GENETIC ALGORITHM TECHNIQUES FOR THE DESIGN OF NONLINEAR MICROWAVE CIRCUITS

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Abstract

Steady state analysis of nonlinear circuits represents the most computational challenging problem in RF/Microwave circuit design. Even though all circuits are assumes as a linear circuits in circuit theory, in fact it is nonlinear circuit. The problem in designing and analyzing the nonlinear circuits usually more complicated than for linear circuits. Many approaches have been done to overcome this problem. Recently hybrid method of analyzing nonlinear circuits has proved to be popular. In this report a hybrid method of Sample Balance Genetic Algorithm (SBGA) used to analyze nonlinear diode excited by RF circuit. The purpose of this report is to minimizing the current difference between nonlinear current which across the nonlinear element and linear current at linear element and voltage across the nonlinear terminal. By using Sample Balance's differential of current linear and nonlinear equation as an objective function, a Genetic Algorithm routine then been constructed. Genetic Algorithm will then recombine, mutate and evaluate the population of solution to find the best solution based on Sample balance equation. This hybrid method manages to get 0.013A of error current and a sinusoidal waveform clipped at 0.7V during first half of the waveform for the nonlinear voltage.

List of Contents

	Page No.
List of Figures	iv
List of Graphs	v
1 Introduction	
1.1 Introduction	1
1.2 Objectives	1
1.3 Structures of Report	2
2 Nonlinear Microwave Circuit Analysis And Genetic Algorithms	
2.1 Nonlinear Microwave Circuits	
2.1.1 Introduction	3
2.1.2 Linearity And Nonlinearity	4
2.1.3 Nonlinear Circuit Elements	5
2.1.3.1 Nonlinear Resistive Elements	5
2.1.3.2 Nonlinear Capacitive Elements	6
2.1.3.3 Nonlinear Inductance	6
2.1.4 Frequency Generation	7
2.1.5 Numerical And Human Requirements For Device Models	10
2.2 Genetic Algorithms	
2.2.1 Introduction	10
2.2.2 Types of Evolutionary Algorithms	11
3 Sample Balance Analysis Of A Simple Nonlinear Circuit	
3.1 Introduction	13
3.2 Advantages of Sample Balance Analysis	13
3.3 Introduction to Sample Balance Analysis	14
3.4 Single-Tone Harmonic-Balance Analysis	
3.4.1 Circuit Partitioning	18
3.4.2 The Linear Subcircuit	19

Page No

3.4.3 The Nonlinear Subcircuit 20
3.5 Process in Sample Balance Genetic Algorithms 23
3.6 Methodology 23
3.7 Objective Function Code: ObjError.m 27

4 Genetic Algorithms
4.1 Introduction 29
4.2 Advantages of Genetic Algorithm Used in Sample Balance or Harmonic Balance Analysis. 29
4.3 Outline of the Algorithm 30
4.4 Crossover
4.4.1 Single-Point Crossover 33
4.4.2 Multi-Point Crossover 34
4.4.3 Uniform Crossover 35
4.4.4 Masked Crossover 35
4.5 Mutation 36
4.6 Methodology 38
4.7 Sample Balance Genetic Algorithm Code: diodeSBGA.m 40
4.8 Results and Discussions
4.8.1 Error Current and Output Voltage for Sample Balance Genetic Algorithm (SBGA) Analysis 43
4.8.2 Time Performance 45
4.8.3 Error Current and Output Voltage for Harmonic Balance Genetic Algorithm (HBGA) Analysis 48

5 Conclusion
5.1 Conclusion 50
5.2 Suggestion for Future Study 50

Acknowledgement 51
References 52

List of Figures

Title of Figure	Page No
Figure 2.1: Two-Terminal Nonlinear Resistor Circuit	7
Figure 2.2: Simple Nonlinear Circuit	9
Figure 3.1: A Simple DC-biased Diode	14
Figure 3.2: A Diode Excited by an RF Circuit	15
Figure 3.3: Equivalent Circuit for Linear Part	16
Figure 3.4: Equivalent Circuit for Nonlinear Part	16
Figure 3.5: A Nonlinear Microwave Circuit	18
Figure 3.6: Diode Circuit	24
Figure 3.7: Diode Circuit Consist of an Ideal Diode and Linear Embedding Network.	25
Figure 4.1: Selection, Evaluation and Recombination Process	32
Figure 4.2: Single-Point Crossover	33
Figure 4.3: Multi-Point Crossover	34
Figure 4.4: Uniform Crossover	35
Figure 4.5: Masked Crossover	36
Figure 4.6: Mutation	37

List of Graphs

Title of Graph **Page No.**

Graph 4.1: Reduction of Objective Function (Error Current) 42

Graph 4.2: The Input and Output Voltage Waveform versus Time Sample 43

Graph 4.3: Error Current Waveform Over One Period (t = 40) 44

Graph 4.4: Reduction of Objective Function ($\log_{10}E$) 45

Graph 4.5: Comparison Chart for Different Number of Individual (Number of Generation = 2000) 46

Graph 4.6: Comparison Chart for Different Number of Generation (Number of Individual = 40) 46

Graph 4.7: Comparison Chart for Single-Point, Double-Point and Shuffle-Point (Number of Generation = 2000) 47

Graph 4.8: Reduction of Objective Function (Error Current) for Harmonic Balance Genetic Algorithm. 48

Graph 4.9: The Input and Output Voltage Waveform versus Time Sample for Harmonic Balance Genetic Algorithm. 49

CHAPTER 1: Introduction

1.1 Introduction

Wireless technology has been growing tremendously, with new application reported almost everyday. Besides the traditional application in communication such as radio and television, RF and microwaves are being used in cordless phones, cellular communication, Local Area Networks (LANs), Personal Communication Systems (PCSs). Keyless door entry, radio frequency identification (RFID), monitoring of patients in the hospital and a nursing home, and cordless mice or keyboards for computers are some of the areas where RF technology being employed. The current rate of growth in RF technology is expected to continue in the foreseeable future.

1.2 Objective

Steady state analysis of nonlinear circuits represents the most computational challenging problem in RF/microwave circuit design. Even though all circuits are assumes as a linear circuit in circuit theory, it is actually nonlinear circuit [1]. In some circuit, sometimes only a weakly nonlinear exist in the circuit, but the usage are still the same or similar to linear circuit. And due to the nonlinearity characteristic exist in the circuit, this characteristic able to degrade the systems performance, thus this circumstances should be minimize.

The problem of designing and analyzing the nonlinear circuits usually more complicated than for linear circuits. Many approaches have been done to overcome this problem. And recently hybrid method of analyzing the nonlinear circuits, in which the linear element were analyzed in frequency domain while the nonlinearities analyzed in time domain [1] were proved to be popular. The Harmonic Balance has extensively developed [2,3,4] by many researchers relies on the use of Fourier Transform techniques while Sample Balance, which was receive less attention than Harmonic Balance use convolution approaches [5,6]. The main difference between both techniques lies in the interface between the frequency domain and time domain. In those researches, these techniques has been used together with Genetic Algorithm as hybrid methods and popularly known as Harmonic Balance Genetic Algorithms (HBGA) and Sample Balance Genetic Algorithms (SBGA).

The aim of this project are to find the voltage across the terminals of the nonlinear device and minimizing the current difference between nonlinear current which across the nonlinear element and linear current at linear part. This can be achieved by inverse Fourier transformed the Harmonic Balance equation (the Harmonic Balance equation can be found in chapter 3) into time domain, and optimized in Genetic Algorithms by using Genetic Algorithms Toolbox in Matlab [7].

1.3 Structure of Report

This report started with an introduction chapter. The objective and the structure of the project also clearly stated in this chapter.

General explanation about nonlinear microwave circuit, nonlinear circuit elements, frequency generation and others will be given in the next chapter. Introductions to the Genetic Algorithm and types of this genetic algorithm also consist in this chapter.

The third chapter explained about nonlinear microwave circuits by using Sample Balance analysis, which is based from Harmonic Balance equations. An explanation on how the equation can be used as an objective function can be found in this chapter. And the last part of this chapter is my script file of objective function.

Then in the following chapter, more details about Genetic Algorithm were explained. Main operators that involve in Genetic Algorithm process also clarified in this division. It pursues with methodology and script file for the genetic algorithm with Sample Balance as its objective function, and follows by results and discussions of the output.

The report finally concluded in the end of the report together with the suggestion for the future work.

CHAPTER 2: Nonlinear Microwave Circuits And Genetic Algorithms

2.1 Nonlinear Microwave Circuits

2.1.1 Introduction

Very high demands in short wavelength radio systems (and later radar) have caused many developments in microwave electronics. By refer to Microwave Electronic Devices book [8], written by Theo G. Van De Roer, the first experiment have been done by Heinrich Hertz in the year 1887 was the pioneer in microwave history. During this experiment, Hertz had produced a signal in a wide frequency band by using spark transmitter. He then selected from these a band at around 420MHz with an antenna that measured half a wavelength at this frequency. The receiver antenna was chose at the same dimension as transmitter antenna. Besides, Hertz has used a parabolic mirror and lenses of dielectric material in his experiment.

Six years later, in the year 1893 Lord Kelvin gave a theoretical analysis of hollow waveguide. Followed shortly by Oliver Lodge by demonstrated waveguides at the frequencies 1.5 to 4 GHz. An impressive result by Marconi in long distance communication had caused development in radio moved towards to the very large wavelength. This result seen too impressive firstly because with these greater distance could be bridged and secondly because at low frequencies it was easier to generate narrow band (sinusoidal) signals.

In the 1930s, a new interest arose for ultrashort waves, mainly because of the development in radio detection and ranging, or its acronym; radar. The first radars used wavelengths of a few meters but it was realized from the start that shorter wavelengths would yield better directivity of the radar beam as well as stronger reflections from small objects such as airplanes. The imminent threat of new wars in Europe and East Asia made it all the more urgent to develop the short wavelength field.

2.1.2 Linearity And Nonlinearity.

All electronics circuits are nonlinear. It is includes the passive components such as resistors, capacitors and inductors. These passive components expected to be linear under all conditions, but actually are nonlinear in the extremes of their operating ranges [1]. For example, heating will changes the resistances of the resistor when a large voltages or currents applied onto it. Capacitors also exhibit nonlinearity especially those made of semiconductor materials. Even RF connectors found to generate intermodulation distortion at high power level that caused by the nonlinear resistance of the contacts between dissimilar metals in their construction.

Linear circuits are defines as those for which are superposition principle holds. Particularly, when excitations x_1 and x_2 are applied separately to the circuit, the responses are y_1 and y_2 respectively. Thus the output for $ax_1 + bx_2$ are $ay_1 + by_2$ where a and b are arbitrarily constants and this constant may be real or complex, time-invariant or time varying. This criterion can be applied to either circuits or systems.

Indirectly, the time-invariant circuits' response only includes those frequencies present in the excitation waveforms. So in this way, linear, time-invariant circuits do not generate new frequencies. As nonlinear circuits usually generate a remarkably large number of new frequency components. This criterion provides an important dividing line between linear and nonlinear circuits.

Nonlinear circuits are often characterized as either weakly nonlinear or strongly nonlinear. Weakly nonlinear can be defined by a Taylor series expansion of its nonlinear current/voltage (I/V), charge/voltage (Q/V) or flux/current (ϕ/I) characteristic around some bias current or voltage. This definition entails that the characteristic's described is continuous, has continuous derivatives, and also does not require more than a few terms in its Taylor series. Assumptions that the nonlinearities and RF drive are weak enough, until it won't perturb the dc operating point.

Another concept in nonlinear circuits is quasilinearity, two-terminal nonlinearities and transfer nonlinearities. A quasilinear circuit's means the circuits can be treated for most purposes as a linear circuit although it may include weak nonlinearities. The effect of the nonlinearities are weak enough, thus the response on the linear circuits is negligible. But it does not mean the nonlinearities are neglected, other type of problem still can occur due to the nonlinearities.

The other two concepts are known as two-terminal nonlinearities and transfer nonlinearities. Two-terminal nonlinearity defines as a simple nonlinear resistor, capacitor or inductor. The value is a function of one independent variable, the voltage or current at its terminals. For transfer nonlinearity, it defined as a nonlinear controlled source. The control voltage or current is somewhere in the circuit other than the element's terminals. It is possible for a circuit element to have more than one control, which is usually the terminal of voltage or current. Thus many nonlinear elements must be treated as combinations of transfer and two-terminal nonlinearities.

2.1.3 Nonlinear Circuit Elements

The nonlinear device models considered in equivalent circuits normally consist of resistors, capacitors and controlled source, and rarely where the nonlinear circuit consist nonlinear inductor. These circuits element can be described by its characteristics; the large-signal, global characteristic or by an incremental, small-signal characteristic.

For the large-signal case, the circuit element is effectively treated as a 'black box' having the prescribed I/V or Q/V characteristic, while in the small signal case, it is a linear or nonlinear small-signal resistor, capacitor or controlled source having a resistance, capacitance or small-signal current that is a function of a dc control voltage. Voltage control, current control and incremental quantities are three concepts critical to the modeling of nonlinear solid-state device. A voltage-controlled element is dependent upon a voltage that either may be applied to its terminal or may exist elsewhere. The element's value must be a single valued function of the control voltage. Conversely, a current-controlled element is one whose value is a single-valued function of a current.

2.1.3.1 Nonlinear Resistive Elements

There are large-signal nonlinear resistive elements and small-signal nonlinear resistive elements contain in resistive elements. For a large-signal nonlinear resistive element, a controlled source or two-terminal can be described either by;

$I = f_v(V_1, V_2, \ldots)$ →2.1

or

$V = f_I(I_1, I_2, \ldots)$ →2.2

The equation (2.2) known as a current-controlled element. Anyway this equation is rarely used due to most microwave devices are best described as voltage-controlled current sources.

For a small-signal nonlinear resistive element, it described by the I/V characteristic $I = f(V)$. It is assumed that it has a dc control voltage V_o, which in practice could be a bias voltage, and a small-signal ac voltage v(t).

2.1.3.2 Nonlinear Capacitance Elements

For a large-signal nonlinear capacitor, the charge, Q_c is described by;

$Q_c = f_Q(V_1, V_2, \ldots)$ →2.3

and for simple nonlinear capacitor, we have

$I = C(V)\frac{dV}{dt}$ →2.4

where the incremental capacitance, $C(V) = \frac{\partial f_Q}{\partial V}$

The C(V) in above equation then will be measured if the nonlinear element were biased at dc voltage, V and a small ac voltage were applied to it.

Then for a small-signal nonlinear capacitance, the component of the charge is

$i = C_1(V_0)\frac{dV}{dt}$ →2.5

where $C_1(V) = \frac{d}{dV} f_Q(V)\Big|_{V=V_0}$ which is also equal to incremental capacitance as given above.

2.1.3.3 Nonlinear Inductance

A nonlinear inductance is shown below by its flux-current characteristic,

$\Phi = F_\Phi(I)$ →2.6

where Φ = magnetic flux

2.1.4 Frequency Generation

A system or circuit is said to be linear if and only if it satisfies the principle of superposition [9]. This principle stated that if input A produce output B and input C produces output D, the principle of superposition holds if input A+C produces output B+D

A —Produce→ B

C —Produce→ D

A + C —Produce→ B + D

If the principle of superposition applies, the system is linear.
So in this case;

$$F[\alpha x_1(t)+\beta x_2(t)] = \alpha F[x_1(t)] + \beta F[x_2(t)]$$

where α and β are real numbers.
If any system does not fit to the equation above, it is said to be nonlinear.
To see how the frequency generated, we will describe by using two-terminal nonlinear circuit.

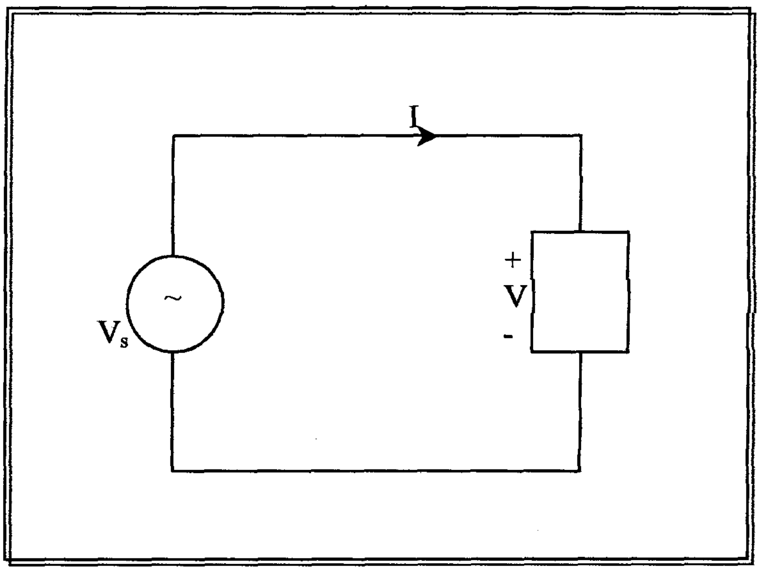

Figure 2.1: Two-terminal Nonlinear Resistor Circuit

Figure 2.1 in previous page shows a circuit with excitation voltage V_s produces current I. This circuit consists of two-terminal nonlinearity. By assuming α, β and γ are constant and real coefficient, and V_s is a two-tone excitation, we get;

The current equation;

$$I = \alpha V + \beta V^2 + \gamma V^3 \qquad \rightarrow 2.7$$

And the voltage equation;

$$V = V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t) \qquad \rightarrow 2.8$$

By substituting equation (2.8) into (2.7), we get;

$$I = \alpha(V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t)) + \beta(V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t))^2 + \gamma(V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t))^3 \qquad \rightarrow 2.9$$

By using Trigonometric Identities, equation (2.9) is equals to below equation.

$$\begin{aligned} I = &\frac{V_1^3}{4}(3\cos(\omega_1 t) + \cos(3\omega_1 t)) + \frac{V_2^3}{4}(3\cos(\omega_2 t) + \cos(3\omega_2 t)) \\ &+ \frac{3}{4}V_1 V_2^2[\cos(\omega_1 - 2\omega_2)t + \cos(\omega_1 + 2\omega_2)t + 2\cos(\omega_1 t)] \\ &+ \frac{3}{4}V_1^2 V_2[\cos(\omega_2 - 2\omega_1)t + \cos(\omega_2 + 2\omega_1)t + 2\cos(\omega_2 t)] \end{aligned} \qquad \rightarrow 2.10$$

From the equation (2.10), it is clear that several new frequencies are generated. For V^2, it able to produce four new frequencies which is $2\omega_1$, $2\omega_2$, ω_1-ω_2 and ω_1+ω_2, while for V^3 more new frequencies were produced. Obviously, each successive term in (2.7) generate more new frequencies than the previous one. In this case, V^2 produce four new frequencies and V^3 produce six new frequencies, which is higher than V^2. If a fourth and fifth-degree nonlinearity included, the number of a new frequency would be greater.

When the two-terminal nonlinear resistor connected in a circuit to build a simple nonlinear circuit, the situation becomes more complex in order to figure out the frequency generated.

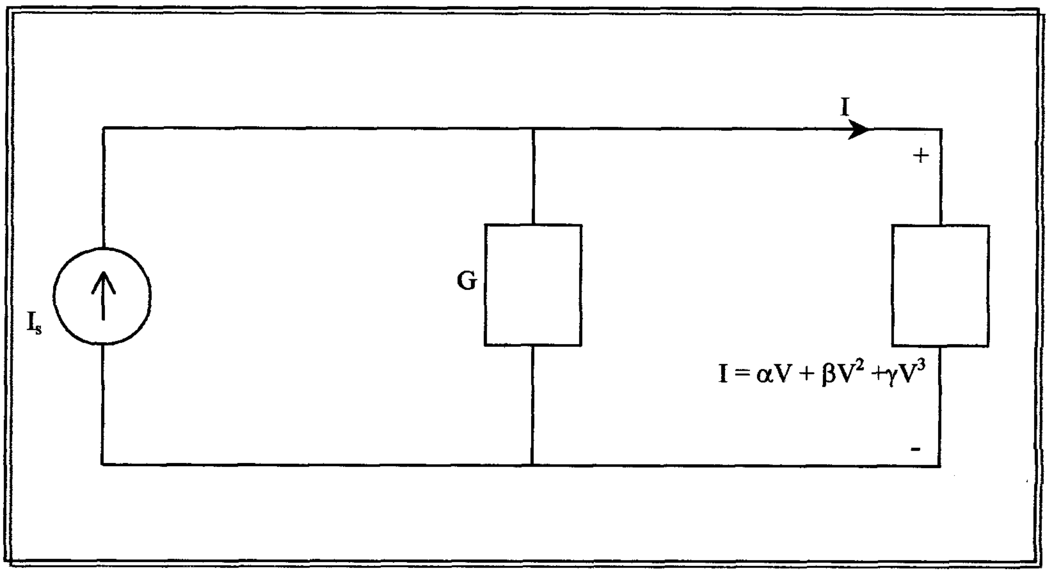

Figure 2.2: Simple Nonlinear Circuit

From the figure above, it creates;

$$I_s = GV + I$$ →2.11

Substituting equation (2.7) into (2.11), we get;

$$I_s = GV + \alpha V + \beta V^2 + \gamma V^3$$ →2.12

Assume G = 1, α = 2, β = 3 and γ = 4.

So;

$$I_s = 1V + 2V + 3V^2 + 4V^3$$

$$= 3V + 3V^2 + 4V^3$$ →2.13

If I_s has the frequencies ω_1 and ω_2, the voltage V will contain all frequencies having the form $n\omega_1 + m\omega_2$ with n and m integers. It clearly shows that a simple nonlinear circuit as that of Figure 2 able to produce an infinite number of frequency.

2.1.5 Numerical And Human Requirements For Device Models

In order to design such a perfect device models, or at least nearly perfect models, it should satisfy requirements imposed by limitation of both simulators and human beings. This is due to the designated models are used in circuit simulators and the operated by human beings. This section will consider some of necessary requirement that suit both simulators and human beings.

i. Continuous derivatives in I/V or Q/V expression

   If this requirement is not satisfied, convergence robustness is degraded.

ii. Accuracy of derivative

   For example: even order derivatives are necessary for dc quantities, which are necessary for accurate calculations of efficiency.

iii. Range of expression

   The I/V function must be well-behaved for outside of the range of voltages and currents that the devices experiences in practice. Harmonic Balance analysis is an iterative method, and it is common during intermediate iterations, for extraordinarily large or small voltages to exist.

iv. Limiting the range of voltage control

   It is necessary to limit the range of control voltages and it must be applied in a numerically acceptable way.

v. Use of polynomials

Mostly used to model difficult I/V or Q/V expression. Simply by increasing the degree of polynomial, the failed process run smoothly.

There are more requirements rather than written above, such as error trapping, lucidity of models and parameters, default of parameters, loops of control voltage and many more.

2.2 Genetic Algorithms

2.2.1 Introduction

In 1859, Charles Darwin published a controversial book, which is popularly known as *The Origin of Species*. In his book he suggested that a species is repetitively developing and his controversial theory implying that man came from ape. Darwin noticed during his exploration that almost all organisms have a huge potential for the production of offspring. He also observed that within a

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