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Simulation of Non-autonomous Chaotic Circuit on LABVIEW Using Nonlinear Electrolytic Device

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Abstract: In the present communication we report simulation results of chaotic circuits designed by using NLED (Non Linear Electrolytic Device) as the nonlinear element. The circuits are simulated on LABVIEW virtual instrumentation software. Program in created in LABVIEW which solves the steady state equations defining the circuits. The front panel of the program traces the attractors between voltages at two points in the circuit. We observe that the attractors obtained on the x-y graph on the front panel of simulation program, are due to chaos in the circuit. It is concluded that nonlinear impedance of electrolytic cell can act the nonlinear element of the chaotic circuit. It is proposed from the above study that electrolytes, which are the prime constituents of biomass, can excite the chaos phenomenon in nature.

Keywords: Chaos, Electronic Chaotic Circuit, Nonlinear Electrolytic Device, LABVIEW software.

1. INTRODUCTION

Most of the Electrical and Electronic applications are on Linear Circuit Elements; nonlinearity is considered alien and creates distortion and spurious signals. Recent advancements in nonlinearity and chaos open a new field of research. Several phenomenons occurring in nature are mostly nonlinear and chaotic. Research in this field promises to reveal the mysteries of nature.

Chaos is a phenomenon that occurs widely in nonlinear dynamical systems. It may be described as a bounded, periodic, noise-like oscillation; a deterministic system appears to behave randomly and is highly sensitive to initial conditions. The theory of chaos has developed over the past 20 years or so [1], largely in the context of mathematical physics, and has only recently begun to filter through to engineering.

Dr. Chua has designed a simple electronic chaotic circuit and he says that it must contain at least one non-linear element besides capacitor and inductor [2]. The nonlinear elements frequently used for implementing a chaotic circuit is a Chua's diode which is based an op-amp. Prof. Muthuswamy has simulated the nonlinear memristor-based chaotic circuit on MATLAB [3]. Chaotic circuits have also been implemented using hysteresis property [4] of nonlinear elements.

Electrolytes are commonly used in cells and batteries as portable electrochemical power source. Electrolytes are also used in electrolytic capacitors. Recently, super capacitors have been designed which use solid electrolytes. Other field of application of electrolytes can be chaotic circuits operating at very low frequency by using Nonlinear Electrolytic Devices.

In our work, we used NLED (Nonlinear Electrolytic Device) [5] as nonlinear element and simulated a non-autonomous chaotic circuit on LABVIEW Virtual Instrumentation Software. Our circuit is different from conventional electronic chaotic circuit in the respect that

1. It is a non-autonomous circuit and is excited by a dc voltage source.
2. It contains the NLED as non-linear resistor.

We have applied the test of chaotic process as described in next section, to our circuits by observation of graphs. The mathematical test by calculation of largest Lyapunov's exponent can be applied on the recorded data for further confirmation of chaotic phenomenon.

2. THEORY OF CHAOS AND CHAOTIC CIRCUIT

Chaos theory [6] is a field of study in mathematics, physics, and philosophy studying the behavior of dynamical systems that are highly sensitive to initial conditions. This sensitivity is popularly referred to as the butterfly effect. Small differences in initial conditions (such as those due to rounding errors in numerical computation) yield widely diverging outcomes for chaotic systems, rendering long-term prediction impossible in general. This happens even though these systems are deterministic, meaning that their future dynamics are fully determined by their initial conditions, with no random elements involved. In other words, the deterministic nature of these systems does not make them predictable. This behavior is known as chaos.

Chaotic behavior [7] has been observed in the laboratory in a variety of systems including electrical circuits, lasers, oscillating chemical reactions, fluid dynamics, and mechanical and magneto-mechanical devices. Observations of chaotic behavior in nature include the dynamics of weather, satellites in the solar system, the time evolution of the magnetic field of celestial bodies, population growth in ecology, the dynamics of the action potentials in neurons, and molecular vibrations. In everyday language, the words chaos and random [8] are used interchangeably. However chaotic sequences are in fact generated deterministically from dynamical systems. This implies that if two orbits are created from identical initial data, then the orbits are same. Two successive realization of a random process will give different orbits, even if the initial conditions are same.Although there is no universally accepted mathematical definition of chaos, a commonly-used definition says that, for a dynamical system to be classified as chaotic, it must satisfy following conditions [9]

1. It must be sensitive to initial conditions, meaning that the trajectories of attractor must be varying exponentially when the initial conditions are varied.
2. It must be topologically mixing, meaning that the trajectories must show topological transition or there must be smooth transition of orbits.
3. Its periodic orbits must be dense, meaning that the trajectories must be very close to each other.

An autonomous (means self-driven) electronic chaotic circuit made from standard components (resistors, capacitors, inductors) proposed by Dr. Chua [10] must satisfy three criteria before it can display chaotic behavior. It must contain: (1) One or more nonlinear elements (2) One or more locally active resistors (3). Three or more energy-storage elements. Chua's canonical chaotic circuit was made from one resistor, two capacitors, one inductor and one nonlinear resistor and is the simplest electronic circuit meeting these criteria.

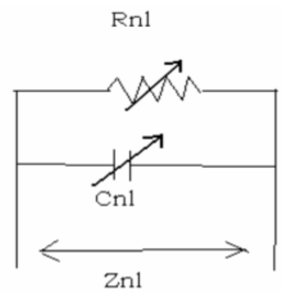
A non-autonomous chaotic system has been described in [11] by ordinary differential equations of at least second order for chaotic phenomenon to be possible. K. Murali [12] *et. al* have demonstrated by computer simulation that a second order circuit made from a capacitor, an inductor, a resistor and Chua's diode(for nonlinear element) driven by sinusoidal voltage source, exhibit chaos.

3. THEORY OF ELECTROLYTIC NONLINEAR DEVICE

We have worked on acetic acid under condition of high concentration to investigate its electrical properties, and reported [5] that the NLED (two-terminal Nonlinear Electrolytic Devices) exhibits nonlinear impedance when a very low frequency ac signal is applied across its terminals. This typical NLED is designed from a solution of 50% (by volume) acetic acid in deionized water at 25ºC. Two probes of copper of diameter 1mm and length 5mm immersed into the solution and kept 5mm apart serve as terminals of NLED.

Upon application of low potential (-2.0 volts to +2.0 volts) a very small current flows through NLED manifesting a very high impedance state (150-50-kΩ). When applied potential increases just above breakdown voltage (-+ 2.0 volts), ions break the bond due to applied electric field and become free to carry charge. Therefore, capacitance reduces and conductance increases. Higher above breakdown voltage, capacitive reactance becomes negligible and impedance becomes constant (approx. 0.5-10 kΩ). The NLED becomes linear resistor in this region. . In this region the acetic acid solution exhibits predicted behavior of weak electrolyte.

Based on above theory, an equivalent circuit for NLED is proposed in fig 1a, the reactance Z_{nl} consists of a parallel combination of a variable capacitance C_{nl} and variable resistance R_{nl}. It may be noted that above characteristic of nonlinearity and hysteresis is exhibited in sub hertz frequency .Above peculiar behavior may be attributed to the dynamic ion–solvent correlations and the cross velocity correlations of the conductivity at finite frequencies and high concentration solution [13].



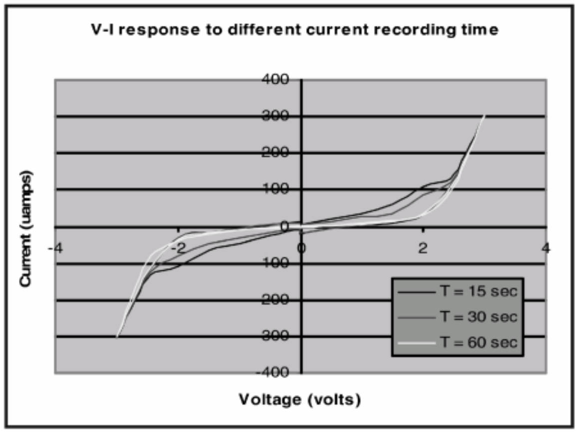


Figure 1a: Equivalent Circuit of NLED at 2.66 mHz between +2.5 to -2.5 Volts (Figure 1b) V-I Curve Across NLED for One Cycle of Applied Voltage (-3 Volts to +3 Volts)

4. DESIGN OF CHAOTIC CIRCUIT USING R, C, L AND NONLINEAR COMPONENT Z_N

Three circuits are designed using passive components C1, C2, L, R1, R2 and nonlinear component Z_N and are driven by dc excitation V_{in}, which are the control parameters. In the present study, we carried out the experiment for different sets of control parameters for three different circuits.

The heart of the chaotic circuit, the nonlinear element Z_N, is the NLED whose voltage-current characteristic is depicted in Figure 1b. The operating point is chosen at 2.25 volts. We observe that the impedance is dynamic in this region. For simplifying the simulation, we neglect the reactive component due to capacitance from the impedance of NLED. We assume that the impedance of NLED is resistive and is equal to 500Ω when the voltage V_Z across its terminals is above 2.29 v or below -2.29 v and 5kΩ when voltage is between +2.29 v to -2.29 v. Thus, the mathematical model of our nonlinear device is a three-segment piecewise linear model and can be expressed by following equation: $Z_N = f(V_Z)$

$$
\begin{aligned}
Z_N(V_Z) &= 500\Omega \text{ for } V_Z \geq 2.29\,; \\
&= 5000\Omega \text{ for } 2.29 < V_Z < 2.29; \\
&= 500\Omega \text{ for } V_Z \leq -2.29;
\end{aligned}
$$

Circuit 1: The circuit uses R_1, R_2, C_1, C_2 and Z_N connected as shown in Figure 2 and is represented by a set of two first – order differential equations:

$$\frac{dV_1}{dt} = \frac{V_{in} - V_1}{Z_N C_1} - \frac{V_1 - V_2}{R1\, C_1}$$

$$\frac{dV_2}{dt} = \frac{V_1 - V_2}{R1\, C_2} - \frac{V_2}{R2\, C_2}$$

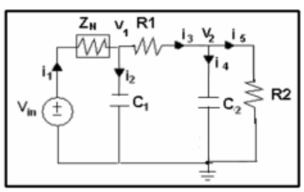


Figure 2: Circuit 1 Using R_1, R_2, C_1, C_2, Z_N

Circuit 2: The circuit uses R, C, L and Z_N connected as shown in Figure 3 and is represented by two first – order differential equations:

$$\frac{dV_1}{dt} = \frac{V_{in} - V_1}{Z_N C} - \frac{V_1 - V_2}{R\ C}$$

$$\frac{dV_2}{dt} = \frac{dV_1}{dt} - \frac{R\ V_2}{L}$$

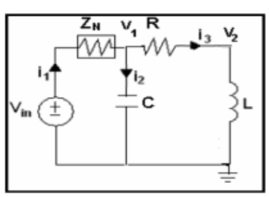


Figure 3: Circuit 2 using R, C, L and Z_N

Circuit 3: The circuit uses R, L, C_1, C_2 and Z_N connected as shown in Figure 4 and is represented by one first – order differential equation and one second – order differential equation:

$$\frac{dV_1}{dt} = \frac{V_{in} - V_1}{Z_N C_1} - \frac{V_1 - V_2}{R C_1}$$

$$\frac{dV_2}{dt} = \frac{V_1 - V_2}{R C_2} - \frac{1}{L_1 C_2}\int V_2\, dt$$

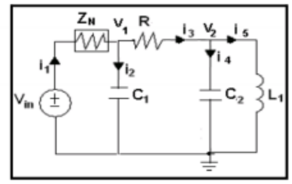


Figure 4: Circuit 3 Using R, C_1, C_2, L, and Z_N

5. SIMULATION OF CHAOTIC CIRCUITS ON LABVIEW

LabVIEW v 10.0.1(32 bit) Service Pack 1 (SP1) for Windows is used to simulate the chaotic circuits. The simulation is two-layered. The main program calls two subprograms; one to input the ODE (Ordinary Differential Equation) and another to solve the ODE. We created three main programs files for simulating three electronic circuits. We also created three corresponding subprogram (for simulating ODE) files. We used the inbuilt subprogram ODE-solver.vi, which is a static referenced subprogram for getting solution of the ODE equations of our circuits. The numerical approximation method used for solving ODE is set for Adams-Moulton method and Rosenbrock method which are variable step size ,multistep, predictor-corrector methods and have error of order $O(h^5)$[14].

The front panel of the main program has a user friendly layout and shows the inputs, time of simulation, the circuit diagram and various parameters of ODE-solver. It also has two graphical outputs; one for demonstrating variation of voltage v1 and v2 with respect to time and another x-y graph for demonstrating variation of v1 with respect to v2. We have also used the Build Table Express function in the subprogram to save the instantaneous values of v1 and v2 for given set of parameters for given initial conditions for given circuit.

The front panel and block diagram of main program named as chaos-ZRLC.vi is created for circuit 2 and reproduced in Figure 5(a,b). The front panel and block diagram of subprogram named as chaos-ZRLC-circuit RHS.vi are reproduced in Figure 6(a,b).Similar files are created for other three chaotic circuit designs but are not reproduced here due to lack of space.

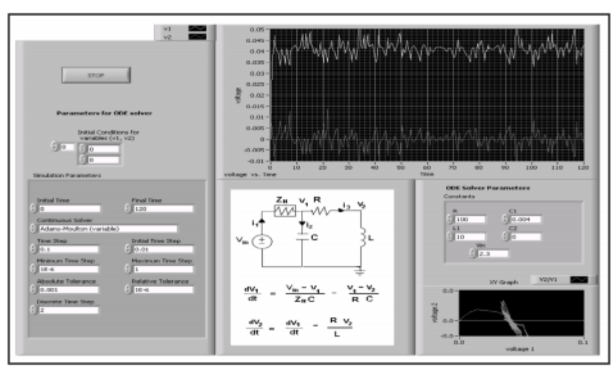


Figure 5a: Front Panel of Program Named as Chaos-ZRLC.vi

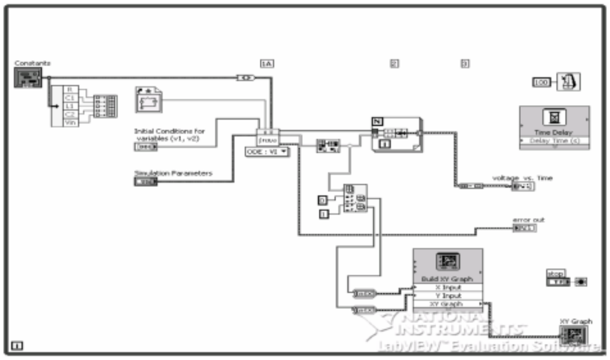


Figure 5b: Block Diagram of Program Named as Chaos-ZRLC.vi

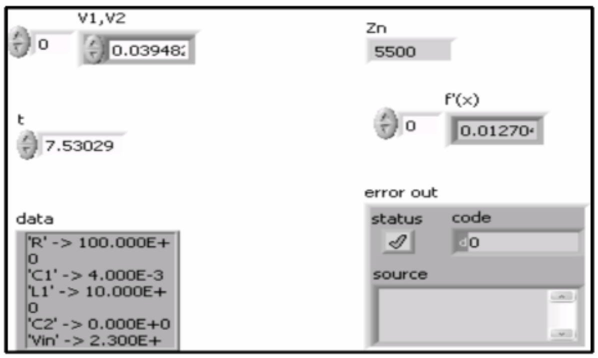


Figure 6a: Front Panel of Subprogram Named as Chaos-ZRLC-Circuit RHS.vi

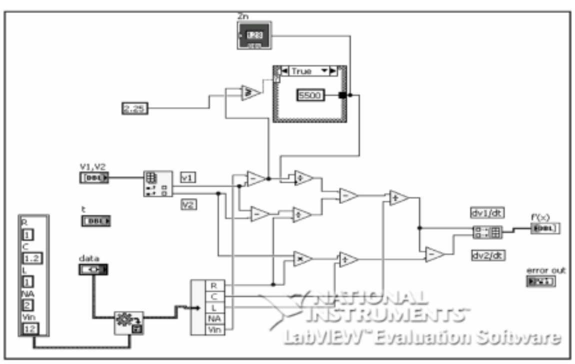
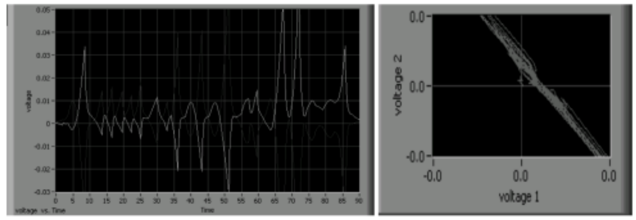


Figure 6b: Block Diagram of Subprogram Named as Chaos-ZRLC-circuit RHS.vi

For studying the phenomenon of chaos in these circuits, we plot the voltage v1 against voltage v2 against time scale. Observation of these graphs (time scale as x-axis) reveal that the voltages v1 and v2 are varying continuously and deterministically with time for given control parameters. The voltage v1 and v2 do not settle to any steady state condition but continue to vary with time. The x-y graph is plotted between v1 and v2. It shows the basin of attraction of the dynamical system, that is, it shows the region in phase space where the system may eventually comes to equilibrium. Six attractors, two for each of the three circuits, are shown in Figure 7(a,b,c,d,e,f) for different set of control parameters.



(i) (ii)

Figure 7a: Attractor of Circuit 1 (i): R1 = 1Ω, R2=1Ω, C_1= 1 F, C_2 = 1F, V_{IN} = 2.3v, t = 90sec, Vb = 2.299v, Zn = 500Ω / 5000Ω, Adams-Moulton ODE Solver

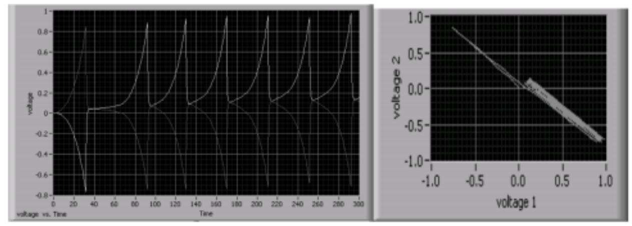


Figure 7b: Attractor of Circuit 1 (i): R1 = 1Ω, R2 = 100Ω, C_1 = 1 F, C_2 = 1F, V_{IN} = 2.3v, t = 300sec, Vb = 2.299v, Zn = 500Ω/ 5000Ω, Adams-Moulton ODE Solver

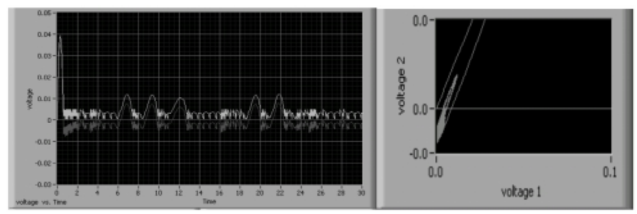


Figure 7c: Attractor of Circuit 2 (i): R = 10Ω, L1 = 15H, C_1 = 0.002 F, V_{IN} = 2.3v, t = 30sec, Vb = 2.298v, Zn = 500Ω/ 5000Ω, Rosenbrock ODE Solver

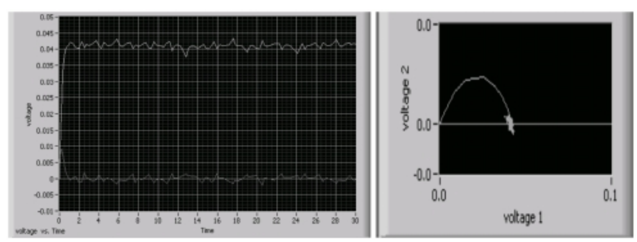


Figure 7d: Attractor of Circuit 2 (i): R = 100Ω, L1 = 10H, C_1 = 0.003 F, V_{IN} = 2.3v, t = 30sec, Vb = 2.25v, Zn = 5500Ω/ 6500Ω, Adams-Moulton ODE Solver

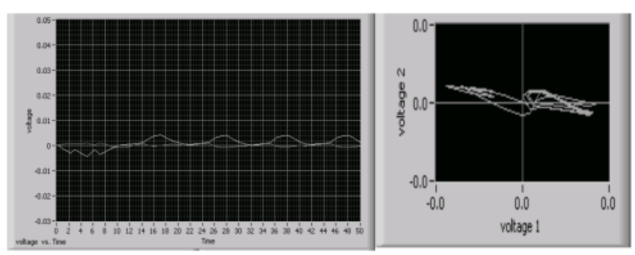


Figure 7e: Attractor of Circuit 3 (i): R = 1Ω, L1 = 10H, C_1 = 1.5 F, C2 = 2F, V_{IN} = 2.3v, t = 50sec, Vb = 2.299v, Zn = 500Ω/ 5000Ω, Adams-Moulton ODE Solver

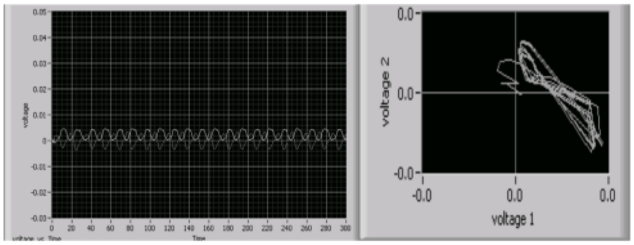


Figure 7f: Attractor of Circuit 3 (i): R = 10Ω, L1 = 6H, C_1 = 1.5 F, C2 = 1.2F, V_{IN} = 2.3v, t = 300sec, Vb = 2.299v, Zn = 500Ω/5000Ω, Adams-Moulton ODE Solver

6. CONCLUSION

We have endured to implement a chaotic circuit based upon Nonlinear Electrolytic Device NLED. Other components used in the circuit are conventional R, L, and C. Only a small region of the nonlinear v-i curve of the NLED has been chosen as the operating region and mathematically modeled and implemented on the chaos-ZRLC-circuit RHS.vi subprogram.

It must be borne in mind that numerical methods for solving ODE have their own limitations and results must be interpreted accordingly. We used Adams-Moulton method and Rosenbrock method which are multistep methods having high speed of calculation and minimum error. Therefore, we conclude that our interpretations are true.

The conclusions are based on visual inspection of time responses of v1 and v2 signals and their x-y graph on front panel of LABVIEW programs. These graphs are compared with graphs obtained by chaotic circuits reported by other researchers [12]. The mathematical calculation of Lyapunov's exponents can further confirm the chaotic behavior.

The voltage V_z across the NLED is (V_{IN} – v1) is non-periodic due to v1 changing randomly. It can be assumed that the natural frequency of the voltage Vz is very low (in subhertz) range because of the high time constant of the circuit due to high value of capacitor (in farad) and inductor (in Henry). In this frequency range, the NLED exhibits nonlinear behavior.

The time responses v1 and v2 of all the three circuits are saved in tables. It is observed that the data is identical for given set of control parameters. It can be said that the response is not random. It is concluded that all the three circuits are deterministic.

When the control parameters are slightly varied, the data stored in the table also shows variation. This is also observed from inspection of v1-v2 attractor on x-y graph. The trajectories are slightly deviating for slight variation in control parameter. These plots demonstrate sensitive dependence on control parameter within the region of phase space occupied by the attractor. Thus, it satisfies the first condition for dynamical chaotic system.

It is observed that different shapes of attractors are obtained from the three circuits for given set of control parameters. As we changed the parameters, the chaotic phenomenon disappeared. Thus, it is concluded that chaos is observed only for certain combination of control parameters in each circuit.

The circuit 1 consists of two capacitors, two resistors and one NLED. Figure 7a demonstrates the time response and corresponding attractor for given set of control parameter. The time response is highly non periodic and the attractor is showing abrupt topological mixing. It can be concluded that this circuit is manifesting behavior close to chaos. The time response of Figure 7b is periodic signal and its attractor is symmetrical. Therefore it is showing chaotic behavior.

When we tested for the chaotic behavior of circuit 2, which consists of one capacitor, one inductor, one resistor and one NLED, we found that this circuit gives deterministic time response. The Figure 7c and Figure 7d, both exhibit periodic time responses. Their attractors are dense, smooth and show topological mixing. Thus, the circuit 2 is exhibiting chaos for both sets of control parameters. We see that this circuit has only two energy storing elements, one less than the three energy storing elements necessitated by Dr. Chua for chaotic behavior. We chose different sets of parameters for this circuit and found that chaos is manifested by several set of combinations of control parameters for this circuit design.

The circuit 3, which is made up of one resistor, two capacitors, one inductor and one nonlinear resistor Z_N (NLED), is the most promising chaotic circuit as it has three energy storing elements. The Figure 7e and Figure 7f, both exhibit periodic time responses. Their attractors are dense, smooth and show topological mixing. The x-y graph between v1 and v2 converges in the basin of attraction and has dense periodic and smooth trajectories. The attractor shows bifurcation and topological mixing within the chaotic region in the phase space. Thus, the circuit 2 is exhibiting chaos for both sets of control parameters.

The NLED, which is used as a non-linear element in our chaotic circuit studies, also has non-linear capacitive element, which has been neglected in our simulation. Including this element in simulation can further enhance chaotic behavior and reduce number of external elements connected in circuit. Also we have approximated the non-linear impedance by a three segment piecewise model which is a vague approximation. Actual NLED has nonlinearity of 8^{th} order [5]. So, the chaotic phenomenon of a real circuit would be more prominent.

It can be finally concluded that we could satisfactorily simulate the electronic chaotic circuit on LABVIEW using NLED. The study can lead to revelation of chaotic behavior of plants and animal bodies, their growth pattern, occurrence of abnormalities etc.

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