Combined Non-Linear and Linearized Envelope Following Circuit Analysis Method

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Abstract* – By analyzing current circuit analysis techniques, like shooting method, envelope following and linearization, this paper proposes a new method in the field called Combined Non-linear and Linearized Envelope Following (CNL-EF). *CNL-EF uses two envelope following analyses along with linearization of the small signals and superposition of small and large signals. To run it and compare to other circuit analysis methods, it was used Python with the numpy, scipy and matplotlib libraries. Relative to a standard Envelope Following (EF), it shows a mean square error (MSE) of 0.00015 V². Finally, it is discussed its limitations compared to other methods, showing how it is an small compromise option if one wishes to apply linear analysis techniques to a given circuit.

***Keywords*: linearization; circuit analysis; envelope following.**

I. Introduction

The development of computer simulation techniques was fundamental to the current state of the art in electronics. Moreover, in the telecommunications field they are imperative, as high frequencies are the cause of many caveats which need to be taken into consideration when designing an electrical circuit. For instance, noise, power transfer, passband etc. Having that in mind, developing models capable of handling all these aspects is very important, but it is not always possible to cover all of them. One of the limitations is computational power. Therefore, it is necessary to find the optimal balance between detailing the circuit and CPU usage.

Currently, there are two branches to circuit simulation: large signals analysis methods and envelope methods. The former is used when a circuit only has periodic stimuli, for example the Shooting Method (SM). The latter is used when a circuit has non-periodic stimuli. Usually, the signals present in such circuits are composed of a carrier with frequency on the order of GHz modulated with a complex envelope with a bandwidth in the MHz range. An example of these methods is the Envelope Following (EF), which is based on the shooting method [1].

This article proposes a solution to simulation of non-periodic circuits similar to [2]. Their method is a linearization of the response of the Circuit Envelope (CE) method and uses superposition to combine the lower and higher amplitudes. It focuses more on frequency response. This paper concentrates on temporal analysis methods.

First, we analyze some current methods for circuit simulation. For large signal analysis, we describe the SM. And for envelope analysis, we look onto EF. Then, we describe the proposed method. And finally, we compare the results to existent methods.

II. Current Analysis Methods

A. Shooting Method (SM)

This method consists of guessing the initial conditions of a system until they are coherent with steady state. In order to do so, in each iteration of a transient analysis, the initial and final values of the state variables are compared. The process continues until the initial and final values are equal, according to the following equation [3]:

$$v(T) - v(0) = 0, \qquad (1)$$

where v is a state variable and T is one period.

Because this method is applied only to periodic signals, it is not necessary to simulate more than one period of the system. So, the following instants in time are just a copy of this simulated period. This decreases the needed computational power.

The diagram in Figure 1 shows how the SM works.

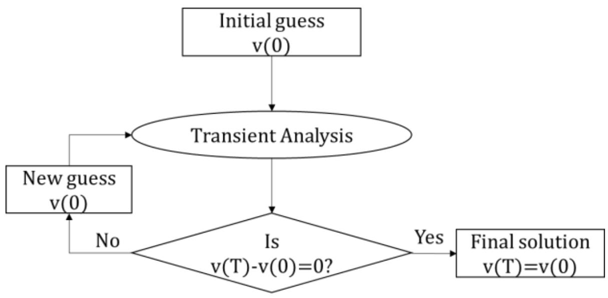

Figure 1 – Shooting Method diagram.

The first step is an initial guess to the state variables which is fed into a transient analysis. After that, the initial values are compared to the final ones – that is, the value of the state variables after one period. If the results are different, a new transient analysis is ran using the final values found in the previous simulation as initial guesses. As said above, the cycle continues until the steady state is met.

B. Envelope Following (EF)

This method is based on the shooting method. A transient analysis is ran for a single period. The next periods are filled with the results from this first analysis. After a determined number of periods, a new analysis is ran and the subsequent periods follow the new results. In other words, the circuit is only simulated after several periods has passed and the in-betweens are filled with the results from their respective previous transient analysis.

This causes a doubling in the state variables compared to the shooting method but allows the simulation of circuits that are not so periodic, for instance, high frequency circuits stimulated by digitally modulated signals. The equations used for this method are shown below [4]:

$$v(t) = v(t-T), \tag{2}$$

$$v(t) - v(t-p) = c \cdot \big(v(t) - v(t-T)\big), \tag{3}$$

where v is a state variable, t is time, p is the amount of time for one step in the transient analysis, T is one period and c is the number of periods between each transient analysis.

Summarizing the method, we get the diagram in Figure 2.

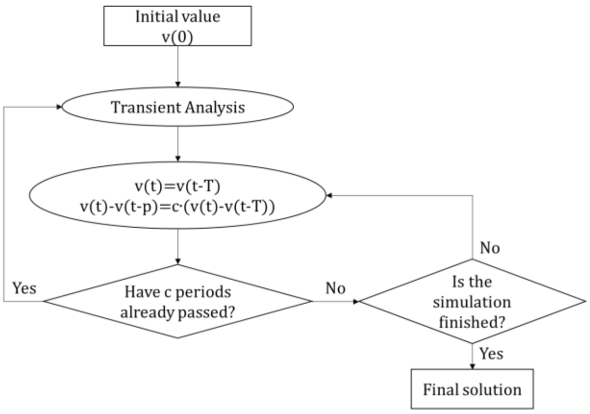

Figure 2 – Envelope following diagram.

As shown, the method takes an initial value and runs a transient analysis for one period. Then, it calculates the values for the state variables using the equations (2) and (3). After, it checks whether c periods have passed, if not, it continues filling the state variables in the next instants of time with the values from the previous transient analysis. Otherwise, it runs a new one. It finishes once the stablished final instant of time is met.

III. Proposed method – Combined Non-Linear and Linearized Envelope Following (CNL-EF)

This paper proposes a method which simulates both large signals and small signals of a circuit, the Combined Non-Linear and Linearized Envelope Following. It does so by running an envelope following analyses for each of them. Also, the small signals are linearized and the large ones are not.

To linearize the small signal component, all non-linear dependent sources are subjected to the equations:

$$f_{lin}(t) = g_m(t) \cdot v(t), \tag{4}$$

$$g_m(t) = \frac{d}{dv} f(v), \tag{5}$$

where f is the non-linear function of the dependent source, f_{lin} is the linearized function of f, v is the circuit variable which the source is dependent on, and g_m is a dynamic variable given by (5).

In the transient analysis, f is then substituted by f_{lin}. The diagram in Figure 3 shows how it works.

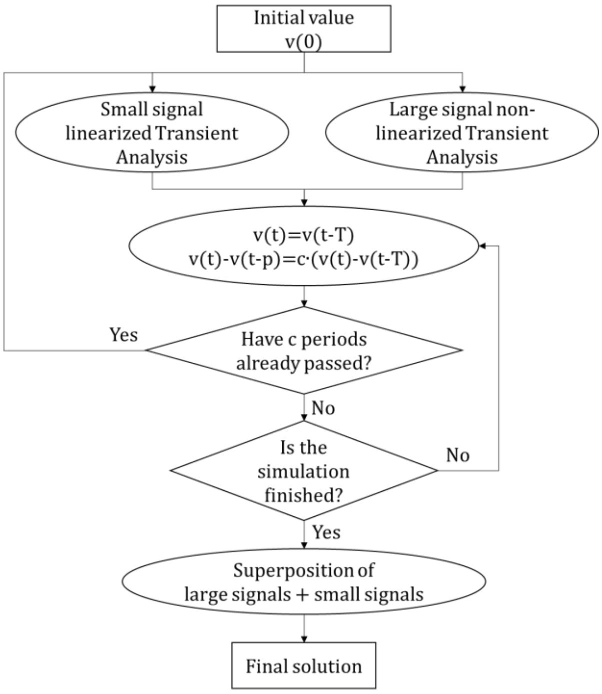

Figure 3 – Proposed method diagram.

So first, it takes initial values for the state variables and runs two transient analyses. The small signal one uses f_{lin} for the dependent sources in the circuit, meanwhile the large signal one does not. They then run through an envelope following method using the equations (2) and (3). After both envelope following methods are complete, the superposition theorem is used, and the signals are added together.

One of the limitations of this method is that it can only be applied if small signals are valid for the independent sources in the linearized circuit. This is because the linearization step does not work for large signals.

IV. Results

The test circuit in Figure 4 was used to validate CNL-EF.

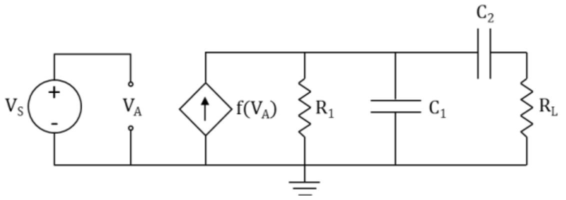

Figure 4 – Test circuit schematic.

In Figure 4 V_s is an independent voltage source, f is a current source dependent on V_A, $R_1 = 1$ kΩ, $R_L = 50$ Ω, $C_1 = 10$ pF and $C_2 = 1$ µF. The equation for f is given by (6) and is the same used by [5]:

$$f(V_A) = \frac{I_{sat} \cdot sign(V_A)}{\left(1 + \left(\frac{V_{sat}}{|V_A|}\right)^s\right)^{\frac{1}{s}}}, \quad (6)$$

where I_{sat}, V_{sat} and s are constants equal to 0.1 A, 1.8 V and 5, respectively.

The independent voltage source V_s is composed by a large signal component of 1 GHz and a small signal component of 2 GHz. Each of them is a combination of a sine and a cosine wave and their amplitudes very in time.

All the simulations were made using Python 3.9.0 with the help of the libraries numpy, scipy and matplotlib. For the solution of the non-linear equations, the function fsolve from numpy was used. Also, in the equation (3) the time step p was chosen to be 10 ps (which respects the Nyquist criterion) and c was set to 10.

For comparison, a second simulation was ran using a single envelope following and without linearizing the small signal component. The results are shown in Figure 5 below, where VL represents the voltage across the load resistance RL.

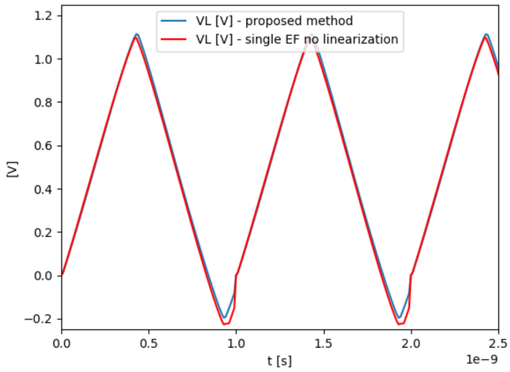

Figure 5 – Comparison between proposed method and single EF with no linearization.

In further analysis, the mean square error (MSE) was calculated in respect to the single EF with no linearization. A value of 0.00015 V^2 was found.

As said before, this method only works if small signals are valid for all independent sources present in the circuit. In the previous results, small signals had an amplitude 4 times smaller than that of large signals. The graph in Figure 6 shows the same simulation, only using small signals which are 1.25 times larger than large signals.

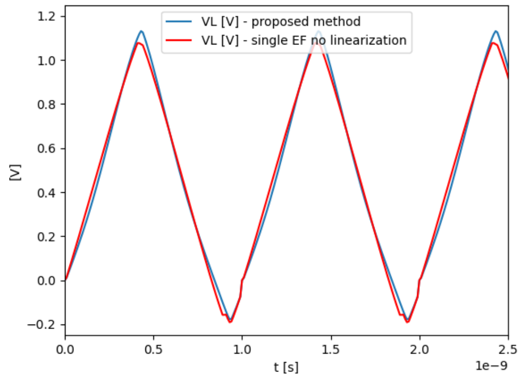

Figure 6 – Waveforms with small signals 1.25 times larger than large signals.

As a result of the linearization, it can be seen by Figure 6 that the proposed method becomes farfetched if small signals are not valid for the independent sources. The MSE obtained for this case was 0.00099 V^2.

V. Conclusion

The proposed method accomplishes the said objective to simulate non-periodic circuit responses. By testing it under different conditions, it was shown how the linearization applied is bound to small signals only. Also, CNL-EF can accurately reproduce results from other circuit analysis methods (such as EF) in the specified conditions with an MSE of 0.00015 V^2 and the benefit of being capable of applying linear analysis techniques.

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