IMPORTANCE AND RELEVANCE OF THE SCIENTIFIC CONTENT

State of the art

A nonlinear circuit is described by a set of first degree nonlinear differential equations and nonlinear algebraic equations [1]. *The time domain circuit analysis* consists in solving circuit equations using a numerical method which starts from a specific initial state. With this kind of analysis the transient response or the steady state response of a nonlinear circuit can be computed [1]. Numerical methods used in time domain circuit analysis are: backward Euler, trapezoidal rule, 2-nd to 6-th order Gear methods; all these methods were developed for equations in normal form $\dot{x} = f(x,t)$, implying the elimination of all circuit variables which are not independent state variables. Because this elimination implies an important computation effort and the result may be affected by errors, companion models are used [2]. These models are equivalent circuits of all dynamic elements, for a specific numerical method. Since, for a higher efficiency, the numerical methods uses a variable time step, all companion models parameters must be recomputed at every time step. In the mathematical literature, time step is chosen in relation to the local truncation error (LTE). This kind of time choice algorithm is used by the time domain SPICE family simulators (SPICE2, PSPICE, SPICE3 and SPECTRE) [3]. In these simulators LTE is evaluated for every state variable of the circuit and is compared with an imposed error $\varepsilon = abstol + reltol\, x_k$, where *abstol* is the imposed absolute error, *reltol* is the imposed relative error and x_k is the k-th state variable. The time step is accepted only if $LTE \le \varepsilon$ for all x_k. Another known time step choice algorithm is described in [4] and was implemented in PAN simulator [5]. The difference between these algorithms is the fact that instead of LTE computation for all state variables, an energetic error is computed for all dynamic elements – the difference between the accumulated energy and the numerically computed absorbed energy by each element during the computed time step; next, the algorithm is similar, starting from the imposed values for *abstol* and *reltol*. This algorithm works much better than the first one, allowing the computation time reduction with an order of magnitude [4, 6]. *In this project a new time step choice algorithm is proposed based on a global energetic error (corresponding to the whole circuit)*, which is different from the algorithm in [4] in which other energetic errors are computed for every state variable.

Consider an RF signal with a bandwidth of 1 KHz-10 MHz and assume that the least common multiple of the spectral component frequencies is 10 MHz. Assuming that 100 samples/period are necessary for an accurate representation of this signal, we need $100 \times 10^4 = 10^6$ time steps to sweep an excitation period. The basic idea of the envelope following (EF) algorithms is to jump over some carrier periods diminishing the number of time steps. There are two known EF algorithms: the algorithm of Kundert [7] implemented in SPECTRE RF and the algorithm of Brambilla [8] implemented in PAN. The efficiency of these envelope following algorithms has been proved to be poor in many cases (in comparison with the usual transient analysis) [7] mainly due to the following reasons:

- The time step of the envelope following analyses is smaller than that of the transient analysis both for SPECTRE RF and PAN, the main reason being that the solution computation in each interval corresponding to a possible jump is considered as a new transient analysis with a drastic time step reduction at its beginning. Moreover, this time step reduction is performed even though the jump is not actually made. By this way it can be explained why an EF analysis with no jump consumes much more time than a TRAN analysis in the same time interval.
- The jump procedure of PAN (which is worse than the jump procedure of SPECTRE RF) as well as the transient analysis procedure of SPECTRE RF (which is worse than the TRAN procedure of PAN) slow down the computation speed.

Doing computations similar to the EF, the multiple time scale analysis [10, 11, 12] may be faster due to the fact that the jump on the slow time axis is established apriori, without checking the error done with its computation. A fast computation of an initial guess may be very useful in some cases [13]. *A new EF algorithm*, avoiding these drawbacks *will be proposed in this project.*

The simplest *frequency domain circuit analysis* is the AC analysis which can be used only for linear circuits. The most known method of nonlinear circuit analysis having as main unknowns the complex amplitudes of the signal harmonic components is harmonic balance (HB). HB assumes the circuit is split into a linear part and a nonlinear part, the linear part being solved in the frequency domain while the nonlinear part is solved in the time domain. Using Discrete Fourier Transform for the correspondence between the time domain and the frequency domain, an error function is minimized using Newton-Raphson iterations. Adopting a truncated spectrum to represent periodic solutions implies that solutions must be "smooth" and must have a limited number of harmonics. In turn this impacts on the nonlinear nature of the circuit to be simulated that must be weakly or mildly nonlinear. A large equation system must be solved if the number of harmonic components increases, leading to numerical errors and a prohibitive CPU time; this drawback can be partially released using Krylov subspace solvers [14]. Even with this feature, HB analysis implemented in commercial simulators APLAC and ADS can deliver unsatisfactory results for simple circuits as amplitude demodulators. *A new method of frequency domain analysis of circuits with resistive nonlinearities is proposed in this project.* The HB analysis of a medium size circuit gives accurate results if the number of harmonic components does not exceed 256. For digitally modulated signals this representation can not lead to an accurate estimation of the modulation spectrum around the fundamental or the adjacent channel interference. This difficulty can be overcome by the Fourier envelope method [15] which considers the signals represented as a Fourier series with time-varying coefficients $V_k(t)$ modulating the carriers with the frequencies f_k. The Fourier envelope analysis relies on HB analysis, a HB computation being performed at each time step. The carrier frequencies f_k are user-defined, each of them being considered as the center frequency of a spectrum of *1/Time step* width; of course these spectra cannot intersect each other, this being usually the case in RF circuits.

Both the literature and the numerical experiments made by the project team agree that HB and Fourier envelope are the most efficient methods to compute the periodic response in a circuit with weak or mild nonlinearities leading to a moderate number of harmonic components. For circuits with strong nonlinearities time domain methods must be used for computation of the periodic response, the simulation time being frequently huge. This time may be shortened using shooting methods, as shooting with Newton-Raphson implemented as the PSS analysis of SPECTRE RF.

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