Design and Analysis of a Chaotic Colpitts Oscillator Using Memristor Emulator

BY

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under the guidance of

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in the partial fulfillment of the requirements
for the award of the degree of

Bachelor of Technology
(a part of Five Year Dual-Degree Course)

School of Engineering
Jawaharlal Nehru University, Delhi
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DECLARATION

I declare that the project work entitled **"Design and Analysis of a Chaotic Colpitts Oscillator Using Memristor Emulator"**, which is submitted by me in partial fulfillment of the requirement for the award of degree B.Tech. (a part of Dual-Degree Programme) to the School of Engineering, Jawaharlal Nehru University, Delhi, comprises only my/our original work, and due acknowledgement has been made in the text to all other material used.

Garbhit Abhishek

JAWAHARLAL NEHRU UNIVERSITY

SCHOOL OF ENGINEERING

CERTIFICATE

This is to certify that the project work entitled **“Design and Analysis of a Chaotic Colpitts Oscillator Using Memristor Emulator”** being submitted by Garbhit Abhishek in fulfillment of the requirements for the award of the **Bachelor of Technology** (part of Five-Year Dual Degree Course) in **Electronics and Communication Engineering**, has been carried out under my supervision.

In my opinion, this work fulfills all the requirements of an Engineering Degree in the respective stream as per the regulations of the School of Engineering, Jawaharlal Nehru University, Delhi. This thesis does not contain any work that has been previously submitted for the award of any other degree.

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Garbhit Abhishek

ABSTRACT

This paper presents the design and analysis of a high-frequency memristor emulator based on a floating MOS topology with its application in a chaotic Colpitts oscillator. The emulator is based on a compact topology with three components: a nMOS transistor, a current source, and a capacitor to simulate prominent memristive behavior such as pinched hysteresis and nonlinearity. The topology does not involve complex biasing circuitry and is therefore well suited for application in high-frequency analog circuits. The emulator is employed as the active device in a modified Colpitts oscillator to study its dynamic response to nonlinear conditions.

Simulations run in NI Multisim validate the chaotic response of the system with typical attractors and waveform analysis. The outcome verifies the application of the emulator to practical applications such as secure communication, encryption, and signal generation. The study verifies an economical and CMOS-compatible approach of investigation and application of memristive behavior in complex nonlinear circuits.

KEYWORDS: MOS, Memristor,NI Multisim, Colpitts Oscillator.

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1. INTRODUCTION AND OVERVIEW

1.1 Introduction

Electronic oscillators are essential components in numerous applications, ranging from the creation of signals within communication systems to usage as timing devices in electronic circuits. Of the various types, the Colpitts oscillator is remarkable for its capacity to generate stable, high-frequency waveforms using fairly straightforward circuitry. Its low profile and high reliability make it a standard feature in RF and high-frequency electronic use.

On a second front, the memristor idea—published by Leon Chua in 1971—promises exciting new developments in circuit design. With the memristor, as a device that bridges the gap between resistance and memory, one can create novel properties unobtainable with standard passive components. While actual-fabrication of memristors in the real world is still costly and complicated, MOS-based circuit emulation does offer a useful means to investigate their applications in nonlinear and dynamic systems.

This paper combines these two technologies through the construction of a Colpitts oscillator with an integrated MOS-based memristor emulator. The intention is to take advantage of the natural high-frequency properties of the oscillator and the nonlinear dynamics of the memristor to produce chaotic signals. Such a device promises potential applications in secure communication, signal masking, and other modern electronic systems where chaos and high frequency are beneficial.

1.2 Problem Statement

The incorporation of nonlinear circuit elements into high-frequency oscillator circuits has created new opportunities in secure communications, random signal generation, and sophisticated electronic systems. Of these, the memristor—a passive two-port device that inherently connects memory and resistance—has the potential to revolutionize because of its novel nonlinear dynamics. The employment of physical memristors, however, is compromised by complexity of fabrication and restricted commercial supply.

To overcome this, memristor emulators present a feasible option for investigating memristive behavior in practical circuits. When used in oscillator topologies such as the Colpitts oscillator, which is characterized by frequency stability and occurs ubiquitously in RF circuits, the resulting circuit system can be made to exhibit chaotic behavior, beneficial for complex signal processing operations. The primary challenge involves creating a compact and efficient emulator-based circuit that creates chaos at high frequencies with good reliability and simplicity of circuit along with performance.

1.3 Objectives

This project focuses on the design and analysis of a high-frequency chaotic Colpitts oscillator utilizing a floating MOS-based memristor emulator. The specific objectives are:

- To study the fundamental characteristics and nonlinear behavior of memristors.
- To implement a compact memristor emulator circuit based on the design proposed by Gupta et al.
- To integrate the emulator into a Colpitts oscillator circuit and induce chaotic oscillations suitable for high-frequency applications and simulate, analyze, and validate the oscillator's performance.
- To evaluate the practical implications of the design for potential use in communication, encryption, and other signal processing systems.

1.4 Organization of Chapters

The thesis is organized into five chapters, summarized as follows:

Chapter 1: Introduction and Overview
Introduces the background, objectives, and significance in learning high-frequency chaotic oscillators with emphasis on the use of memristor emulators in Colpitts oscillator topologies.

Chapter 2: Literature Review
Reviews memristor, memristor emulator, chaotic oscillator, and their circuit-level implementations bibliography and current literature. Summarizes major developments and gaps filled by this contribution.

Chapter 3: Proposed Work and Design Methodology
Explains the theoretical basis, MOSFET and RC network emulator circuit design, and integration with the Colpitts oscillator.

Chapter 4: Simulation and Results
Offers circuit simulation routines, waveforms at output and chaotic behavior analysis.

Chapter 5: Conclusion and Future Work
The research sets out its contribution by emphasizing the real-world applicability of memristor emulators in high-frequency circuits. It also suggests areas for enhancement, including the physical implementation and integration into contemporary communication networks.

References:
Lists all sources cited in the thesis.

2. LITERATURE REVIEW

2.1 Overview

Nonlinear circuits have become very popular in recent years due to their capacity to generate complex, chaotic signals, which find widespread application in secure communications and signal processing, among others. Of these, the Colpitts oscillator is notable for its simplicity and high-frequency reliability. While this was happening, the memristor with its nonlinear and memory-dependent nature has unlocked new horizons in circuit design. This review covers the evolution of chaotic oscillators, the foundational position of the Colpitts oscillator, the theory and applications of memristors, and how their integration makes chaotic dynamics possible in high-frequency circuits.

2.2 Colpitts Oscillator: Background and Applications

The Colpitts oscillator, developed in 1918, is an LC oscillator whose frequency is determined by a capacitive voltage divider [1]. The tunability and stability of the oscillator make it applicable in RF transmission and sensors [2]. The oscillator can be chaotic if feedback paths or components are adjusted [3], and its behavior has been analyzed using bifurcation, phase portraits, and Lyapunov exponent analysis [4].

The building blocks, as illustrated in Fig. 2.1, consist of the following:

- An active component (a transistor or op-amp typically) used for amplification.
- A voltage divider made of two capacitors.
- A resonant LC tank circuit is formed by an inductor in parallel to the capacitive divider.
- A feedback loop from the tank circuit back to the active device's gate or base.

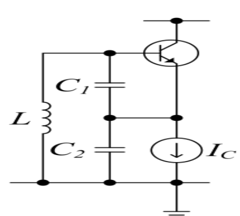


Figure 2.1: *Simple common-collector Colpitts oscillator (with simplified biasing)*

2.3 Chaos in Oscillators

Chaos refers to deterministic, aperiodic dynamics in nonlinear systems. Chaotic signals have applications in encryption, radar, and secure data transmission in electronics [5]. Classical oscillators such as Colpitts can produce chaos with small variations under certain parameter conditions, and this enhances their signal dynamics [6].

2.4 Memristor: Theory and Emulation

2.4.1 History and Development of the Memristor

The memristor was initially proposed in 1971 by Leon Chua as the fourth fundamental passive circuit component, theoretically defined by the duality between charge and magnetic flux linkage [7]. The idea was mostly theoretical until 2008, when Hewlett-Packard (HP) Labs researchers successfully created a memristor using a titanium dioxide (TiO_2) thin film structure [8]. The success created a great amount of interest, and it encouraged researchers to explore applications in non-volatile memory, neuromorphic systems, analog computation, and nonlinear circuits, including oscillators and chaotic systems.

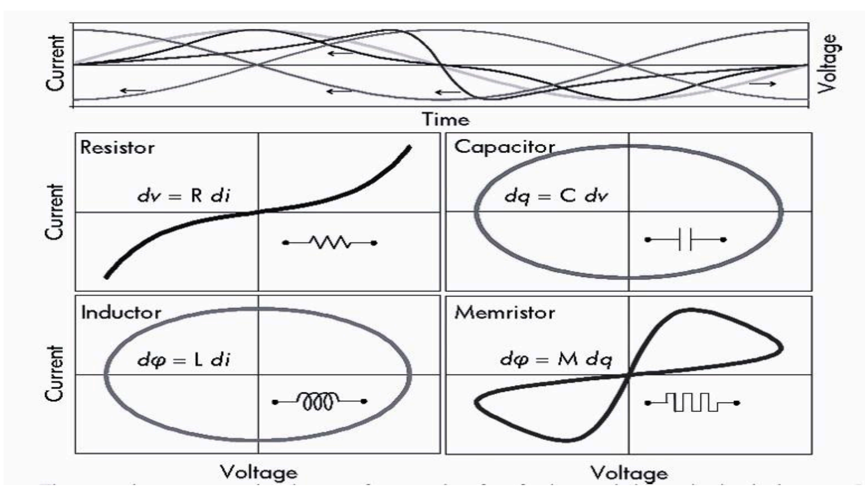


Figure 2.2: *This visually compares the four fundamental passive circuit elements—resistor, capacitor, inductor, and memristor. The top part shows how each device responds to a sinusoidal voltage over time, illustrating different phase relationships between current and voltage. The lower section presents their current-voltage (I–V) curves.*

2.4.2 What Is a Memristor?

A memristor is a two-terminal nonlinear element whose resistance depends on the history of the current and voltage across it. This memory-dependent behavior enables it to retain its resistance even after the removal of external stimuli, making it a promising candidate for non-volatile memory and neuromorphic computing. Its characteristic behavior is a pinched hysteresis loop in the current-voltage (I–V) curve, distinguishing it from linear passive components.

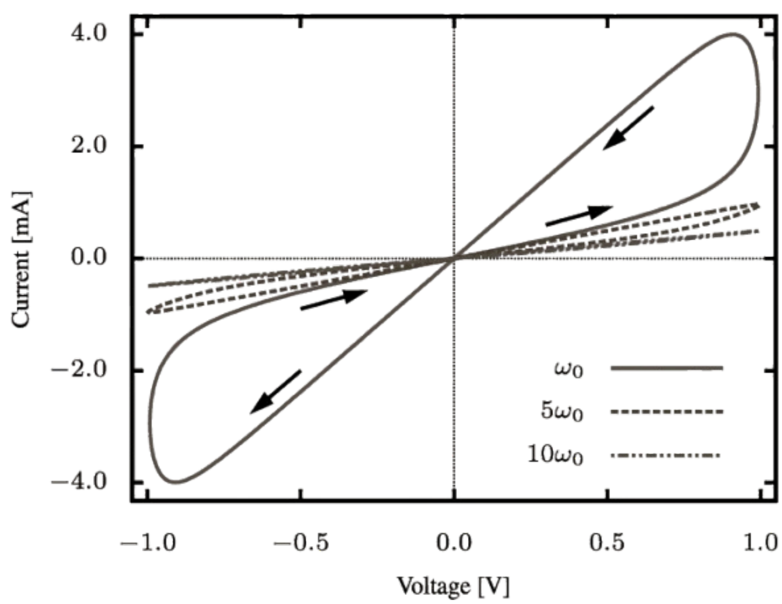


Figure 2.3: *Pinched hysteresis loop in the I–V characteristic of a memristor.*

2.4.3 Types Of Memristors:

(1) Physical Memristors

- Physical memristors tend to be fabricated with transition metal oxides, such as TiO_2, and work through the displacement of ions within an electric field to change resistance.
- Thin-film deposition and nanolithography techniques allow for miniaturization and property tailoring of materials.
- Scalability, integration with CMOS technology, and uniformity of fabrication remain key concerns.

(2) Memristor Emulators

- These employ MOSFETs, resistors, and capacitors to emulate memristive behavior.
- The emulator in this study consists of a diode-connected MOSFET, a current source, and an RC network. The feedback-controlled varying conductance of the MOSFET mimics the resistive switching found in real memristors.
- Affordable, ideal for prototyping, good for high-frequency use, and does away with nanofabrication.

(3) Hybrid Memristors
These integrate physically fabricated components with emulator-based control systems, offering a balance between realism and controllability.

2.4.4 High-Frequency Applications of Memristors:

Memristors have demonstrated vast promise in numerous high-frequency electronic components such as:

- RF Oscillators: They are employed in oscillator circuits of Colpitts, Hartley, and Wien bridge to generate nonlinearity and chaos [9].
- Analog Computing: For dynamic signal processing applications that involve adaptive filtering and real-time feedback control.
- Neuromorphic Circuits: High-speed brain-like systems take advantage of switching and memory characteristics of memristors.

This work utilizes a floating MOS-based memristor emulator in a chaotic Colpitts oscillator to show how it can be efficient in high-frequency circuit applications[10].

2.5 Memristor-Based Chaotic Oscillators

The integration of memristors in oscillator circuits increases both dynamic complexity and nonlinearity. This has led to the demonstration of broadband chaotic sources for use in communication and sensor technologies [11]. In particular, Colpitts oscillators with memristor integration have higher-order chaotic dynamics and better tunability [12][13].

2.6 Simulation and Modeling Software

The Colpitts oscillator design and analysis were performed using circuit simulation software that enables precise performance analysis:

- **NI Multisim:** An easy-to-use SPICE-based simulator utilized to examine oscillator characteristics, such as frequency response and transient performance[14].
- **Cadence OrCAD:** Professional EDA software used for schematic capture and accurate circuit simulation, beneficial for ensuring high-frequency performance and stability[15].

These software tools facilitated effective modeling and simulation of the oscillator coupled with the memristor emulator.

2.7 Recent Developments

Over the last few years, there has been impressive advancement in memristor technology development and applications through emulators. HP Labs has reported memristor prototypes using revolutionary materials such as hafnium oxide and tantalum oxide that improve switching performance and reliability [16]. Additionally, IBM has demonstrated hybrid memristor-CMOS circuits that enable power-efficient in-memory computing designs, and this foretells a shift towards neuromorphic hardware platforms [17].

Also, FPGA-based reprogrammable memristor emulator arrays have gained popularity because of their flexibility and real-time reactivity in emulating memristive characteristics in different situations [18]. Further, attempts are being made to emulate memristor characteristics in different temperatures and frequencies in order to customize them for RF and high-frequency circuit applications and extend their use in wireless communication systems [19].

These developments witness the expanding pace in physical memristor production and emulator circuit design, and with increasing applicability to secure communication, memory architecture, and nonlinear signal processing.

2.8 Summary

The chapter introduced the basics and memristor-emulator modeling of a high-frequency chaotic Colpitts oscillator. Background theory involved a review of nonlinear dynamics and memristive system dynamics. The emulator circuit structure, implemented using MOSFETs and passive elements, was able to replicate the main characteristics of memristive behavior, such as pinched hysteresis and nonlinearity.

Using circuit simulations in NI Multisim and OrCAD, the behavior of the oscillator was verified, exhibiting typical characteristics of chaos, including random waveforms and sensitivity to initial conditions. Memristor modeling was extremely useful in this instance, offering a functional and cost-effective alternative for real memristors at high frequencies.

Developments in memristive materials, hybrid circuits, and programmable emulation platforms in recent years keep the area on the go, with increasing potential in secure communication and brain-like processing.particularly useful in this situation, providing a practical, cost-effective alternative for real memristors in high-frequency regimes. Recent developments in memristive materials, hybrid circuits, and programmable emulation platforms continue to drive this area forward, with increasing potential in secure communication and neuromorphic computation.

The next chapter, *Design Methodology,* outlines the methods and techniques employed in the method.

3. PROPOSED WORK AND DESIGN METHODOLOGY

3.1 Introduction

In this chapter, the design and implementation strategy of a high-frequency chaotic Colpitts oscillator using a memristor emulator circuit is presented. The main objective is to examine the impact of memristive dynamics on oscillator behavior and verify the functionality of using a floating MOS-based memristor emulator in conventional analog oscillator circuits. This method utilizes proven emulator architectures and adapts them to enhance frequency performance and respond to non-linear dynamics.

3.2 Memristor Emulator Circuit Design

The memristor emulator employed in this work is constructed from one nMOS transistors, a current mirror circuit, and a capacitor feedback system. This gives the requisite properties of actual memristors, including a pinched hysteresis loop and time-dependent resistive switching.

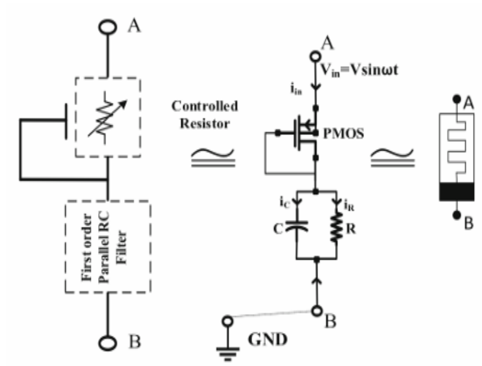


Figure 3.1: *Block diagram notation and MOSFET implementation of a memristor emulator*

3.2.1 Key Features

1. Compactness: The design minimizes the number of parts, leading to less area usage.
2. Frequency Compatibility: Operates up to 80 MHz, thus rendering it RF application compatible.
3. Nonlinear Behavior: Is able to produce memristive effects such as memory-dependent resistance.

The circuit does so by dynamically adjusting the conductance of a diode-connected MOSFET based on capacitor voltage, emulating memristor behavior without the need for nanoscale materials or unwieldy fabrication processes.

3.2.2 Design Methodology

The memristor emulator is designed using a diode-connected PMOS transistor in series with a first-order RC network. This setup enables emulation of memristive behavior by modulating the channel conductance based on the capacitor voltage.

The PMOS operates in the saturation region, where its drain current iD is expressed as:
$i_D = -\mu_p C_{ox}(W/L)(v_{gs} - V_{th})^2$, assuming the gate and drain are shorted ($v_{gs} = v_{ds} = v_c - v_{in}$), the current becomes a function of the capacitor voltage, enabling a voltage-dependent conductance gm.

Using Kirchhoff's laws and capacitor-resistor dynamics, the emulator's governing equations are derived as: $i_C = C(dv_c/dt)$, $i_R = v_c/R$, and $i_C = i_D - i_R$

The state equations become:
$dv_c/dt = k(v_c - V_{th})^2/C - v_c/RC$
$dq/dv_c = k(v_c - V_{th})^2 - v_c/RC$

These define the dynamic behavior of the emulator and confirm its memristive properties. The emulator impedance is frequency-dependent, given by:
$M_R = 1/g_m + 1/(1/R + sC)$

From this, memristance is modeled as:

$$\boldsymbol{M_R = 1/(v_c - v_{in} - V_{th}) + 1/(1/R + sC)\ ,\text{where } g_m = k.(v_{gs} - V_{th})}$$

This formulation highlights the emulator's ability to replicate the nonlinear and memory characteristics of physical memristors using standard CMOS components.

3.3 Integration with Colpitts Oscillator

The Colpitts oscillator, for most uses an LC tank circuit bonded with a transistor amplifier, is the basic configuration. Because the memristor emulator will be employed to substitute the common transistor or operational amplifier in order to investigate nonlinear dynamics, the oscillator is designed into a system that can exhibit chaotic dynamics.

3.3.1 Critical Changes

1. The emulator of the memristor is the active nonlinear component, thereby generating chaos.
2. Individual inductance and capacitance are particularly chosen to provide feedback with resonance and stability.
3. System parameters such as the MOSFET aspect ratio and capacitors are adjusted to control the onset of chaos.

The circuit was redesigned to create higher-order dynamics by introducing additional energy storage elements and nonlinearity in the feedback loop.

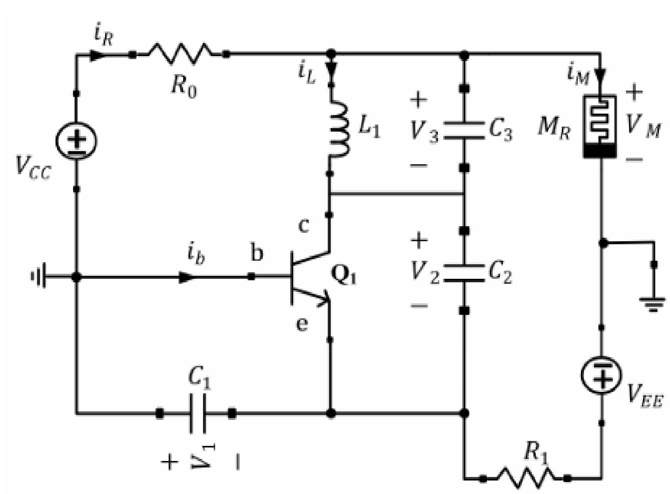


__Figure 3.2:__ Schematic of the designed Chaotic Colpitts Oscillator

3.3.2 Design Parameters

The most significant design parameters of the chaotic Colpitts oscillator are:

● Capacitance Values (C1 and C2): Selected such that the frequency of oscillation.

● Inductance (L): Tuned to resonance with the capacitive network.

● Memristor Characteristics: Regulated by MOSFET width-to-length aspect ratio (W/L) and external capacitor.

3.4 Simulation Strategy

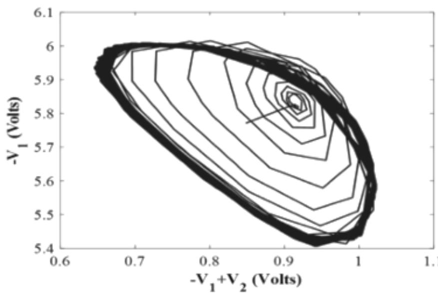
Simulations were done with NI Multisim and validated in Cadence OrCAD to make the behavior of the circuit repeatable and accurate.

3.4.1 Simulation Workflow

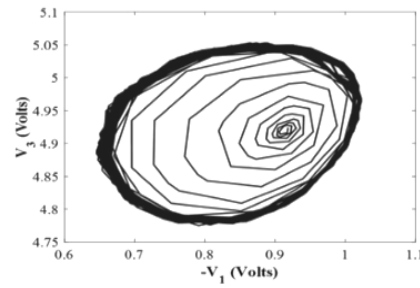
1. Emulator and oscillator circuits were constructed from predefined models.
2. Initial voltages and current (e.g., V1 = 0.01 V, V2 = 0.01 V, V3 = 0 V, iL = 0 A) were supplied to record transient and steady-state response.
3. Time-domain traces were recorded for the investigation of chaotic attractors and to confirm the occurrence of hysteresis.

3.4.2 Expected Results

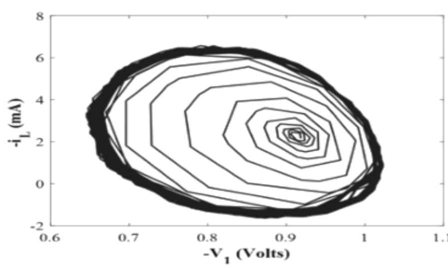
State-space dynamics plots (e.g., V1 vs. V2, V3 vs. V1, iL vs. V1) must exhibit a butterfly-like attractor, i.e., chaotic dynamics , as illustrated in Figures 3.3, 3.4, and 3.5. All three graphs viz Figures 3.3, 3.4, and 3.5 are for the Memristive chaotic Colpitts oscillator with initial values of the state variables as V1(0) = 0.01 V, V2(0) = 0.01 V, V3(0) = 0 V, i L = 0 A. Oscillations must be sensitive to initial conditions and long-term unpredictable.



(a)



(b)



(c)

Figure 3.3: (a): *Phase plot of V_1 versus (V_1 + V_2) illustrating the nonlinear dynamic relationship in the chaotic regime,* ***(b):*** *Phase plot of V_3 versus V_1 showing the interdependent voltage dynamics across the circuit nodes, and* ***(c):*** *Phase plot of inductor current iL versus V_1 highlighting the oscillatory behavior of the memristive chaotic system.*

3.5 Summary

This chapter explained the methodology adopted to realize a memristor-based chaotic Colpitts oscillator. Memristor emulator circuit-level modeling and its successful implementation in a conventional oscillator framework were emphasized. Simulation techniques were also explained to simulate the emergent chaotic dynamics.

The subsequent chapter, simulation and results, will go on to explain the simulation results, observed dynamics, and the performance analysis.

4. SIMULATION AND EXPERIMENTAL RESULTS

4.1 Introduction

This chapter presents the experimental and simulation results of the Colpitts oscillator with a floating MOS-based memristor emulator added to it. Of primary interest is the observation of how the addition of the emulator introduces nonlinearity and leads to chaotic oscillations in a linear oscillator. The waveform characteristics, and frequency response were simulated using NI Multisim. Experimental results wherever possible were also achieved. The results verify the capability of the memristor emulator to produce nonlinear dynamics and chaotic oscillations.

4.2 Circuit Simulation Methodology

The simulation was performed with NI Multisim. The configuration parameters utilized were:-

1. Circuit Components: A floating MOS-based memristor emulator (an nMOS transistor (ZVN2106A), an external capacitor), and a typical Colpitts oscillator circuit with an LC feedback network and an NPN BJT (ZTX 1053A).
2. Operating Conditions: The component values and supply voltage were selected to enable memristive switching behavior and generate chaotic oscillations.
3. Performance Measures: The most important measures of performance were frequency spectrum and properties of chaotic dynamics like aperiodicity and sensitive dependence on initial conditions.

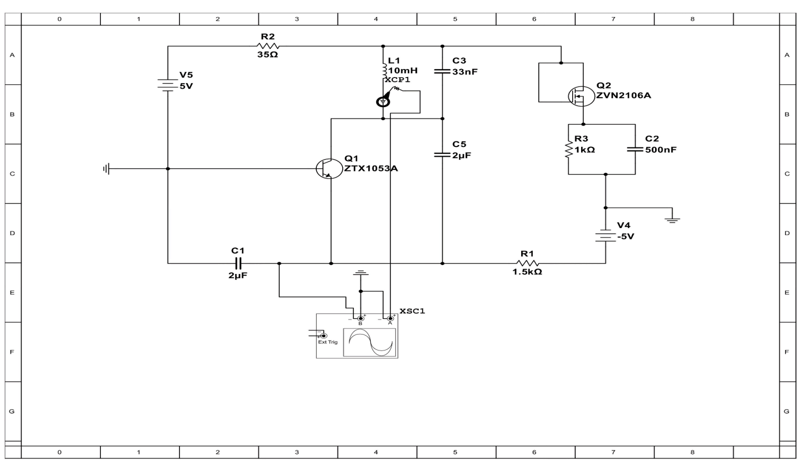


Figure 4.1: *Setup of Chaotic Colpitts Oscillator on NI Multisim*

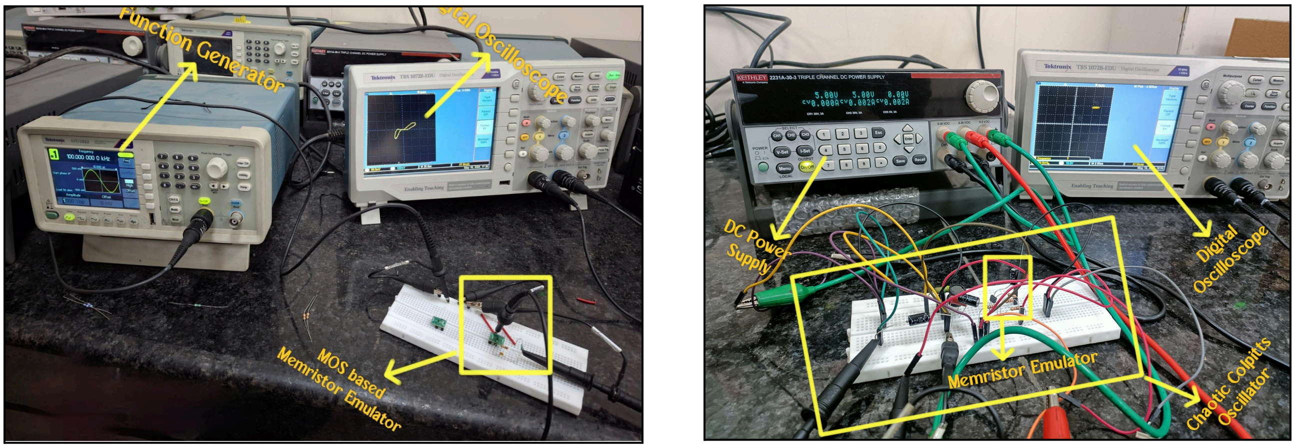


Figure 4.2:(a) *Experimental Setup of Memristor Emulator, and* ***(b)*** *Experimental Setup of Memristor Emulator based Colpitts Emulator*

4.3 Results

4.3.1 Simulation Findings

The memristor-based chaotic Colpitts oscillator output waveform was discovered to be a nonlinear, aperiodic waveform close to a spiral attractor in the state-space plots, confirming the occurrence of chaotic dynamics. The oscillator's behavior was confirmed from following phase plots :

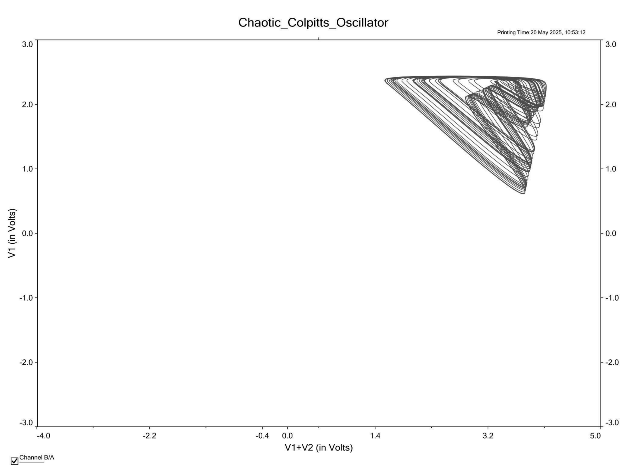


Figure 4.3: (a) *V_1 vs. ($V_1 + V_2$) graph*

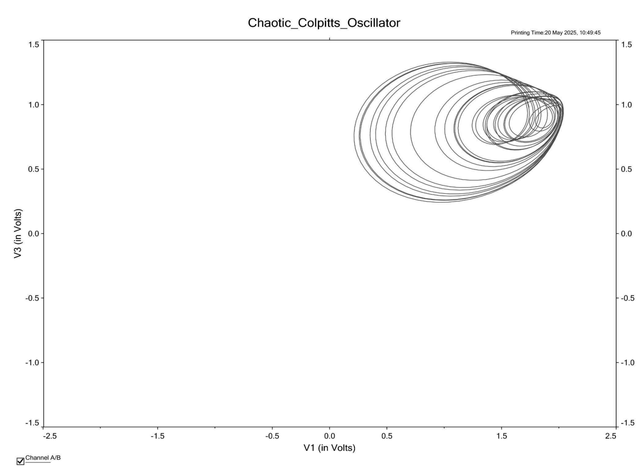


Figure 4.3: (b) *V_3 vs. V_1 graph*

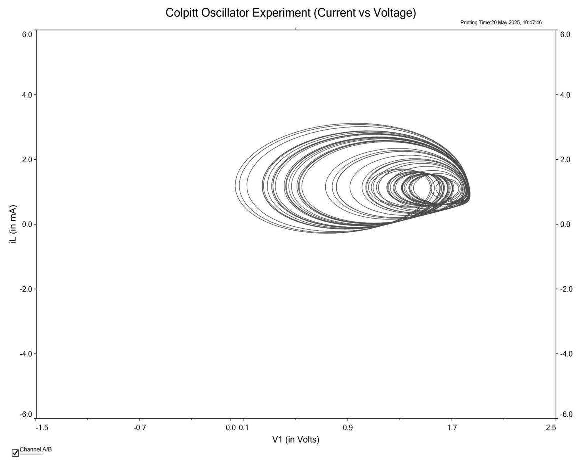


Figure 4.3: (c) *iL vs. V_1 plot*

Furthermore, frequency-domain analysis was conducted with the Spectrum Analyzer of the NI Multisim. The spectrum, as in Fig 4.4, showed the broadband distribution having high signal energy focused in the low-frequency end, decreasing quickly towards higher frequency. This is characteristic of the lack of a prominent resonant frequency and is one of the characteristic signatures of chaotic oscillations.

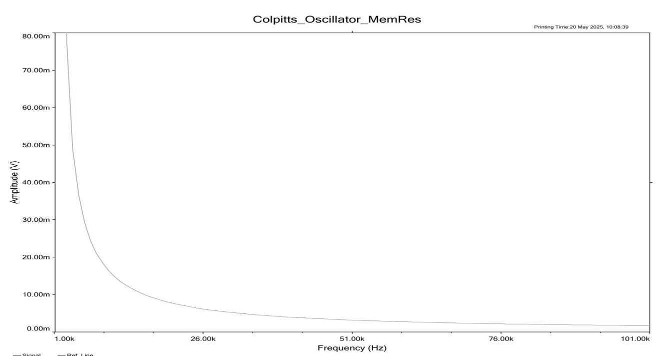


Figure 4.4: *Frequency Spectrum of Memristive Colpitts Oscillator*

4.3.2 Experimental Findings

The measurement employed a Tektronix TBS1072B-EDU oscilloscope in XY mode. Figure 4.5 illustrates the hysteresis curve, which verifies the nonlinear, memory-dependent memristor emulator response, and Figure 4.6 is the V3 vs V1 plot of the chaotic Colpitts oscillator. The aperiodic trajectory is an evidence of chaos and the correct application of the memristor emulator to provide nonlinearity.

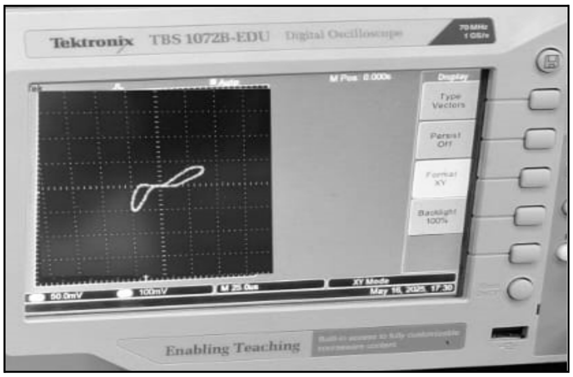


Fig 4.5

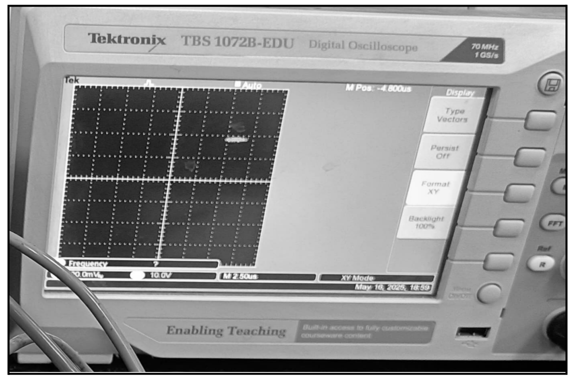


Fig 4.6

Figure 4.5: *Hysteresis curve showing memristor emulator's nonlinear behavior*
Figure 4.6: *V_3 vs. V_1 phase-space plot of the chaotic Colpitts oscillator*

These findings validate the simulation and theoretical findings, establishing the emulator's real-world feasibility.

4.4 Discussions

Simulation results show that the memristor emulator presented here effectively brings nonlinearity to the Colpitts oscillator in a way that the circuit can exhibit chaotic behavior. The time-varying nature of the memristor resistance affects the oscillator dynamics, as seen from the generated aperiodic waveforms and the resulting spiral attractors.

The spectrum of frequencies also bears witness to the random behavior of the circuit. The lack of high spectral peaks and the presence of a continuous range over a broad frequency range ensure that the oscillator is not oscillating at some fundamental frequency. Rather, it produces a multitude of frequency components—synonymous with deterministic chaos.

These findings validate that the floating-MOS-based memristor emulator is satisfactorily reliable to be applied in high-frequency nonlinear circuits, including secure communication systems and random signal generation.

5. CONCLUSION AND FUTURE WORKS

5.1 Conclusion

This work was able to simulate and design a floating MOS-based memristor emulator and interface it with a Colpitts oscillator, and chaotic waveform generation was realized. The key findings of the study are:

- Demonstration of the successful emulation of the memristive behavior such as pinched hysteresis and dynamic resistance of the floating MOS-based emulator.
- Emulation was coupled with a conventional Colpitts oscillator to transform it into a nonlinear chaotic system.
- Verification by Multisim simulations of the oscillator's aperiodic response and broadband frequency spectrum—both of which are hallmarks of chaos.

The results confirm the usability of using MOS-based emulators to obtain memristive characteristics in analog oscillator circuits for nonlinear high-frequency applications.

5.2 Future Work

The novel memristor emulator in a chaotic Colpitts oscillator is intriguing, but opportunities also exist to improve the design, performance, and functionality. Some of the most important areas for future research and development include:

1. **Generalization to Other Topologies**

   Future research can incorporate the memristor emulator into the oscillator circuits such as Hartley, Wien Bridge, or Clapp. This will contrast the chaos-generation in various topologies and assist in the development of best structures for given applications.

2. **Frequency Scalability and Optimization**

   Such efforts can be done to increase the frequency of the chaotic oscillator for RF or microwave applications by trimming the emulator circuit and passive components for low-loss, high-speed performance in communication systems.

3. **Memristor Hardware**

   With the advent of commercial memristors, experiments can substitute emulators with real devices. This facilitates experimental investigation of theoretical limits and pragmatic aspects such as variation, aging, and tolerance to noise.

4. **Integration in Secure Communication**

   The chaotic oscillator may be engineered to offer secure communication in IoT, spread spectrum, or encryption networks. In the near future, a secure modulation/demodulation platform using chaotic signals for safe data transfer may be a reality.

5. **Applications of Neuromorphic and Analog Computation**

   Nonlinear memristor oscillator dynamics can be investigated for computing in analog processors or neuromorphic circuits by pattern recognition, reservoir computing, or adaptive learning owing to memristor memory.

6. **Reconfigurability and Tunability**

   Dynamic adjustment of parameters like bias currents or capacitance through digital control would make it more useful. Chaotic behavior would be modulatable in real-time, which would be useful for learning algorithms and adaptive systems.

7. **Experimental Confirmation Under Changing Conditions**

   It should be tested under varying conditions—temperature, voltage, and stress—to determine its reliability and endurance in actual conditions.

8. **Enhanced Modeling and Simulation**

   Advanced simulation techniques such as Verilog-A behavioral simulation or hybrid hardware-in-the-loop would accelerate emulator design and result in more accurate and shorter development time for future prototypes.

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