Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 5s (2025)

Design and Simulation of Subsonic Frequency, Frequency-Selective Circuit Using Active Inductor

Ramesh Krishna[1], Nagaraja Kamsali[2], Sathisha N[3]

[1]Department of Physics, Bangalore University, Bengaluru, India, rameshkrishna.assr@gmail.com

[2]Department of Physics, Bangalore University, Bengaluru, India, kamsalinagaraj@gmail.com

[3]Department of Electronics and communications, K R Pete Krishna Govt Engineering College, Krishnarajpete, Mandya, India, nsathisha@gmail.com

Article History:

Received: *06-10-2024*

Revised: *27-11-2024*

Accepted: *04-12-2024*

Abstract:

Designing very low frequency (VLF) tuning circuits poses a significant challenge due to the impractical size of inductors required at these frequencies. As the frequency decreases, the inductance value needed becomes larger, making it difficult to implement physically. To address this issue, this paper presents an alternative approach that replaces the traditional passive inductive component (L) with a simulated inductor. The simulated inductor, designed specifically for VLF applications, offers a practical solution to overcome the limitations of using large inductors. The design of the simulated inductor is explained in detail, and its application in VLF tuning circuits are demonstrated. By replacing physical inductors with simulated counterparts, the circuit's size is significantly reduced, while maintaining the desired frequency-selective characteristics. The simulation of the designed circuit is carried out using PSPICE, an analog simulation software. The performance of the simulated inductor in tuning circuits are evaluated, and the results are graphically represented using Python. These simulations provide valuable insights into the effectiveness and accuracy of the proposed method in replicating the behaviour of large inductors at very low frequencies. The results confirm that simulated inductors offer a viable solution for VLF circuit design, reducing component size without sacrificing performance. This approach is expected to benefit various applications where size constraints and frequency selectivity are critical.

Keywords: Active Inductor, Analog Circuit, Circuit Design, Circuit Simulation, Frequency-Selective Circuit, Inductive Emulation, Low-Frequency Circuits, Subsonic Frequency.

1. Introduction

The design and implementation of very low frequency (VLF) tuning circuits have long been a challenge in the field of electronics. As electronic systems continue to advance, the need for reliable and efficient components that operate at very low frequencies often extending into the subsonic range has become increasingly critical. One of the primary difficulties in designing these systems is the requirement for large inductors. At VLF domain, the inductance values necessary for proper circuit operation become significantly high, leading to impractical physical sizes for passive inductors. Inductors are fundamental components in analog electronics, used for tuning, filtering, and signal processing. However, as the frequency of operation decreases, the inductance required increases proportionally, which can lead to excessively large and cumbersome inductors. These large inductors pose several problems: they can be physically unwieldy, difficult to integrate into compact designs, and costly to manufacture. Moreover, the performance of these inductors can be affected by their size, leading to potential issues with stability and accuracy in the circuit's operation.

To address these challenges, researchers have been exploring alternative methods to achieve the desired inductive effects without relying on large passive components. One such method involves the use of simulated inductors. Simulated inductors [1] are electronic circuits designed to emulate the behaviour of inductors using active or passive components in combination. This approach offers several advantages, including reduced physical size, improved integration with other circuit elements, and potentially lower manufacturing costs. The proposed simulated inductor is designed specifically for VLF applications, where conventional inductors would be impractically large. The design process involves creating an equivalent circuit that mimics the inductive behaviour while using components that are more manageable in size. This approach allows for more compact circuit designs without compromising on performance or functionality.

This paper presents a novel approach to overcome the limitations of large passive inductors by utilizing simulated inductors in the design of VLF tuning circuits. The key innovation lies in replacing the traditional, physically large inductors with simulated inductors that can be realized using standard electronic components and techniques. This alternative method not only addresses the size constraints but also provides flexibility in circuit design and optimization. The proposed simulated inductor is designed specifically for low-frequency applications, where conventional inductors would be impractically large. The design process involves creating an equivalent circuit that mimics the inductive behaviour while using components that are more manageable in size. This approach allows for more compact circuit designs without compromising on performance or functionality.

To validate the effectiveness of the simulated inductor, the design and implementation are thoroughly analysed using the analog simulation [2] software, PSPICE. This software provides a comprehensive platform for modelling and testing electronic circuits, allowing for detailed analysis of the simulated inductor's performance in various circuit configurations. Additionally, Python is employed to graphically represent the simulation results, offering a clear visualization of the circuit's behaviour and performance characteristics. The results of these simulations demonstrate the feasibility and advantages of using simulated inductors in VLF [3] applications. By effectively emulating the behaviour of large inductors, simulated inductors provide a practical solution to the design challenges associated with VLF circuits. This paper aims to contribute to the ongoing efforts in electronics design by offering a viable alternative that enhances the efficiency and practicality of VLF tuning circuit systems.

2. Problem Statement

The issues in designing the VLF tuning circuits are as follows:

(i) **Size Constraint**: Low-frequency amplifiers require large inductors, which are impractical for compact electronic designs.

(ii) **Practical Realization**: Large inductors needed for subsonic frequencies are difficult to physically implement, complicating real-world applications.

(iii) **Performance Issues**: Large passive inductors can affect the performance and stability of low-frequency circuits, necessitating alternative solutions.

3. Objectives of the proposed work

The objective of this proposed work is to design and simulate a subsonic frequency-selective circuit using an active inductor. The study aims to achieve high performance in frequency selectivity, reduced circuit size, and enhanced tuning capabilities, enabling its application in low-frequency communication systems and signal processing with improved efficiency and precision.

(i) **Design of Simulated Inductor**: Create and implement a simulated inductor to replace large passive inductors in tuning circuit, addressing size constraints.
(ii) **Performance Evaluation**: Use PSPICE and Python to simulate and evaluate the performance of the simulated inductor in various low-frequency circuit configurations to ensure it meets design specifications.
(iii) **Demonstration of Practical Advantages**: Employ Python to graphically illustrate and confirm the benefits of simulated inductors, focusing on compactness, efficiency, and integration in low-frequency applications. Simulated inductor using active component

One method of realizing the high value of the inductor is the use of a Generalized Impedance Converter (GIC). Nowadays such simulated inductor [7], [15] is used in the design of analog filters. It is also used in the design of low-pass filter using FDNR (Frequency Dependant Negative Resistance) which uses transformation in the simulated inductor [4]. One more such application is the use of a simulated inductor in the generation of spectral purity sine waves with reduced harmonics [6]. This GIC consists of the active component namely the operational amplifier [5], resistances and capacitances as shown in Figure-1 and it is proposed by Antoniou.

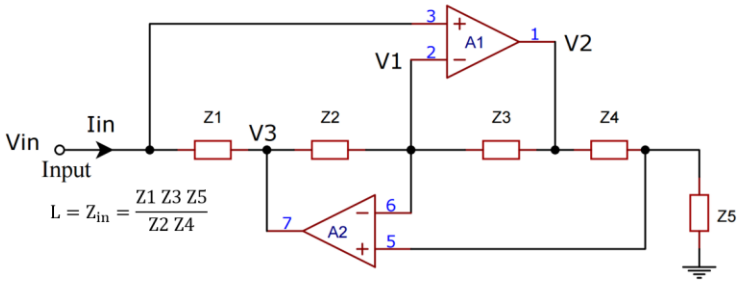

Figure-1: Original active inductor

The active inductor proposed by Antoniou is modified in this paper. Figure-1 is the basic active inductor proposed by Antoniou that will be modified to enhance the Q value that is crucial for VLF application. Z1, Z2, Z3, Z4, and Z5 are passive impedance, A1, and A2 are operational amplifiers V1, V2 and V3 are the voltages at different locations in the circuit. then

$$V2 = \frac{(Z4 + Z5)\ V1}{Z5} \tag{1}$$

$$\frac{(V3 - V1)}{Z2} = \frac{(V1 - V2)}{Z3} \tag{2}$$

From equation (1) and (2)

$$V3 = \frac{(Z3\ Z5 - Z2\ Z4)\ V1}{Z3\ Z5} \tag{3}$$

The current at the input is given by

$$I_{in} = \frac{(V_{in} - V3)}{Z1} \tag{4}$$

The input impedance of the circuit is written as

$$Z_{in} = \frac{V_{in}}{I_{in}}$$

$$Z_{in} = \frac{Z1\ Z3\ Z5}{Z2\ Z4} \tag{5}$$

When Z1 = R1, Z2 = R2, Z3 = R3, Z5 = R5 and Z4 = 1/sC4

$$Z_{in} = \frac{R1\ R3\ R5\ sC4}{R2} \tag{6}$$

4. Quality Factor

The quality factor (Q) is a parameter used to describe the selectivity performance of a filter. For VLF applications, achieving high-Q performance with an active inductor can be quite challenging due to the low frequencies involved. For a first-order filter, the Q parameter relates the distance of the filter pole to the jω –axis. For a more selective filter or tunable [16], the Q value must be high. A high Q implies that the poles of the filter have to be closer to the jω –axis.

The Q of a filter [9] can be calculated by taking the inverse of the normalized bandwidth of the filter. Calculations for normalization can be achieved by using the half-power (3dB) point of the filter [18]. The passive inductor in the conventional tuning circuit is replaced by an active inductor (floating inductor) circuit that emulates inductance using an RC network, and a pair of operational amplifiers [11]. Figure-2 illustrates the conventional LC circuit that operates based on the principle of resonance. The center frequency of the tuning circuit is determined by:

$$f_c = \frac{1}{2\pi\sqrt{LC}} \tag{7}$$

The quality factor is given by,

$$Q = \frac{f_c}{BW} \tag{8}$$

Where BW is the bandwidth given by, BW = R/L

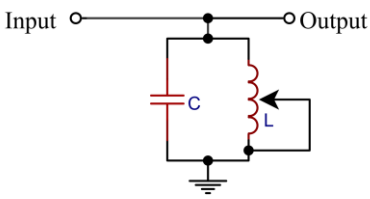

Figure-2: Conventional LC circuit

Modified Active Inductor

The lossless grounded inductance simulator [19], [20] are implemented by using low-frequency filters. An active inductor is a two-port passive circuit [8] element used in electrical circuits that simulates the behaviour of an inductor and a capacitor without storing energy. It introduces a phase shift between voltage and current, effectively allowing for the transformation of a voltage signal into a current signal and vice versa. They provide a way to implement inductive behaviour in circuits where traditional inductors would be impractical, such as in miniaturized electronics.

The active inductor can be paired with capacitors or resistors to create complex impedance networks [10], [12]. Active inductors are used in various applications, such as active filters, impedance matching, and simulation of inductive components in integrated circuits. Typically, the active inductors are realized using operational amplifiers or transistors in active circuits, as well as in specialized components in passive designs. The modified active inductor is shown in Figure-3. The active inductor has an additional positive feedback network to the amplifier A1 through an impedance Z6.

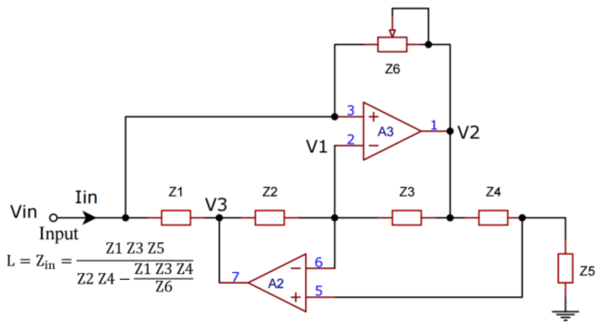

Figure-3: Proposed active inductor

The input current of the modified circuit is given by

$$I_{in} = \frac{(Z1 + Z6)\ V1}{Z1\ Z6} - \frac{V2}{Z6} - \frac{V3}{Z1} \tag{9}$$

Substituting equation (1) and (3) in (8)

$$Z_{in} = \frac{Z1\ Z3\ Z5}{Z2\ Z4 - \frac{Z1\ Z3\ Z4}{Z6}} \tag{10}$$

To obtain the high value of the Q factor, the design is considered as Z1 = R1, Z2 = R2, Z3 = R3, Z5 = R5, Z6 = R6 and Z4 = 1/sC4

$$Z_{in} = \frac{R1\ R3\ R5\ R6\ sC4}{R2\ R6 - \ R1\ R3} \tag{11}$$

From the above equations and analysis, it can be observed that the modified active inductor circuit can be used to simulate the active inductor as similar to that of the original active inductor as shown in Figure-1.

The proposed active inductor circuit considers the following design factors:

(i) **Inductance Value**: The required inductance value for VLF applications is typically very high. Ensuring that the active inductor can achieve and maintain this inductance at low frequencies is crucial.
(ii) **Q Factor**: The Q factor, or quality factor, measures the efficiency of the inductor and is critical for VLF applications to minimize losses and ensure performance.
(iii) **Frequency Stability**: Active inductors must provide stable performance over a wide range of frequencies, especially in the VLF range, where even small variations can significantly affect performance.
(iv) **Implementation Technology**: Active inductors can be implemented using various technologies, including operational amplifiers (op-amps), current conveyors, or dedicated active inductor circuits.

The passive inductor in the conventional tuning circuit is replaced by an active inductor circuit that emulates inductance using an RC network, and a pair of operational amplifiers [13]. The simulated inductance values for the original active inductor and modified active inductor at frequencies of 19.80 kHz and 22.20 kHz are calculated using Equations (6) and (11) respectively and the values are tabulated in Table I. The inductance emulated by the modified active inductor circuit has an enhanced inductance value, indicating that the circuit can closely approximate the theoretical inductive values.

Table I: Inductance emulated by the original and proposed active inductor for different frequencies

Frequency(kHz)	Inductance (mH)		
	Theoretical value	Simulated	
		Original	Modified
19.80	32.30	26.64	26.83
22.20	25.69	20.70	20.95

The tuning circuit is designed with an operational frequency range of 18.00KHz to 76.00KHz and for the frequencies 19.80KHz and 22.20KHz, both original active inductor and the proposed active inductor circuits inductance values are computed. The proposed active inductor circuit is modified to obtain a high value of the Q factor and is implemented in conventional LC circuit [14] by replacing passive inductor (L) which is shown in Figure-4. This circuit is designed with an operational frequency range of 18.00 kHz to 76.00 kHz. The component values of the capacitors and resistors for this modified proposed active inductor circuit are given in Table II for frequencies 19.80KHz and 22.20KHz. Here, R5 is a variable resistor of 10KΩ that tunes to the desired frequency, while R6 is a 1MΩ variable resistor that optimizes the Q-value of the circuit.

Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 5s (2025)

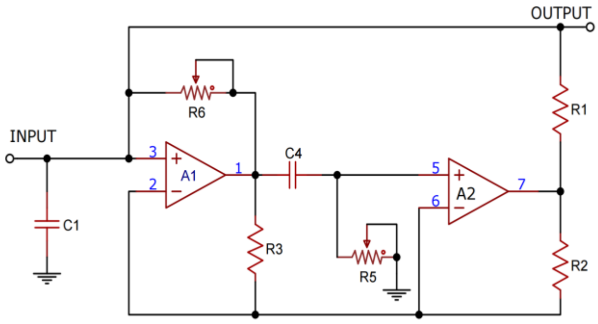

Figure-4: LC circuit with active inductor

Table II provides the component values of this modified circuit for the tuning frequencies 19.80KHz and 22.20KHz. R5 is a variable resistor of 10KΩ that tunes to the desired frequency, while R6 is a 1MΩ variable resistor that optimizes the Q-value of the circuit.

Table II: Component values of modified proposed active inductor circuit for different frequencies

Sl. No.	Center frequency (kHz)	C1 (nF)	C4 (nF)	R1 (KΩ)	R2 (KΩ)	R3 (KΩ)	R5 (KΩ)	R6 (KΩ)
1.	19.80	2	1	3.6	3.6	3.6	7.40	500
2.	22.20	2	1	3.6	3.6	3.6	5.75	300

The quality factor Q of the simulated modified proposed active inductor circuit is computed using the equation (8), and this is implemented using the Python programming language. The Python program screenshot is shown in Figure-5., in which values of different parameters are varied. The capacitors (C1 and C4) and resistors R1, R2 and R3 are kept constant and the values of resistors R5 and R6 are changed for the low frequencies of 19.80KHz and 22.20KHz. For all these variations, the resulting values of bandwidth and quality factor Q are computed. From Table-III, it is observed that the Q-factor value increases with the increase in the value of resistance R6 and correspondingly the bandwidth of the circuit decreases.

```
[ ]  import math

     # Function to calculate Q factor
     def calculate_q(fr, BW, R, C, L):
         # Q factor using resonant frequency and bandwidth
         q_resonant = fr / BW

         # Q factor using resistance, inductance, and capacita
         q_rlc = (1 / R) * math.sqrt(L / C)

         return q_resonant, q_rlc

     # Example values (You can replace these with actual input
     fr = 1000  # Resonant frequency in Hz
     BW = 50    # Bandwidth in Hz
     R = 10     # Resistance in Ohms
     C = 1e-6   # Capacitance in Farads
     L = 0.01   # Inductance in Henrys

     q_resonant, q_rlc = calculate_q(fr, BW, R, C, L)

     print(f"Q factor (using resonant frequency and bandwidth)
     print(f"Q factor (using RLC formula): {q_rlc}")

     Q factor (using resonant frequency and bandwidth): 20.0
```

Figure-5:Python Program for computing the Q-factor.

Table III: Q-value of modified active inductor for different R6 values

Frequency (kHz)	Value of R6 (kΩ)	Bandwidth (Hz)	Q-value
19.80	100	354	55.93
	300	146	135.61
	500	90	220.00
22.20	100	650	34.15
	200	171	129.82
	300	110	201.81

5. RESULTS AND DISCUSSION

The output response of the modified proposed active inductor circuit comprising the original and modified active inductors is evaluated when tuned at 19.80KHz and 22.20KHz respectively, using SPICE simulation software. The evaluation at two specific frequencies emphasizes the circuit's performance and provides an overview of its operational abilities before the realization of the tuning circuit. The two tuning circuits have been analyzed using frequency response (over the range of 10KHz to 30KHz), noise figure analysis, and temperature sweep analysis (27°C is maintained for the analysis). The tuning circuit is designed specifically for VLF applications and is coupled to an antenna producing an output voltage in the range of millivolts. The simulation utilizes an input voltage of 10 millivolts from a signal generator.

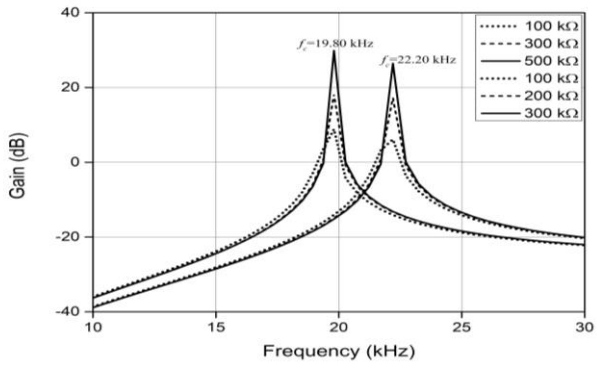

Figure 6:Q-values of tuning circuit for different values of R6 at 19.80KHz and 22.20KHz

Figure-6 illustrates the output response of the modified tuning circuit at 19.80KHz and 22.20 kHz to demonstrate the advantage of the modified active inductor. The variable resistor (R6) is varied to optimise the Q-value of the circuit at the desired frequency. The output frequency response when R6 at 100KΩ for 19.80KHz and 22.20KHz (dotted line), R6 at 300KΩ for 19.80KHz and 200KΩ for 22.20KHz (dashed line), and R6 at 500KΩ for 19.80KHz and 300KΩ for 22.20KHz (solid line) show an increase in Q-value when R6 is systematically varied. The bandwidth and Q-value are derived from Figure-6 and are presented in Table III.

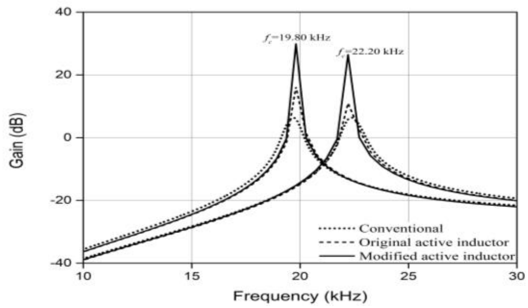

Figure-7:Circuit output response of tuning circuit

Figure-7 illustrates the output response in the frequency domain of the tuning circuit comprising the conventional inductor (dotted line), original active inductor (dashed line), and modified active inductor (solid line). These circuits provide the maximum voltage gain at 19.80KHz and 22.20KHz illustrating that the circuits are tuned to the desired frequencies, by allowing specific frequency. The tuning circuit with a modified active inductor offers a narrow bandwidth of 90 Hz and 110 Hz with a high Q-value of 220 and 201.81 at 19.80KHz and 22.20KHz, respectively. Table III provides a summary of the results shown in Figure-7.

Table III: Bandwidth and Q-value of the tuning circuits

Circuit Type	Frequency (kHz)	Bandwidth (Hz)	Q-value
Passive	19.80	540	36.67
	22.20	600	37.00
Tuning circuit 1	19.80	160	123.75
	22.20	300	74.00
Tuning circuit 2 (Modified)	19.80	90	220.00
	22.20	110	201.81

The tuning circuit comprising the conventional inductor provides a lower Q-value due to the limitations of the passive inductor [17]. The tuning circuit comprising the original active inductor lacks the property of simulating negative impedance in series with the simulated inductance that results in the simulation of high Q-inductance. However, this limitation is overcome by the modified inductor. The noise analysis in the circuit evaluates the contribution of each resistor and semiconductor component, characterizing them as a distinctive noise source. The noise figure is a quantitative measure of the additional noise introduced by an element in a circuit system [14]. The noise figure analysis is simulated at an ambient temperature of 27 °C, in the frequency domain over the frequency range of 10KHz to 30KHz.

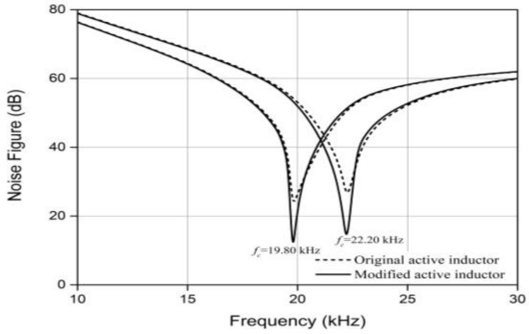

Figure-8: Total Noise figure of tuning circuit

Figure-8 illustrates the total noise figure of the tuning circuit comprising of original active inductor (dashed line) and modified active inductor (solid line). The total noise figure for the original active inductor at 19.80KHz is 25.70dB, whereas for the modified active inductor, the value is 12.49dB. The noise figure for the original active inductor at a frequency of 22.20KHz is 29.62dB, whereas for the modified active inductor, the value is 14.77dB. The modified active inductor has a reduced total noise figure than the original active inductor, making it advantageous for VLF applications.

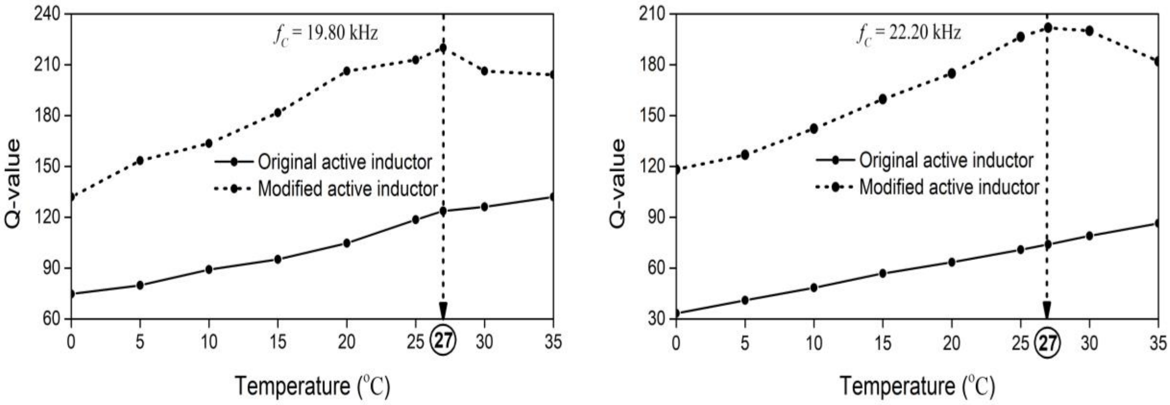

Figure-9: Q-value of tuning circuits tuned at different

Figure-9 illustrates the Q-value of tuning circuits when tuned at 19.80KHz (on the left) and 22.20KHz (on the right) over the temperature range in the frequency domain. The temperature analyses show the influence of temperature on circuit performance, emphasizing the need to design circuits that can operate accurately over the temperature domain in the range from 0°C to 35°C. Both circuits demonstrated a linear increase in trend with an increase in the temperature. The tuning circuit with the original active inductor offered Q-values ranging from 74.71 to 162.29 when tuned at 19.80KHz and ranging from 33.28 to 102.77 when tuned at 22.20 KHz. The tuning circuit with a modified active inductor offered Q-values ranging from 132 to 220 over a temperature range of 0°C to 35°C, with a maximum Q-value of 220.00 at 27°C when tuned at 19.80KHz, while Q-values range from 118.08 to 201.82 over the same temperature range with maximum Q-value of 201.82 at 27°C when tuned at 22.20KHz. The increase in the Q-value of the tuning circuit is a result of modifications made to the original active inductor, making it suitable for VLF applications and employing dynamic temperature conditions.

6. Conclusion

The tuning circuits comprising original and modified active inductors were simulated in the frequency domain when tuned at 19.80KHz and 22.20KHz to evaluate Q-value, noise figure, and temperature effects. The proposed active inductor offers a tuning range of 17.30KHz to 76.00KHz and provides the advantage of fine-tuning, allowing for the optimization of Q-value. The tuning circuit offered a narrow bandwidth to enhance the filtering of undesired signals with bandwidths of 90Hz and 110Hz at 19.80KHz and 22.20KHz. In addition, the tuning circuit yields a Q-value of 220 and 201.81 at said frequencies. The tuning circuit also offers a reduced total noise figure, measuring 12.49dB at 19.80KHz and 14.77dB at 22.20KHz at 27°C, leading to the minimization of noise generation within the circuit. The temperature analyses indicate the influence of temperature on the operation of the tuning circuit while maintaining a stable center frequency between 0°C and 35°C. The findings demonstrate a substantial improvement in Q-value with a narrow bandwidth and a reduced noise figure in comparison to the tuning circuits that include the original active inductor. This makes it well-suited for very low-frequency applications.

7. References:

[1] Susan, D. and Jayalalitha S. (*2017)* "Frequency selective circuits using Op-Amp based simulated inductor." *IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI),* 2310-2314.

[2] Susan D. and Jayalalitha S. (2016), "Simulated inductor-its relevance in analog track", ARPN J. Eng. Appl. Sci. (11) 19.

[3] Susan, D. & Jayalalitha, S. (2012) "Low frequency amplifier and oscillator using simulated inductor", Procedia Engineering. 30. 730-736.

[4] Anshita Jain, Gamad R. S., Ajnar D.S. (2021) "Realization of gyrator circuit and its application to high order filter", IJCRT, (9) 12, ISSN: 2320-2882.

[5] Hamdaouy Ridouane, Boussetta Mostapha, Khadija Slaoui. (2017) "Application of the active inductor circuit (AI) based band pass Filter (BPF)", IJMCTR, (5) 12, ISSN: 2321-0850.

[6] Rachita Angadi and Shasidhar Tantry. (2020) "Realization of Gyrator Circuit and its Application Demonstration on Cadence Tool". IEEE International Conference for Innovation in Technology (INOCON) Bengaluru, November 25, 2020.

[7] Ye, Xin & Wang, Yuxin & Tang, Xiao-Yu & Ji, Haifeng & Wang, Baoliang & Huang, Zhiyao. (2019), "On the Design of a New Simulated Inductor Using a Contactless Electrical Tomography System as an Example", Sensors. 19. 2463. 10.3390/s19112463.

[8] Harish S B. H. Lavanya Vaishnavi D A and Anil Kumar C (2024), "Filter based analysis for the mri data in biomedical engineering", OGF, vol. 34, no. 3s, pp. 2476–2484.

[9] Kewin Bellows, Edgar Sánchez-Sinencio "Advantages and Disadvantages of Active Inductors on Chip over Monolithic Inductors", ECEN 2013

[10] Jain, Megha et al. "VDTA Based Fractional Order Floating Inductor and its Applications." 2020 7th International Conference on Signal Processing and Integrated Networks (SPIN) (2020): 929-934.

[11] Soliman, A.M. (2010), "On the realization of floating inductors". Nat. Sci. 2010, 8, 167–180.

[12] Adel S.Sedra and Kenneth C.Smith, (2010), "Microelectronic circuits", Oxford University Press, Sixth edition.

[13] S. V. Utyuzhnikov, A. V. Konyukhov, and D. V. Rudenko (2004), "Simulation of Subsonic and Supersonic Flows in Inductive Plasmatrons", AIAA JOURNAL, Vol. 42, No. 9, September 2004.

[14] Vaidyanathan, Sundarapandian & Sambas, Aceng & Mohamed, Mohamad A & Mamat, Mustafa & Sanjaya, W. S. Mada & Sudarno, Sudarno. (2021). "A new 2-D multi-stable chaotic attractor and its MultiSim electronic circuit design". Indonesian Journal of Electrical Engineering and Computer Science. 22. 699.

[15] Yuce, Erkan & Sssafari, LLleila & Minaei, Shahram & Ferri, Giuseppe & Barile, Gianluca & Stornelli, Vincenzo. (2021). "A New Simulated Inductor with Reduced Series Resistor Using a Single VCII. Electronics". 10. 1693. 10.3390/electronics10141693.

[16] Agrawal, D.; Maheshwari, S. (2021) "Electronically Tunable Grounded Immittance Simulators Using an EX-CCCII". Int. J. Electron.2020,107, 1625–1648.

[17] Yuce, E. (2007) "Inductor Implementation Using a Canonical Number of Active and Passive Elements", Int. J. Electron.2007, 94, 317-326.

[18] Fang, Yujia & Hu, Yinuo & Li, Junxiao. (2023), "Design and Implementation of a Wideband Practical Chua's Chaotic Signal Generator", Highlights in Science, Engineering and Technology. 32. 163-176. 10.54097/hset.v32i.4987.

[19] Abdullah Yesil,Firat Kacar, Koray Gürkan. 2014. "Lossless grounded inductance simulator employing single VDBA and its experimental band-pass filter application", International Journal of Electronics and communications. 68: 143-150.

[20] Yuce, E.; Minaei, S. (2017), "Commercially Available Active Device Based Grounded Inductor Simulator and Universal Filter with Improved Low Frequency Performances", J. Circuits Syst. Comput. 2017, 26, 1750052. https://doi.org/10.1142/S0218126617500529.