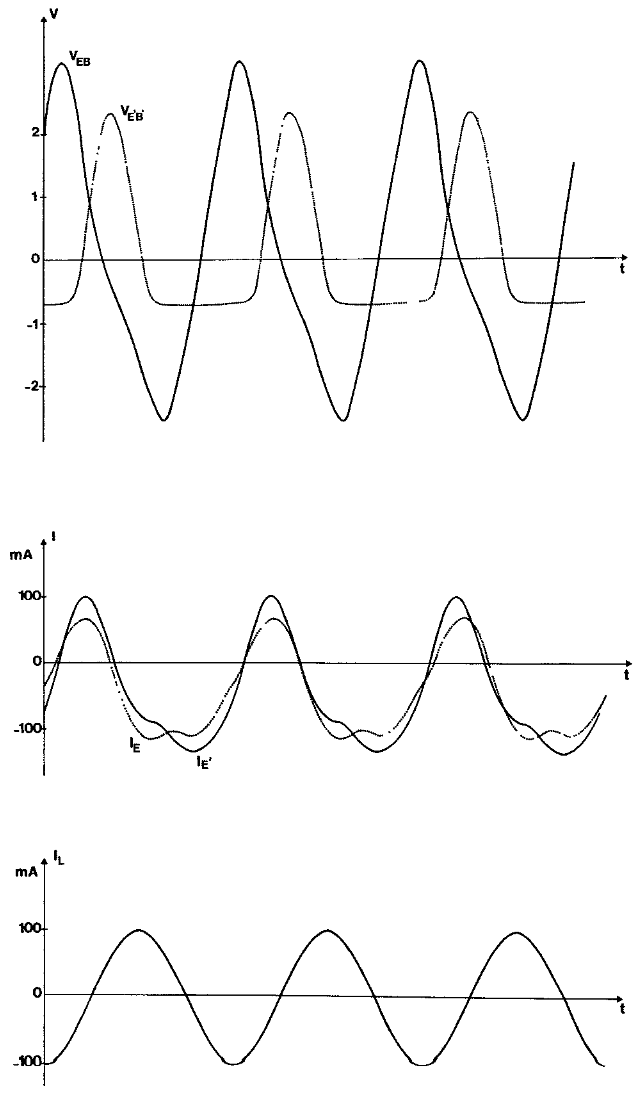

Figure 3: The computed waveforms in the class-C transistor amplifier:

a) the emitter to base voltages V_{EB} and $V_{E'B'}$

b) the emitter currents I_E and $I_{E'}$

c) the current I_L in the load Z_L