

Grounded Simulated Inductor - A Review

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Abstract: Inductor is a passive component which is used in the implementation of various electronics circuits for different applications. But the use of a physical inductor poses many problems. One common among them is that physical inductors are larger in size and have too many numbers of turns which makes it impossible to realize practically. This paper deals with the overall review of the various disadvantages of using physical inductor and various methods of replacing the inductor by the simulated inductor using active components. Also the paper deals with the various applications of simulated inductor in analog circuits.

Key words: Inductor • Simulated inductor Generalized Impedance converter • Analog filters • Low frequency amplifier • Low frequency oscillator

INTRODUCTION

The recent trend in the development of electronics is the reduction in size of the circuits [1]. This needs the integration of various components on the integrated chip. The fabrication of the active components and the passive components like the resistors and capacitors on the IC fabrication is possible but, it is impossible to fabricate the inductor [2], because the physical inductor is larger in size and has more number of turns which makes it impossible to fabricate. In the survey, UMESH KUMAR and SUSHIL KUMAR SHUKLA highlighted many disadvantage of physical inductor [3,4]. Some are listed below.

- The magnetic material forming the core and the conductors forming the windings are deposited on the semi-conducting material surface which does not exhibit the ferromagnetism. This arrangement results in inductors of very low inductance L and poor quality factor Q .
- Reduction in the size of the inductor reduces the quality factor
- The best attainable value of the quality factor with the inductor is 1000 since the large inductors are lossy. But even higher values of 5,000 to 10,000 can be attained with the capacitor.
- At low frequencies, inductors are seldom used because the inductors are bulky.

- As the inductors made of ferromagnetic materials are nonlinear in nature, they generate harmonic distortion, unless the amplitude of the signal handled is kept small and direct currents are avoided.
- Inductors tend to act as small antennas, radiating as well as picking up electromagnetic waves. This can result in undesirable noise and coupling of signals in circuits containing inductors.

Hence, the conventional wire wound inductors used in analog circuits are bulky and costly. There also exists another serious and a fundamental limitation that it cannot be fabricated on IC chips where there is a need for miniature in size. Hence it is not compatible with the today's IC Technology.

Even though many disadvantages are mentioned in the literature, the one which is of high importance is the limitation of use of inductors at low frequencies. The inductors cannot be used at low frequencies because of many disadvantages mentioned in [3]. The disadvantages includes that (i) the size and weight of the inductors are large and physically bulky. (ii) The quality factor becomes very low. (iii) Their characteristics are also quite non-ideal. (iv) Moreover, the inductors are impossible to fabricate in monolithic form [5, 6] and are incompatible with any of the modern techniques for assembling in electronic systems.

One way to overcome this difficulty is the use of some other equivalent circuit which simulates the physical inductor. This paper presents the review of various methods of implementing the physical inductor to eliminate most of the above mentioned disadvantages and its applications in analog circuits. The performance of the simulated inductor should be same as that of the physical inductor over the entire range of frequencies. The simulated inductor is used in the design of filters, amplifiers, oscillators and tuned amplifiers.

Methods of Simulating Grounded Inductor -Theory

Gyrator Circuit: The most commonly used circuit for realizing the inductor using the active circuit is the gyrator [7-9] as shown in Figure 1. It is an element represented by a two port network with the terminal 1-2 and 3-4. The two port voltage and current equations are represented by the equations.

$$v_1 = Ki_2$$

$$v_2 = Ki_1$$

where v_1, v_2 and i_1, i_2 are voltages and currents at the port 1-2 and 3-4 respectively.

The impedance matrix $[Z]$ for the gyrator circuit is represented by [10-12]

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} 0 & -K \\ K & 0 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}$$

where K is the gyrator resistance. If the gyrator is terminated by a capacitor, it is used to realize the inductor as shown in Figure 1.

Riordan Circuit: The gyrator circuit [7] can be realized using a circuit which makes use of the active component op-amp, the resistors and capacitors. One such circuit formed is called the Riordan circuit as shown in Figure 2 whose impedance is given by

$$Z_{in} = \frac{R_1 R_3 R_5}{R_4} Z_2$$

where Z_{in} is the impedance at the port 1-2. The mathematical derivations are derived on the assumptions that the op-amp gain is assumed to be

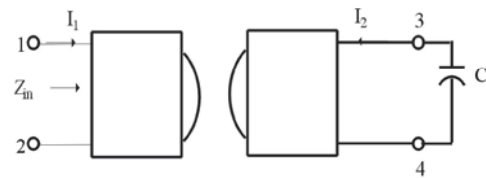


Fig. 1: Gyrator circuit and gyrator terminated with the capacitor

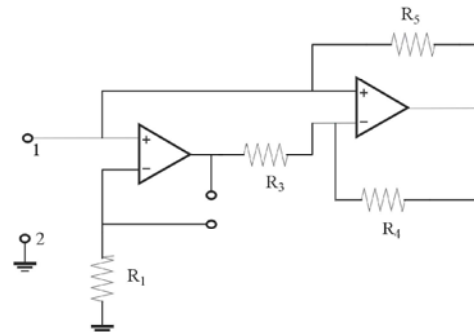


Fig. 2: Riordan circuit from Gyrator

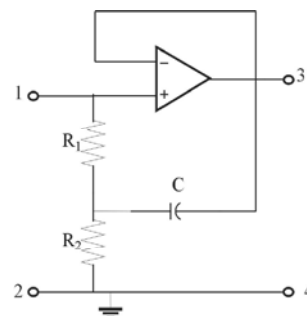


Fig. 3: Grounded inductor using single op-amp-Type I

theoretically infinite, the potential differences across the terminals are assumed to be zero and the current drawn by both the terminals of the op amp is assumed to be zero.

There are different ways of implementing the gyrator and the various methods are discussed below.

Grounded Inductance Realization Using Single Op-Amp:

The circuits are formed with single op-amp for the grounded inductor. The circuit shown in Figure 3 shows one type of realization of a lossy inductor whose input impedance is given by.

$$Z_{in} = R_1 + R_2 + sR_1R_2C$$

From this, the inductance value is $L = R_1R_2C$ and $R = R_1 + R_2$. The drawback of the circuit is that the quality factor is poor.

The second type of circuit used for realizing grounded inductor is shown in Figure 4.

The inductance of the circuit is given by

$$L = \frac{R_2 C (R_1 - R_2)}{1 + \omega^2 C^2 R_2^2}$$

The quality factor of the circuit is given by

$$Q = \frac{\omega C (R_1 - R_2)}{1 + \omega^2 C^2 R_2^2}$$

This circuit has the disadvantage that the inductor is a function of the frequency and the equation above shows that the value of inductance decreases with increase in frequency. This is done experimentally and the reasons for this are 1) the finite value of gyrator resistance 2) the gain of the op-amps also varies with frequency. So this type of simulated inductor circuit cannot be used for the wide range of frequencies.

Grounded Inductor Simulation Using Two op-Amp:

The most commonly used circuit is the Antoniou's circuit named after the scientist Antoniou as shown in Figure 5 which is derived from the Generalized Impedance Converter (GIC) [6, 11,13, 14].The impedance of the circuit is derived using the basic nodal voltages and accordingly, the impedance of the circuit is given by

$$Z_{in} = \frac{sC_4R_1R_3R_5}{R_2}$$

If $R_1 = R_2 = R_3 = R_5 = R$ and $C_4 = C$, then

$$Z_{in} = sCR^2$$

The inductor realized is an ideal inductor. All the above mentioned circuits are used for the realization of a physical inductor which must be a grounded inductor [15].

The graph in Figure 6. shows the experimental verification of simulated inductor for Antoniou circuit.

The experiment was carried out to validate the simulated inductor. For the Antoniou's circuit, Table 1 shows the value of simulated L for different values of resistance R5.

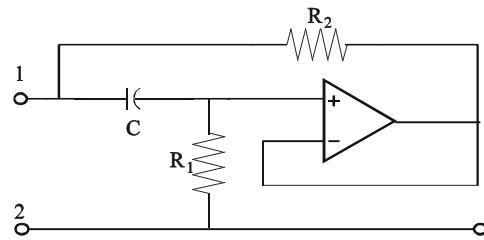


Fig. 4: Grounded inductor using single op-amp-Type II

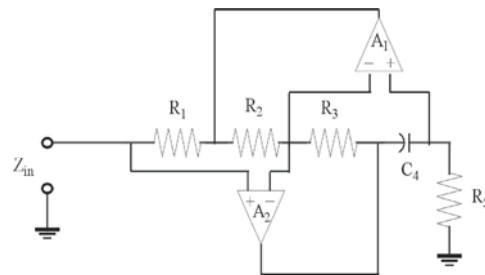


Fig. 5: Grounded inductor using two op-amp

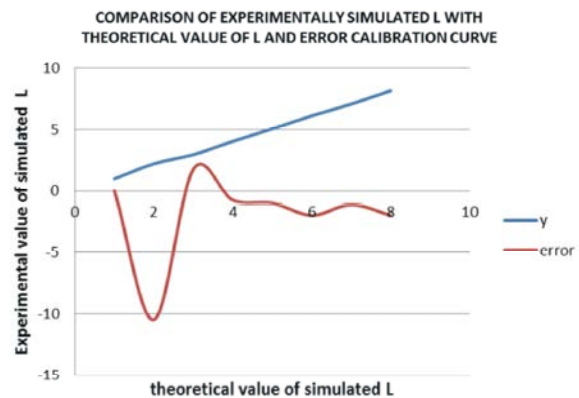


Fig. 6: Grounded inductor using single op-amp-Type II

Table 1: Design Values of Simulated I

| C4=1µf,R=1KO | |
|--------------|---------|
| R5 | L=C4RR5 |
| 1K | 1H |
| 2K | 2H |
| 3K | 3H |
| 4K | 4H |
| 5K | 5H |
| 6K | 6H |
| 7K | 7H |
| 8K | 8H |

Table 2 shows that the theoretical value of the nductor (L) matches with simulated value of L with an error percentage of -1.95.

Table 2: Comparison Between the Theoretical Value of L and Simulated l

| Theoretical value of simulated L | Experimental value of Simulated L | % Error |
|----------------------------------|-----------------------------------|---------|
| 1H | 1H | 0 |
| 2H | 2.21H | -10.5 |
| 3H | 2.947H | 1.77 |
| 4H | 4.03H | -0.75 |
| 5H | 5.05H | -1 |
| 6H | 6.12H | -2 |
| 7H | 7.08H | -1.14 |
| 8H | 8.16H | -2 |

Applications of Grounded Simulated Inductor in Analog Circuits Using Antoniou Circuit: At present the simulated inductor finds many applications in analog circuits and many researchers are concentrating on the application of simulated inductor. One major application is analog filter. Some of the applications of simulated L validated by S.JAYALALITHA AND D.SUSAN [16-19] are given with their simulated results using the PSPICE.

Design and Implementation of Analog Filters: There are different ways of implementing the inductorless filters. Some mentioned in the literature are

Electronically Programmable Inductorless Filters: Electronically programmed inductorless ladder filters [20] are those in which the frequency responses of the filters are electronically programmed by an external analog or digital signal. An active ladder structure is used. These programmable filters are capable of greater selectivity and flexibility of operation.

Linear Transformation Filters: The linear transformation filters make use of the linear transformation of port variables from the V-I domain to a new domain in which the filters are realized actively. Such filters are called Linear Transformation Active filters (LTA) filters [21,22].

Filters Using Grounded Parallel Inductance Simulators: A novel method of grounded parallel inductance simulator is used for realizing the filters [23]. This circuit consists of four second generation current conveyors using two dual-output current conveyors (DO-CCIIS) and three passive components to realize the inductor and it is used for realizing inductor simulator. This method has the advantage of greater linearity, lower power consumption, wider bandwidth, higher accuracy and better dynamic range

Electromechanical Filters-inductor less Filter: This electromechanical filters (inductorless filter) [24, 25] make use of the energy storage property of inductors and capacitors to realize the frequency selectivity. Some of the advantages of this types of filters includes 1) negligible power dissipation 2) practically no noise.

Simulated Inductor Using Second Generation Current Conveyors (CCII): The high Q grounded inductances are implemented using the second generation current conveyors (CCII) [26-36]. This makes use of current conveyor and three or four passive components namely the resistors and capacitors. The first method is shown in Figure 7.

This simulates series RL impedance which is given by

$$Z_{in} = R_2 + sCR_1R_2/2$$

It is found that the inductance value is independently controlled using the resistor R_1 and hence the quality of L is improved. The Figure 8. shows the second method of realizing ideal L tunable through R_2 . This finds application in band pass filters, band reject filters and oscillators.

Low Pass Butterworth Filter: The analog filters are constructed from the basic LCR resonator circuit [37] shown in Figure 9.

By properly connecting the nodes x, y and z either to the input, output or to ground, different types of filters are realized like low pass filter, high pass filter, band pass filter, notch filter and all pass filters. It is used for various applications. For example low pass filter is used to reject unwanted signal frequencies [38] and notch filter is used to reduce power line hum [39].

For example, to design a high pass filter for the cut-off frequency of $f_0 = 10$ Hz, assuming $C = 0.1\mu F$ & using $f_0 = 1/(2\pi\sqrt{LC})$, the required value of L is 2,535.59 H [25]

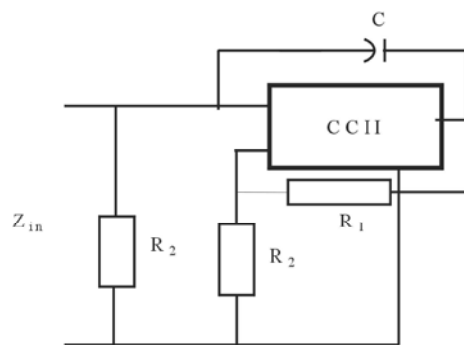


Fig. 7: Second generation current conveyor-Method I

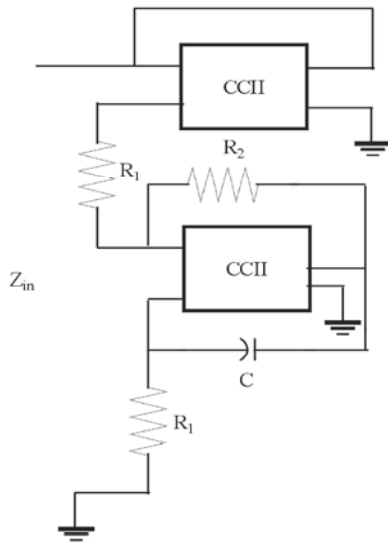


Fig. 8: Second generation current conveyor-Method II

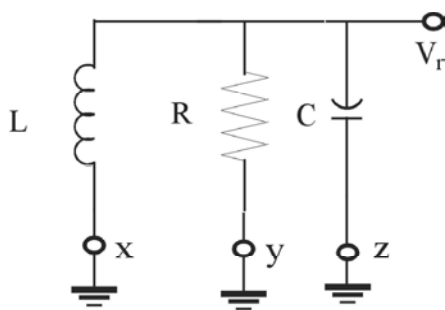


Fig. 9: Basic LCR resonator circuit

Similarly for $f_0 = 100\text{Hz}$, assuming $C = 0.1\mu\text{F}$, the required value of $L = 25.36\text{ H}$. Such a high value of inductor is difficult to implement and there is a need for inductorless filters [40]. In this paper, the design of analog filters at low frequencies [41] is given and they are implemented using simulated inductor. The basic LCR resonator connection for high pass filter using simulated inductor is shown in Figure 10.

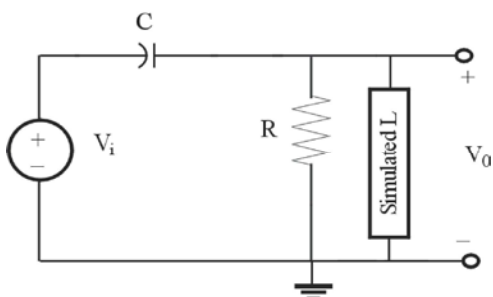


Fig. 10: High pass filter from basic LCR resonator using simulated L

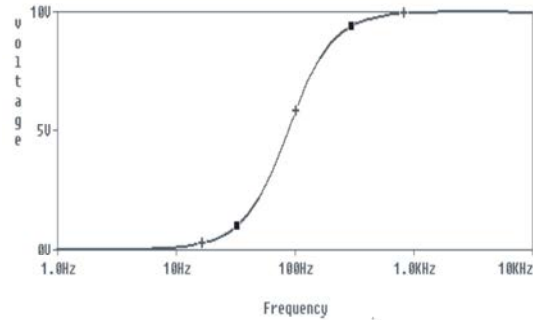


Fig. 11: Frequency response of high pass filter for $f_0=100\text{Hz}$

The transfer function of the high pass filter is given by

$$T(s) = \frac{Ks^2}{s^2 + s\frac{1}{CR} + \frac{1}{C^2R^2}}$$

The frequency response of the high pass filter whose cutoff frequency is 100Hz is shown in Figure 11. Similarly all the type of filters are designed and can be implemented [16]. This concept using simulated L can also be applied for Bessel filter implementation [17]. Bessel filter removes noise frequencies [42].

Active Filter Tuned Oscillator Using Simulated Inductor:

Another application of simulated inductor is the active tuned oscillator used for generation of low frequency sine wave [18]. To generate a sine of 100Hz which is a low frequency, the value of L required is 158.47H. Hence such a large value is implemented using only the simulated L. The circuit diagram of the active filter tuned oscillator is shown in the Figure 12. This consists of the active band pass filter using simulated L and whose centre frequency is

$$f_0 = 100\text{Hz}$$

Let

$$C_1 = C_2 = 16\text{nF}$$

$$L = \frac{1}{4 \times \pi^2 \times f_0^2 \times C_2}$$

$$L = 158.47\text{H} = C_2 R^2$$

$$R = \sqrt{\frac{L}{C_2}} = R_2 = R_3 = R_4 = R_5 = 99.522\text{K}\Omega$$

$$R_6 = 1\text{K}\Omega, R_{1POT} = 50\text{K}\Omega - 200\text{K}\Omega$$

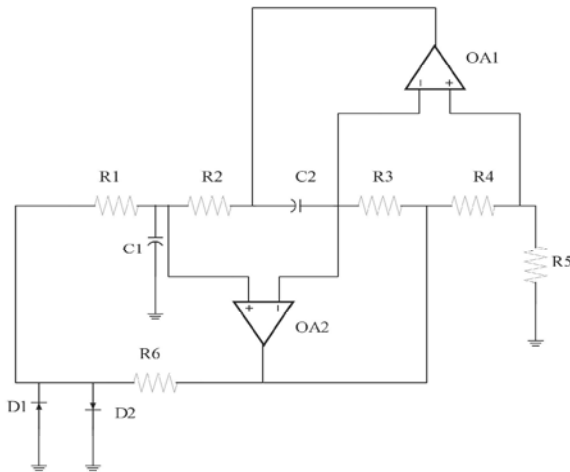


Fig. 12: Active filter tuned oscillator

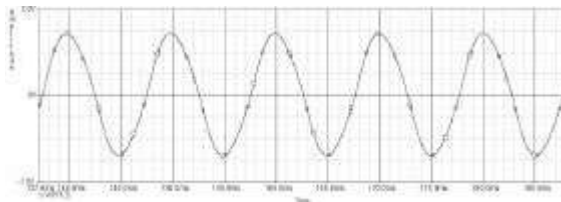


Fig. 13: Output of Active filter tuned oscillator for the frequency of 100Hz

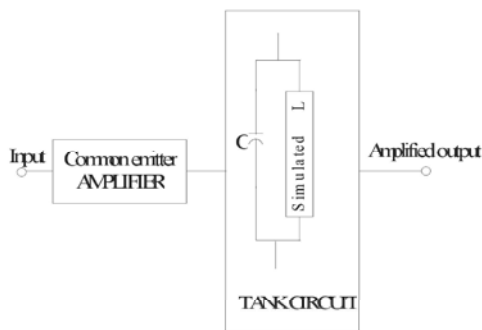


Fig. 14: Block diagram of single tuned low frequency amplifier

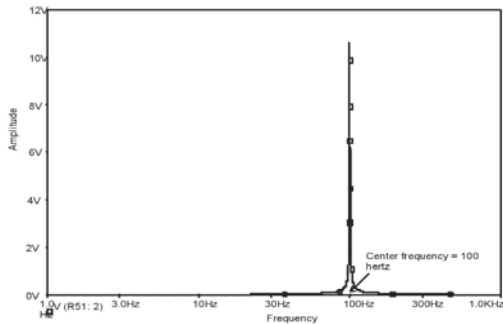


Fig. 15: Frequency spectrum of single tuned amplifier for 100Hz

the frequency of the sine wave generated. The limiting diodes are used as feed back circuit. Figure 13 shows the sine wave generated from the active tuned oscillator. The circuit design is given below.

Design of Active filter tuned oscillator using simulated Inductor

Single Tuned Amplifier Using Simulated Inductor: another application of the simulated L at low frequency is the single tuned amplifier [19] which basically consists of a tuned circuit. The block diagram of the single tuned amplifier is shown in Figure 14. The tuned circuit is intended to get a resonant frequency same as the incoming frequency signal which appears at the input of the amplifier. The Single Tuned Amplifier gives highest amplification to that particular received frequency which equals the resonant frequency of the tuned circuit and attenuates all other frequencies. Thus it gives sharp selectivity with a high Q-factor. Simulated L can also be realized using unity gain amplifier and differential amplifier [43, 44].

To design such a low frequency amplifier for 100Hz, the requirement of L is 2.536H.

The design shows the use of simulated L to generate 100Hz sine wave. The frequency response of the amplifier is given in the Figure 15.

Amplifier Design:

Given : $V_{CC} = 10V, I_C = 10mA, \beta = 150, S = 2$

Values : $R_1 = 5.9647K\Omega, R_2 = 1.222K\Omega$

$R_E = 1K\Omega, C_E = 50nF$

Where R_1 is the voltage divider resistor near the supply, R_2 the other resistor, R_E the emitter resistor and C_E the bypass capacitor.

Tank circuit and simulated inductor design:

$$f_0 = 100\text{hertz}, C = 1\mu F, L = 2.536H$$

$$L = CR^2, C = 1\mu F, R = 1.592K\Omega$$

LC Oscillator Using Simulated Inductor: The LC oscillators namely Colpitts and Hartley oscillators are usually designed for audio frequency range. The design aspect of the oscillators is given below.

The frequency of oscillation for Hartley oscillator is given by

$$f_0 = \frac{1}{2\pi\sqrt{(L_1 + L_2)C}}$$

If $L_1 = L_2 = \frac{L}{2}$ then $f_0 = \frac{1}{2\pi\sqrt{LC}}$

The frequency of oscillation for Colpitts oscillator is given by

$$f_0 = \frac{1}{2\pi \sqrt{\frac{C_1 C_2}{C_1 + C_2} L}}$$

If $C_1 = C_2 = 2C$ then $f_0 = \frac{1}{2\pi \sqrt{LC}}$

The design of Hartley and Colpitts oscillators for low frequency [19] say 100Hz use inductor of 1.268H for the assumed capacitance value of 0.01μF. As the value of inductance is high the oscillators are designed and implemented with simulated inductor. The block diagram of the oscillator (say Hartley) is given in Figure 16

(Single Tuned Amplifier):

Amplifier : Dessign

Give $V_{cc}=10V, I_c=10mA, \beta=150, S=2$

Designed values : $R_1 = 5.9647 \Omega, R_2 = 1.222 k\Omega$

Stabilization Resistor and Capacitor :

$R_E = 1k\Omega, C_E = 50nF$

Tank Circuit Design : $f_0=100hz, C=1\mu F, L=2.536H$

Simulated L design : $L=CR^2, C=1\mu F, R=1.592k\Omega$

Amplifier Design : Given : $V_{cc}=10V, I_c=10mA, \beta=150, S=2$

Designed Values

Voltage Divid: $R_1=33k\Omega, C_E=13.99\mu F$

Stabilization Resistor and Capacitor :

$R_E = 1k\Omega, C_E = 1.67nF$

Tank Circuit (Hartely Oscillator) Design :

$f_0=100Hz, C=1\mu F, L_1=L_2=2.536H$

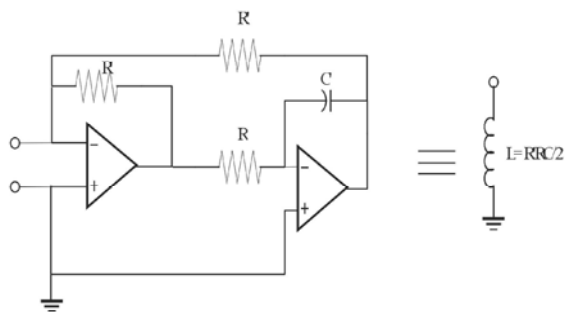


Fig. 16: Block diagram of LC oscillator(Hartley)

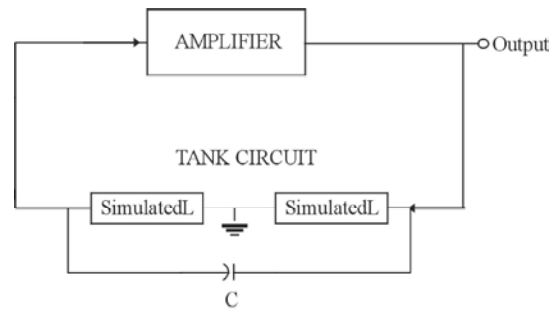


Fig. 17: Output of LC oscillator

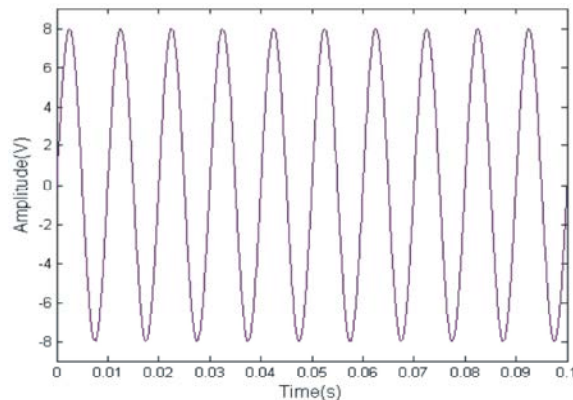


Fig. 18: Low Q factor inductor circuit

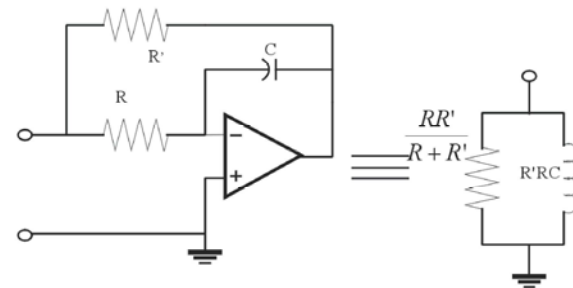


Fig. 19: Negative resistance circuit

Simulated L design :

$L=CR^2, C=1\mu F, R=1.126k\Omega$

Tank Circuit (Colpitts Oscillator) Design:

$f_0=100Hz, C_1=C_2=2\mu F, L=2.536H$

Simulated L design : $L=CR^2, C=1\mu F, R=1.592k\Omega$

The output of the oscillator is given in Figure 17

Active Filters and Oscillators Using Simulated Inductance-another Approach: Most active filters and oscillators consist of basic LCR resonator circuit where the L is replaced by some active circuit having appropriate

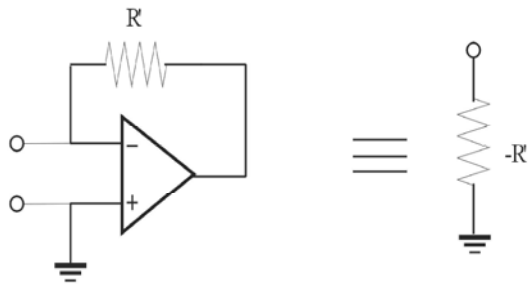


Fig. 20: High Q factor inductor circuit

impedance [45]. To provide proper input impedance equivalent to the inductor without loading, the following active circuit shown in Figure 18 which provides an input impedance equivalent to that of L in parallel with a resistor is used. This provides low Q factor. Hence a negative resistance as shown in Figure 19 is connected in parallel with that which provides L of high Q. This is shown Figure.20. This high quality simulated inductor is used for active filters and oscillator. This method is applicable only when inductor is grounded. If the inductor is floating, transformation is used which converts resistance to capacitance, capacitance to D element and inductor to resistance [46].

CONCLUSION

Inductors are bulky and costly because the volume of the inductor required for storing the energy in the magnetic field is more compared to the volume required to store the same amount of energy in electric field. But reducing the size will reduce the quality factor. Another limitation of realizing the inductor is that it is not suitable for integrated circuit applications. Hence, considering these constraints, this paper presents an overall view of the various methods used for simulating the inductor and its applications. Various methods are analyzed with its basic circuits and its advantages and limitation are discussed. The main limitation of simulated inductor is the variation of L with the frequency.

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