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Single Operational Amplifier Based Grounded Meminductor Emulator & Its Applications

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Abstract: - One can create the meminductor emulator from the memcapacitor emulator, and vice versa, by exchanging the positions of the memristor and capacitor. Two emulators were constructed using one operational amplifier, one component, three resistors, and two capacitors. The third simulation device was built using "one operational amplifier, two memristors, two resistors, and two capacitors". The proposed meminductor emulator circuits are designed using hp memristor at a frequency range 500KHz. The performance of the suggested meminductor emulators is considered satisfactory across a wide range of frequencies. The meminductor emulators were developed and tested with the LTspice software. An experimental oscillator was developed to assess the performance of a proposed meminductor emulator with frequency range at 500 KHz.. Constructed and simulated a high pass filter using the recommended meminductor emulator to verify its performance. A chaotic oscillator with a suggested meminductor emulator has been developed to showcase the effectiveness of the concept.

Keywords: *Operational amplifier; Meminductor; pinched hysteresis loop; chaotic oscillator; Memristor.*

I. INTRODUCTION

Scientists and engineers are exploring new devices for potential use in electrical and electronics engineering. These gadgets serve distinct purposes in circuits compared to conventional devices [1]. Memory elements, such as memristors, memcapacitors, and meminductors", are becoming increasingly popular among researchers because of their unique characteristics and broad array of uses. Scientists have broadened the idea of memristors to encompass capacitors and inductors, resulting in memcapacitors and meminductors [2].

The initial component of mem-elements, referred to as the memristor (a blend of memory and resistor), was first recorded [2]. The device retains past charge and flux data to adjust its resistance accordingly. HP Labs successfully created the first physical memristor using titanium dioxide (TiO2) at the nanoscale. Scientists are currently exploring the potential of two additional components, meminductor and memcapacitor, following the successful use of memristors [3].

These devices are currently unavailable for purchase, so researchers are developing meminductor emulator circuits. An emulator of a floating meminductor was built using "two current conveyors, one memristor, one resistor, and one capacitor" [5]. An emulator for a floating memcapacitor was developed by utilising two current conveyors, a memristor, a resistor, and an inductor. Emulators mimicking meminductors were created using mutator and memristor elements. The memristor emulator was constructed using two traditional operational amplifiers (op-amps), seven resistors, one capacitor, two AD844 op-amps, and one multiplier [3].

A meminductor emulator was developed using hp memristor at a frequency range 500KHz [6]. A simulation of a mutator-based meminductor was developed using two CCII+s, one multiplier, two current sources, one buffer, eight resistors, and two capacitors. A groundbreaking circuit was created to transform a memristor into a meminductor, utilising three transimpedance amplifiers [4]. A proposed emulator for a meminductor utilised an "adder, subtractor, resistor, memristor, and capacitor. An innovative circuit was developed to transform a memristor into a meminductor.

The idea of memory in memristors, memcapacitors, and meminductors was also investigated in reference materials outside of those dealing with meminductor emulators [5]. Reference [9] introduced the SPICE modelling for various memory components. The conversation in [8] explored the concept of disorder in a simple

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electrical circuit and its approach to design. A chaotic oscillator was described in reference [7], utilising the mathematical model of a current-controlled meminductor. An erratic oscillator was developed using the mathematical principles of the memcapacitor and meminductor. An oscillator was created using a model that incorporates a charge-based memcapacitor and flux-based meminductor. Conventional techniques for developing meminductor emulators are not well-documented in the current literature. Several meminductor emulator designs incorporate analogue multipliers, leading to higher circuit complexity. Meminductor emulators usually function within the Hz and kHz frequency ranges. This project aims to develop meminductor emulators using a traditional method that does not involve analogue multiplier circuits, leading to the creation of six unique meminductor emulator circuits [5].

In Figure 1, they established a connection between the charge-integral of flux (ρ) and the meminductor, as well as between the flux (φ) and the charge-integral of time (σ) through the use of the memcapacitor. Because these devices can store information, their previous values affect how they work now [6].

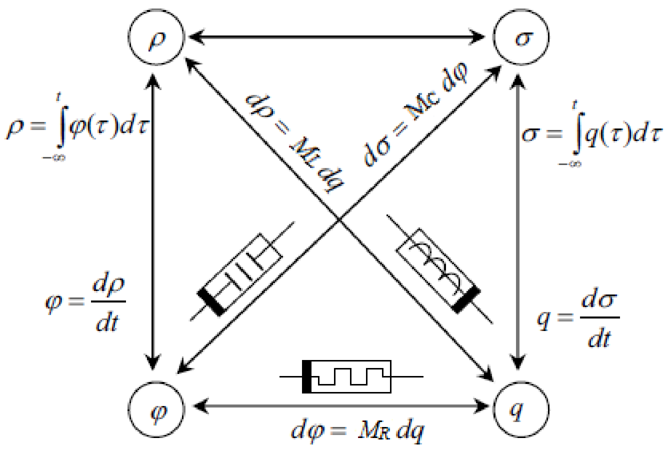


Figure 1: The relationship between circuit element [5]

Systems with memristive, meminductive, and memcapacitive features have been demonstrated since the memristor was discovered. In order to characterize meminductive and memcapacitive systems, two variables were defined. The connections are illustrated in Figure 1. New circuit components called meminductor and memcapacitor can be created by applying the memristive system's unique characteristics to inductors and capacitors. As shown in figure 1, the change from memristor to meminductor is achieved by analyzing the relationship between the variables in their respective mathematical equations. The meminductor circuit design is accomplished by a thorough analysis of the equations followed by the practical implementation utilising electrical components [11][12].

Existing research on meminductor emulators designed with memristors often use components that are not readily accessible in the market. These emulators have several active and passive components, which contribute to the complexity of the circuit and make it difficult to create on a breadboard. The meminductor emulator is built utilising operational amplifiers that are easily accessible at a modest price [13].

The paper is organised as described below. Section 2 presents a literature review on meminductive systems. Section 3 outlines the methodology of the proposed meminductor emulator circuits. Section 4 presents simulation results and comments. Section 5 will provide the conclusions.

II. RELATED WORK OF MEM-ELEMENTS

Researchers have explored different emulators to transform memristors into memcapacitor and meminductor circuits. Various emulators for memcapacitors and meminductors have been created using a variety of passive and active components. The memristor was proposed as a two-terminal circuit element by [18][19] Memristive systems demonstrated a nonlinear relationship between flux $\emptyset(t)$ and charge q(t). A hysteresis loop is shown between V(t) and I(t) to analyse the system's memristive behaviour [20].

$$\emptyset(t) = M_L I(t) \tag{1}$$

$\emptyset(t)$and $I(t)$represent the induced flux and its associated current in the meminductive system, respectively. The constricted hysteresis loop of the meminductive system occurs within the range of $\emptyset(t)$ and $I(t)$
Existing research on memelement emulators indicates that the circuits described are mostly complex. Analog multipliers are often used in several emulation circuits. This paper presents a basic circuit that emulates memcapacitor and meminductor.
Memristor, memcapacitor, and meminductor are collectively known as memelements. Researchers have envisioned the extensive use of the other two components of memelements following the creation of several intriguing applications utilising memristors. In order to investigate the many potential uses of mem-elements, several emulator circuits and SPICE models of mem-elements have been suggested [16] [17]. To show the device as a memelement, four physical quantities—voltage (v), current (i), charge (q), and flux)—are used to build pinch hysteresis loops. Equation (2) defines the charge-controlled memristor as the rate of flux change with respect to charge.

$$M(q) = \frac{d\phi_m}{dq} \tag{2}$$

$$M(q) = \frac{\frac{\mathrm{d}\phi}{\mathrm{dt}}}{\frac{\mathrm{d}q}{\mathrm{dt}}} = \frac{V(t)}{I(t)} \tag{3}$$

$$\mathrm{M_C} = \frac{\mathrm{d}\sigma}{\mathrm{d}\phi} \tag{4}$$

Memristors' pinched hysteresis curves can be obtained by relating flux (∅) and charge (q) or voltage (v) and current (i). According to Equation (4), the memcapacitor (Mc) is the derivative of σ with respect to flux (∅).

$$\sigma(t) = \int_{-\infty}^{t} q(t)\mathrm{d}t$$
$$\phi(t) = \int_{-\infty}^{t} V(t)\mathrm{d}t \tag{5}$$

(6)

$$q(t) = \int_{-\infty}^{t} I(t)\mathrm{d}t \tag{7}$$

$$M_L = \frac{\mathrm{d}\rho}{\mathrm{d}q} \tag{8}$$

$$\rho(t) = \int_{-\infty}^{t} \phi(t)\mathrm{d}t. \tag{9}$$

$$\phi(t) = [M_L(x, I_{ML}, t)]I_{ML}(t) \tag{10}$$

$$I_{ML}(t) = [M_L^{-1}(x, \emptyset, t)]\emptyset(t) \tag{12}$$

Inductive and capacitive systems can now easily accomplish the characteristic of memristive systems—the ability to associate memories. A comprehensive examination of the interaction between numerous variables can transform memristive systems into meminductive ones. [13].

III. METHODOLOGY

Analytical use of the memristor element in the suggested circuits has allowed for the building of meminductor emulator circuits that exhibit meminductive behavior and inherit the memory retention property. The proposed meminductor emulator circuits' input admittances are derived, which confirms this. The circuit diagrams for the suggested meminductor emulators are displayed in Figure 2. The proposed meminductor emulator circuits shown in figure have been designed using one operational amplifier, one memristor (R2), one resistors (R1), one capacitors (C) and memristor (M_R)

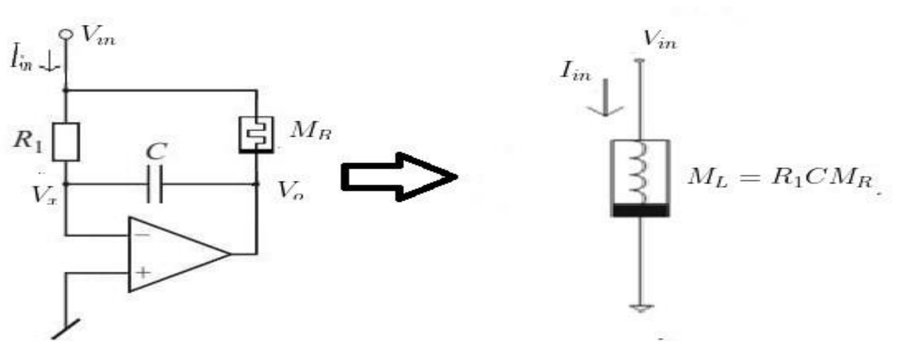


Figure 2: Proposed meminductor emulator circuits [14].

In these configurations, the noninverting terminal of the operational amplifiers is linked to the input voltage (V_{in}) as seen in figure 2. Two operational amplifiers, one memristor, two identical resistors (R), one capacitor, and one feedback resistor comprise the proposed meminductor prototypes. Figure 2 depicts the construction of the meminductor emulator circuit, which comprises one feedback resistor (RF), two operational amplifiers, and two capacitors (C and MR, respectively) [15].

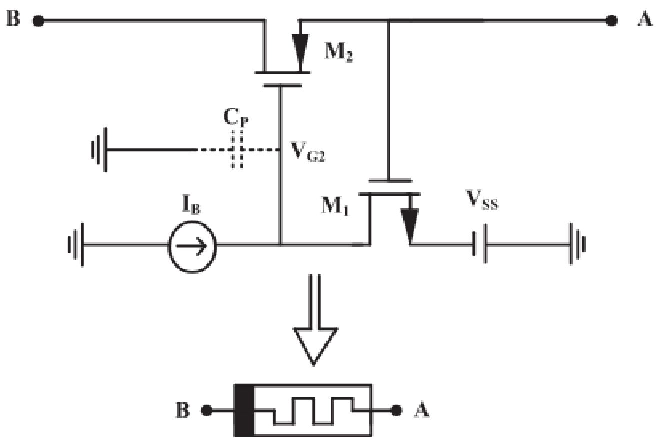


Figure 3: Memristor circuit [6]

The circuit diagram of the proposed flux controlled MOS based floating memristor emulator is shown in Figure 3. This circuit is constructed utilizing a single NMOS transistor (M_1), a single PMOS transistor (M_2), and a single current source (I_B). The feedback network in this circuit design consists of an NMOS transistor, a current source, and a supply voltage (V_{SS}). The feedback network is responsible for modulating the source-to-gate voltage of M_2. The memristor's primary current is equivalent to the source-drain current of the M_2 transistor, which is regulated by a feedback network.

$$I_{in} = \frac{V_{in}-V_O}{R_1} + \frac{V_{in}-V_0}{M_R} \quad (13)$$

$$\frac{V_{in}}{R_1} = \frac{V_x-V_0}{\frac{1}{SC}} \quad (14)$$

$$\frac{V_{in}}{R_1} = (V_x - V_O)SC \quad (15)$$

Where, $V_0 = -\frac{V_{in}}{SCR_1}$

$$V_{\propto} = 0$$

From equation (13) and (15)

$$I_{in} = \frac{V_{in}}{R_1} + \frac{V_{in}+\frac{V_{in}}{SCR_1}}{M_R} \quad (16)$$

$$\frac{I_{in}}{V_{in}} = \frac{1}{R_1} + \frac{1}{M_R} + \frac{1}{SCR_1 M_R} \quad (17)$$

$$Y_{in} = \frac{1}{SCR_1 M_R} \quad (18)$$

Where, $\frac{1}{R_1} + \frac{1}{M_R} = 0$

$$M_L = R_1 C M_R \quad (19)$$

IV. RESULT AND DISCUSSION

A. Transient Analysis

The LTspice simulation application from Analog Devices was used to model the suggested meminductor emulator [18] [21]. It can be observed that pinched hysteresis loop is obtain between current and flux at 500KHz frequency for proposed meminductor emulator. Value of R_1=1.5KΩ and C=8p. Power supply to AD711 is ± 500mV

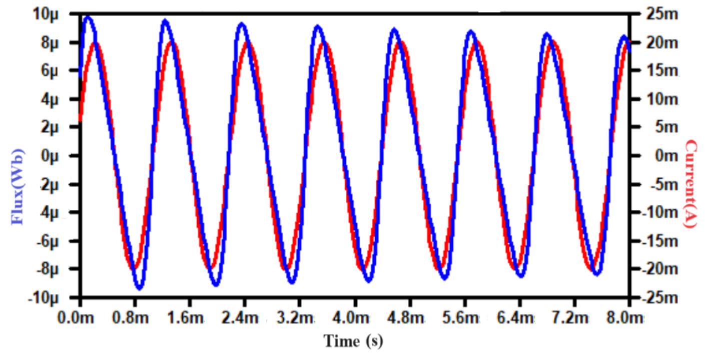


Figure 4: Transient analysis of proposed circuit

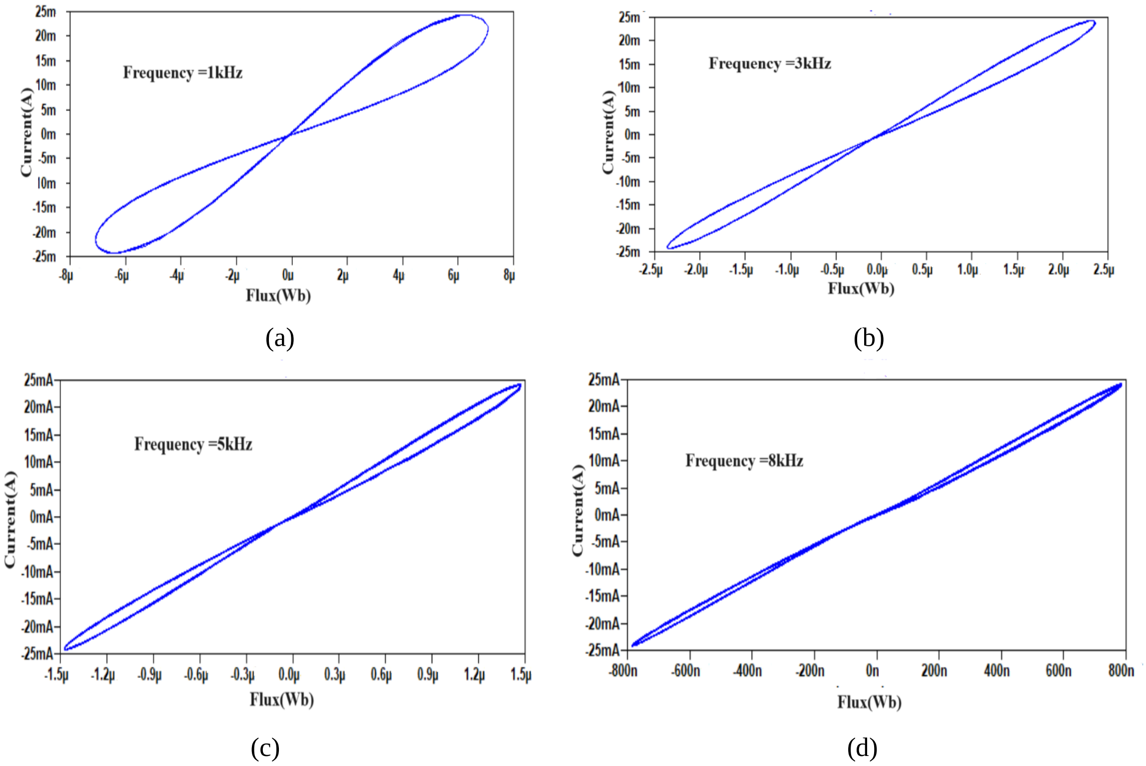


Figure 5: PHLs for suggested meminductor emulator circuit at various frequencies (a)1KHz (b)3KHz (c)5KHz (d)8KHz.

The pinched hysteresis loops (PHLs) for the projected meminductor emulator were generated by applying a sinusoidal signal with an amplitude of 500mV and frequencies range is 500KHz. By observing the flux value (ϕ) on the x-axis of Figure 5, it is evident that as the operating frequency increases, the loop area decreases. At higher frequencies, the pinched hysteresis loop starts to distort [23].

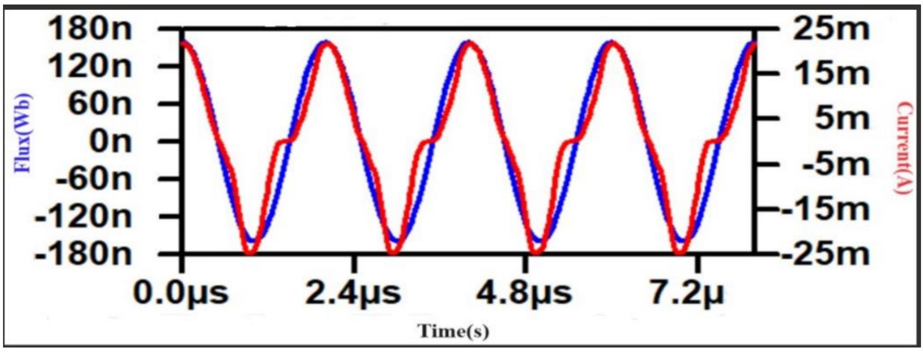


Figure 6: Transient analysis of proposed meminductor circuit

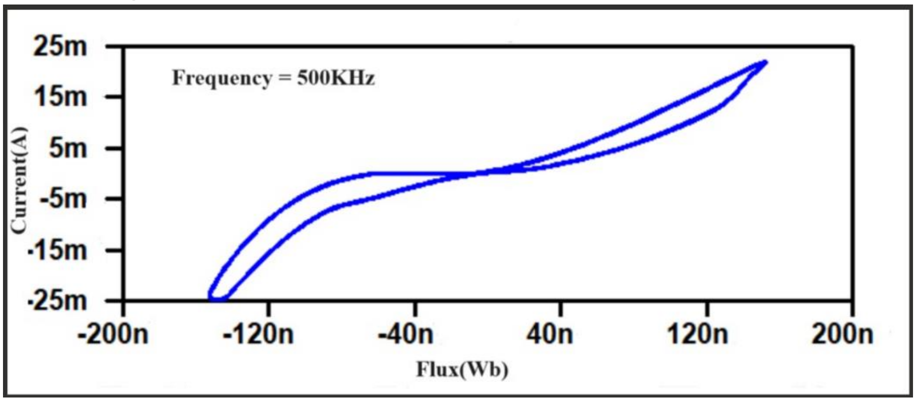
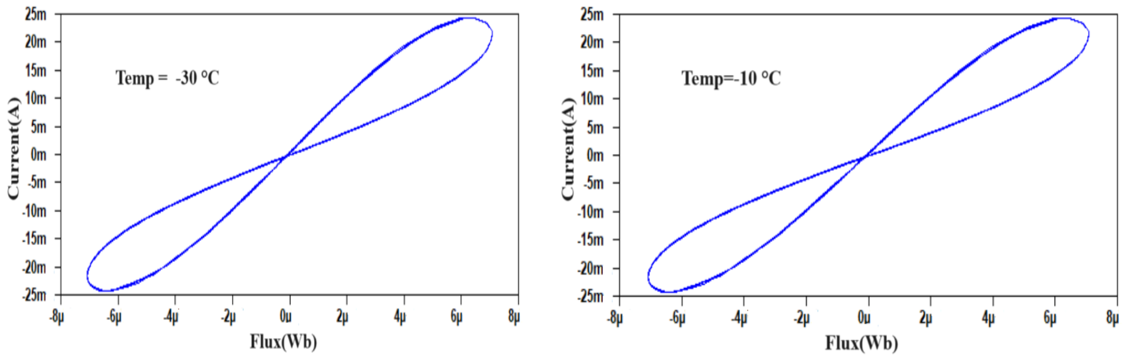


Figure 7: Pinched hysteresis loop of proposed meminductor circuit at frequency 500KHz

The pinch hysteresis loop is a crucial characteristic of a proposed meminductor, [6]. The property of maintaining the Pinch hysteresis loop of the proposed meminductor at a frequency of 500KHz is observed from Figure 7. The value of R1 and C is 1.5 K and 8p phl.

B. Temperature Analysis

The circuit's stability was tested by simulating it at temperatures ranging from -30°C to 30°C. An input wave with a sinusoidal waveform, 500mV amplitude, and 500KHz frequency was used for the study. Figure 6 data indicate that temperature does not impact the pinched hysteresis loops. Therefore, we may infer that the suggested decremental/incremental meminductor is capable of functioning effectively under severe temperatures.



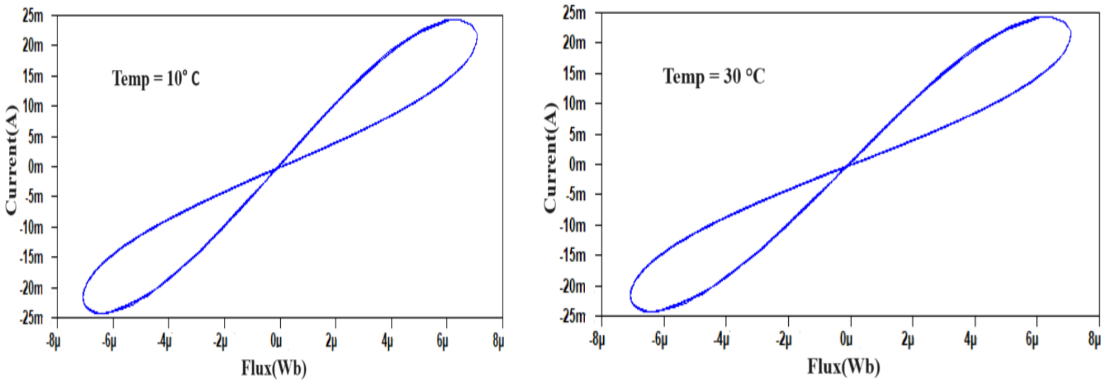


Figure 6 : Temperature analysis of suggested meminductor

C. Non-Voltaity Test

The proposed AD711 meminductor emulator was tested for non-volatility with pulse input. Input pulse with amplitude =50mV, Ton = 1µs and Time period =5µs. The value of the meminductor varies in response to a high input but stays constant outside of the pulse period. This proved how much data the planned meminductor emulator could hold.

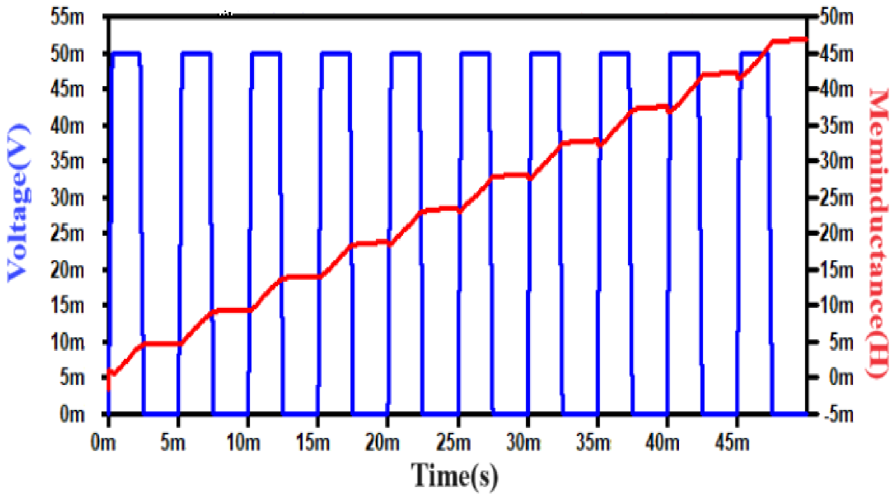


Figure 8 : Non-Volatility Test for proposed meminductor

D. Supply Voltage Variation Analysis

In figure 9, the effect of supply fluctuations on pinched hysteresis loops is shown by varying the supply voltage in the proposed meminductor emulator from 9 V to 15 V. power supply lesser than shows PHL is moving from right to left and get diminished.

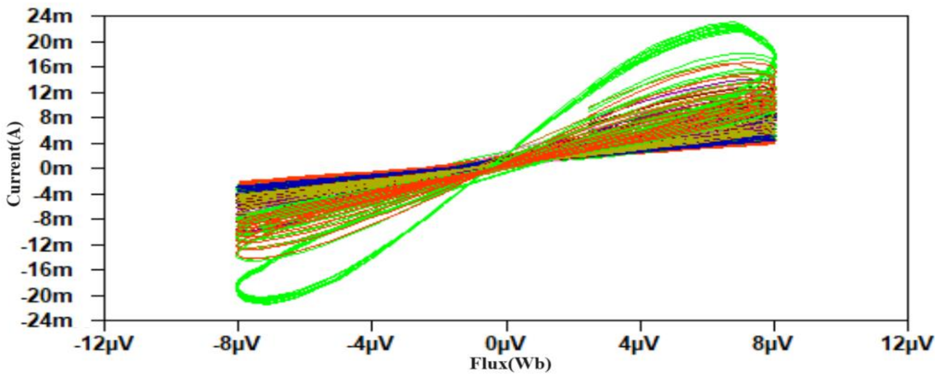


Figure 9: Effect of supply voltage variations on the pinched hysteresis loops

E. Monte Carlo Analysis

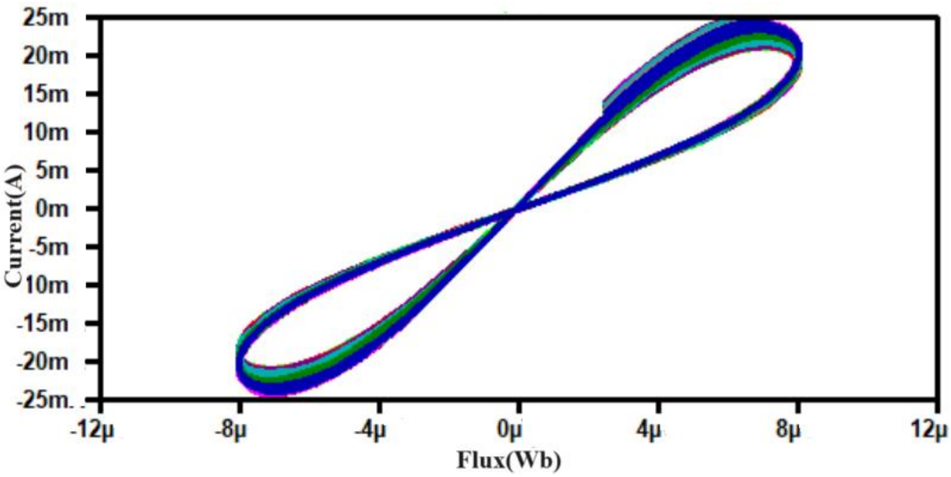


Figure 10: Monte Carlo analysis results for the proposed meminductor emulator circuits

Check the robustness of circuit Monte carlo analysis for 200 runs. Sensitivity depends on resistor use in Circuit . Gaussian random variation applied to vary the value of resistor as seen in figure 10.

F. Application of Proposed Meminductor Emulators

1. Chaotic Oscillator

The proposed meminductor emulator circuit has been used to realize a chaotic oscillator. Figure 12 shows a basic version of a chaotic oscillator. One meminductor (ML), a resistor (R), two capacitors (C1 and C2), and two negative conductances (-G1) and (-G2), achieved by an op-amp based negative impedance converter, make up the oscillator.

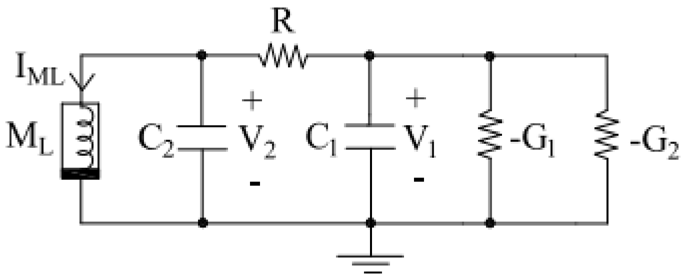
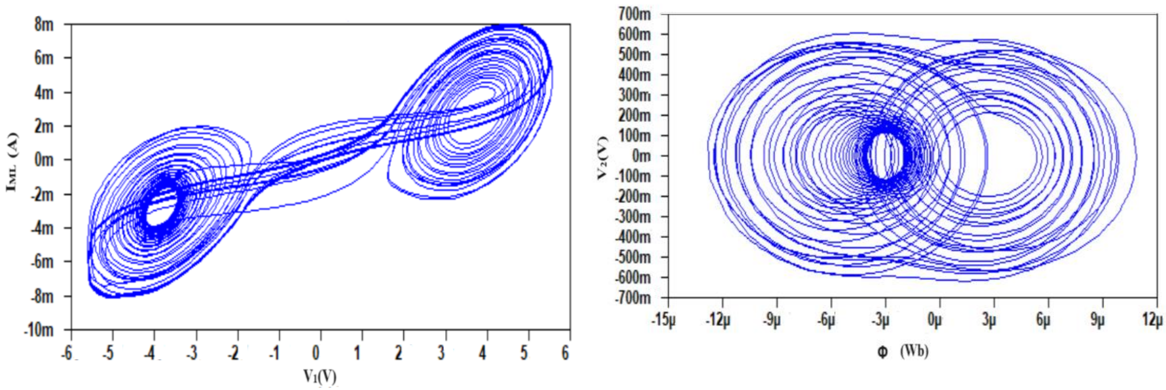
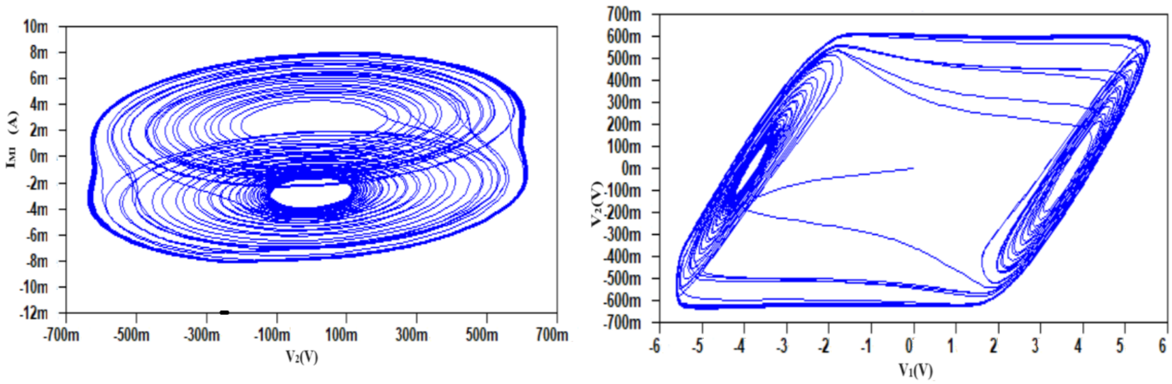


Fig 12: Chaotic oscillator circuit



(a) (b)



(c) (d)

Figure 13: The 2D projection plots of the chaotic oscillator based on the proposed meminductor

Table 1: Tabular Comparison of various emulators

Author and Year	Number of active components	Number of passive components	Memristorless	Maximum Frequency	Floating (F) or Grounded (G)	Power Supply
Zhao et al., (2019), [4]	1 op-amp, 3 CCIIs, 1 multiplier	1MR,1R,1C	No	4Hz	G	-
Yu et al., (2014) [21]	3 CFOAs	1MR,2R, 1C	No	20Hz	F	-
Liang et al., (2014)[22]	4 CFOAs, 2 op-amps, 1 multiplier	5R, 1C	Yes	36Hz	F	$\pm 15V$
Sah et al., (2014) [23]	4 op-amps, 2 CCIIs, 1 multiplier	2 R, 1 C, 12 MOSFETs	Yes	300Hz	G	$\pm 5V$
Fouda and Radwan, (2014) [24]	3 CCII, 1 multiplier, 1 Adder	3 R, 1 C	Yes	5Hz	G	-
Fang et al., (2016),[25]	4 op-amp, 2 multipliers	8 R, 2 C	Yes	180 Hz	F	$\pm 5V$
Babacan, (2018)[26]	1 OTA, 1 voltage reference	1 L, 1 R, 1 C	Yes	500Hz	G	$\pm 5V$
Yuan et al., (2020)[4]	4 AD844, 1 op-amp, 1 Varactor diode	5 R, 1 C	Yes	5KHz	F	$\pm 15V$
Yu et al., (2019)[5]	2 VDTA, 1 multiplier	2 C	Yes	1MHz	F	-
Taşkran et al., (2020)[6]	4 AD844s, 1 op-amp, 1 varactor diode	5 R, 2 C	Yes	8 kHz	F	$\pm 15\ v$
Yuan et al., (2020)[7]	1 CBTA	1 MR, 1C	No	100KHz	F	$\pm 5\ v$
Vista and Ranjan, (2019)[8]	2 OTAs, 2 multipliers	2 R, 2 C	Yes	10KHz	G	$\pm 15\ v$
Singh and Rai, (2021)[10]	1 VDCC	1MR, 1C	Yes	700KHz	F	$\pm 5\ v$
Proposed	1 Op-amp	1MR, 1R, 1C	NO	500KHz	G	$\pm 15\ v$

Sozen and Cam, (2020) [15]	1 OTA, 1 multiplier, 2 CCIIs, 1 CFOA	9(2C, 7R)	Yes	5 kHz	Both	$\pm 15\ v$
Singh, and Rai, (2021) [28]	2 Op-amp, CFOA, OTA,	3R, 2C	Yes	2 MHz	Both	$\pm$ 15 v

V. CONCLUSION

A meminductor emulator was developed using single op- ampand phmemristor withrequency range is 500KHz Through thermal analysis, it has been confirmed that the emulator operates effectively over a wide temperature range. The suggested circuit is easy to construct and utilizes affordable ready-made components. A chaotic oscillator has been created using the suggested meminductor emulator to evaluate its performance. The findings from the chaotic oscillator confirm the effectiveness of the suggested designs as meminductors. The findings of this study are: PHL characteristics has been verified, Non-Volatility property has been verified, Input frequency range for OP-AMP based meminductor emulator is from 1kHz-8KHz, Emulator circuits were used in Chaotic oscillator verify their application in practical environment.

Future work

- Increase the frequency circuit as observed in other meminductor emulators.
- Probable applications, random number generator, neuromorphic, computing, brain inspired computing etc.

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