Simulation and Analysis of Variable Gain DVCC Based Active Inductance and its Application in Constant K Prototype and Resonance Filter

Ramkrishna V Yenkar[1], Manoj Kumar Nigam[2]

[1]Research Scholar, *School of Engineering and IT, MATS University, Raipur, India*
rvyenkar@gmail.com

[2]Professor, *School of Engineering and IT, MATS University, Raipur, India*
nigam74_123@yahoo.com

Abstract*: The inductor is an essential component in many electronic systems. But the passive inductance is not suitable due to its dimension and magnetic interference. To overcome these issues, active inductance is preferred. Active inductance is simulated using the RC network connected with an active device(s). Here, VG-DVCC (Variable Gain Differential Voltage Current Conveyor) is proposed as an active device. The VG-DVCC with two external R and one C component forms the Impedance Converter which converts Active RC network into Active Inductance. This paper gives an overview of the design-simulation of Active Inductance and the frequency range analysis of its linearity. Also, it highlights applications in the realization of constant k-prototype and resonance filters.

***Keywords*: Current Conveyor, Impedance Converter, Active Inductor, LC filters**

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I. INTRODUCTION

The passive Inductance has a large size and induces magnetic interference. Due to this, passive inductance is not preferred in electronic systems. Hence there is a need for developing a circuit without the use of inductance or find some alternative to develop it, without core and coil. Thus the alternate way of designing an inductance is the impedance conversion technique.

The impedance conversion means converting an Active RC network into an Active inductance. Many impedance converters were commercialized using different active devices. Those are Op-Amps [1, 2], CCs [3-5], CFA [6-7], OTA [8], VDTA [9-10], and VDCC [11-12]. Also, Op-Amp has limitations being voltage mode active element [13]. The VG-DVCC (Variable Gain Differential Voltage Current Conveyor) being a current mode active element has auspicious performance characteristics; such as high Z_{in}, low Z_{out}, high bandwidth and high slew rate [14]. Thus current mode VG-DVCC is used for simulation of inductance.

II. THE VG-DVCC

A. *Basic Principles*

The VG-DVCC (Variable-Gain Differential-Voltage-Current-Conveyor) is categorized on the basis of current at the output port. Those are VG-DVCC+ (positive current output) VG-DVCC- (negative current output) and VG-DVDOCC (dual current output). Out of these, VG-DVDOCC is used for the realization of floating Inductance.

The VG-DVDOCC is five ports Active Device, namely Y1, Y2, X, Z-, Z+. Also, it has three additional terminals a, a` and b for connecting two external components. Fig 1 shows the Symbolic representation of it. A floating Z_1 connected between p-q and a grounded Z_2 connected at terminal [15].

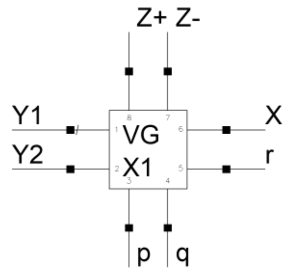

Fig 1: Symbol of VG-DVDOCC

The port characteristics are as follows.

- The Current drawn from port Y1 and Y2 is extremely small (ideally Zero) and independent. (Iy1 = Iy2 = 0).
- The voltage at the port X is proportional to the voltage difference between the signal applied at Y_1 and Y_2, and independently on the current Ix drawn from it. ($V_x=A (V_{y1}-V_{y2})$ where A is variable gain).
- The Current at both the Z ports is independent of load connected and voltage built up across the load.
- The current at the Z+ port is equal to the current generated at port X and Z- port is equal but opposite in direction to the current generated at port X. (Iz+ = Ix and Iz- = -Ix).

These port characteristics are expressed by Matrix as given below.

$$\begin{bmatrix} Iz- \\ Iz+ \\ Vx \\ Iy1 \\ Iy2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & +1 & 0 & 0 \\ 0 & 0 & 0 & A & -A \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Vz- \\ Vz+ \\ Ix \\ Vy1 \\ Vy2 \end{bmatrix} \quad ..(1)$$

Where A = Z_2/Z_1 is a variable gain.

B. *CMOS Circuit*

The detailed CMOS circuit of VG-DVDOCC is shown in fig. 2. The CMOS circuit has 4 different building blocks: Those are 2 voltage followers, one current mirror and one conventional Dual-out Current Conveyor and two external impedances.

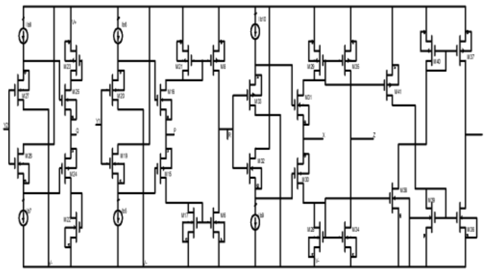

Fig 2: CMOS circuit of VG-DVDOCC

III. Proposed Active Inductance

A. *Types of Inductors*

In the RF electronic system such as filters, VCO, tuned amplifiers inductor is prominently used [16]. The inductances used in RF systems are classified as passive inductance and active inductance. The passive inductance is typically constructed using an insulated wire and a magnetic core that stores energy. Active inductances are constructed by using gallium arsenide or silicon technology. However, silicon technology is cheaper and it consumes low power [17]. The silicon-based spiral inductor consumes more area on a silicon wafer in chip fabrication. Also, the spiral inductor has fixed value and weak Q factor [18]. Hence researchers are developing the CMOS based active inductor using Impedance converter techniques which offers many advantages such as low chip area, provides tuning facility, high bandwidth, and good Q factor [19].

B. *Principle of Inductance*

The principle of inductance is that 'a changing magnetic field induces the voltage' – Joseph Henry. The induced voltage is proportional to the time rate of change of current flowing through it[20]. Thus, the v(t) - i(t) relation of inductance is expressed as v=L di/dt.

C. *Impedance Converter*

The Impedance Converter is capable of simulating frequency-dependent elements [21] such as Inductor, capacitor-multiplier, resistor-multiplier and FDNR (frequency-dependent negative resistance). The impedance convertors are two types: Grounded and Floating. The Grounded Impedance converter using CCII- and CCCII- was presented by Khan and Zaidi in 2003 [3] and floating GIC based DCCDVDOCCII [14] was described. The floating Inductor is more similar to passive inductor which can be connected anywhere in the circuit, between two or more components. Both ends of the impedance converter can be connected to two different levels of voltages or one end at the ground. But the one end of grounded impedance converter needs to be connected to the ground. It means a floating impedance converter offers more flexibility over grounded one.

D. *Floating Active Inductance*

For floating impedance converter Differential voltage input dual output current type of configuration is necessary. Here a proposed Dual out VG-DVCC is best suited for floating impedance converter as it has dual output current and differential voltage input. The proposed floating impedance converter using Dual out VG-DVCC is as shown in fig. 3.

The equivalent input impedance observed between input terminals Y1-Y2 terminal is expressed in terms of Z1 between p-q, Z2 at r and Z3 at X.

$$Z= \frac{Z1*Z3}{Z2} \quad …. 2$$

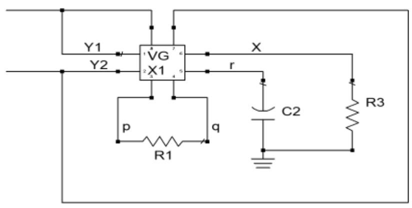

Fig 3: Floating Impedance converter based Active Inductor

E. *Simulation and Analysis*

The VG-DVCC based active inductance realization is shown in fig 3. In this the Z_1 & Z_3 are resistances R_1, R_3 respectively and Z_2 is a capacitance C_2.

From equation 2

$$Z = \frac{Z1*Z3}{Z2} = \frac{R1*R3}{1/jwC2}$$
$$= j\omega(R_1R_3C_2)$$
$$= j\omega L$$
$$\therefore L= R_1R_3C_2 \quad ¨ (3)$$

It means the circuit acts as Inductive reactance. To validate that the circuit shown in fig 3 acts as Inductor, simulation was done for transient and frequency analysis.

Transient Simulation: For simulation purpose R_1=300k, C_2=0.7pF and R_3 = 300k are used, which gives theoretical value of active inductance 63mH. The simulated value calculated from slope of the v - di/dt characteristics shown in fig 4 gives 61.3mH, which is within ±2.5%.

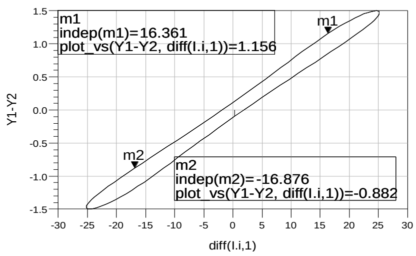

Fig 4: di/dt - V characteristics of Active Inductance

AC Simulation: The active inductance of in fig 3, is also Simulated for frequency domain analysis. For this purpose Ac signal connected to Y1 and Y2 grounded as shown in fig 5. The Fig 6 shows frequency response for C_2=1pF, R_1=R_3=300kΩ. It shows that, the AI offers Linear Inductive Reactance over 3 KHz to 30 MHz frequencies.

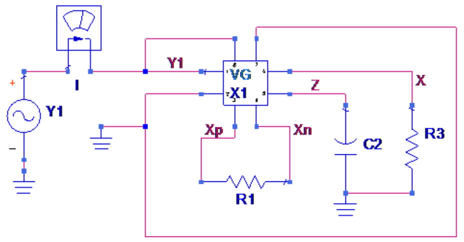

Fig 5: AC simulation of AI

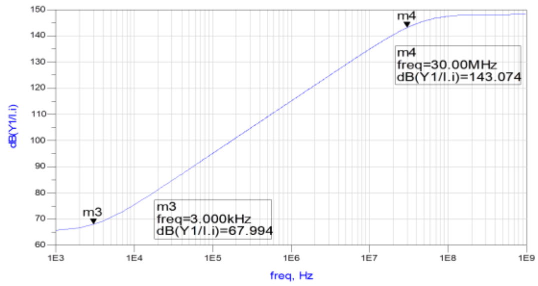

Fig 6: Frequency Response of Inductive Reactance of AI

Similarly, the frequency responses were studied for different values of C_2 by keeping R_1=R_3=300kΩ constant and the frequency range over which Impedance of active inductance |Z|=2πfL remains linear i.e. |Z|∝ f (or effective inductance L remains to its designed value) were observed and the result is compiled in Table 1.

TABLE I. USABLE FREQUENCIES OF ACTIVE INDUCTANCE

Sr. No	C_2	Designed Value of AI (L) Eq.(3)	Range of frequency in which Inductive reactance is Linear	
			Lower Frequency	*Higher Frequency*
1	0.01pF	0.9mH	0.3 MHz	3 GHz
2	0.1pF	9mH	30 KHz	300 MHz
3	1pF	90mH	3 KHz	30 MHz
4	10pF	900mH	0.3 KHz	3 MHz
5	100pF	9H	30 Hz	300 KHz
6	1nF	90H	3 Hz	30 KHz

From this frequency domain analysis, it is observed that effective inductance offered by Active Inductance remains within ±2.5% of its designed value for 4 decade of frequencies. This frequency domain analysis of AI helps filter designer to choose a particular value of C_2 based on signal and noise frequencies.

IV. CONSTANT K-POTOTYE AND RESONANCE FILTERS

Constant k-prototype [22] LC high-pass, low-pass and RLC resonance [23] type band-pass, band-stop filters are realized using simulated Active Inductance.

A. *High Pass Filter*

The constant K-prototype T-section LC circuit of the high pass filter using AI (Active Inductance) is shown fig 7. This circuit has cut off frequency $f_C = \frac{1}{4\pi\sqrt{LC}}$ and constant k= $\sqrt{\frac{L}{C}}$ [24]; where L is effective Inductance of AI and C $= \frac{C1}{2} = \frac{C2}{2}$ is passive capacitance.

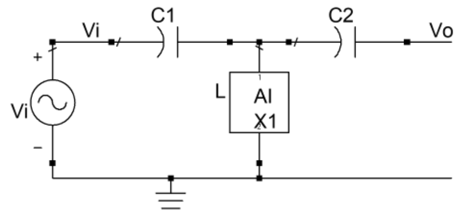

Fig 7: High-Pass Filter

This circuit is simulated for frequency response, having fc=10MHz and k=3.6 $\pi \times 10^5$ with circuit components L(AI)=9mH and C1=C2=0.014pF. The frequency response curve of this high pass filter is as shown in fig 8.

From this frequency Response, following points were observed.

- -3dB Cut-off frequency = 9.52MHz
- Roll of rate is -62.3dB/decade.
- Peak gain overshoots of 2.37dB@12.3MHz.
- Frequency Range for gain overshoots is 10.45MHz to 21.25MHz.

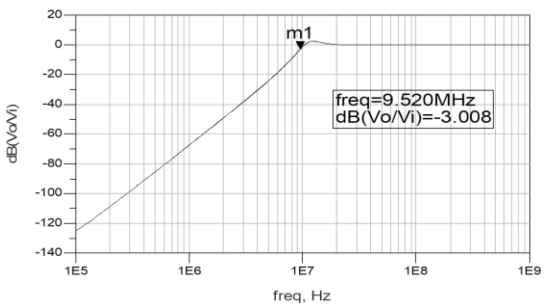

Fig 8: Frequency Response of high-pass filter

B. *Low Pass Filter*

The constant K-prototype π-section LC circuit of the low-pass filter using AI (Active Inductance) is shown fig 9. This circuit has cut off frequency $f_C = \frac{1}{\pi\sqrt{LC}}$ and constant k= $\sqrt{\frac{L}{C}}$ [24]; where L is effective Inductance of AI and C =2C1=2C2 is passive capacitance.

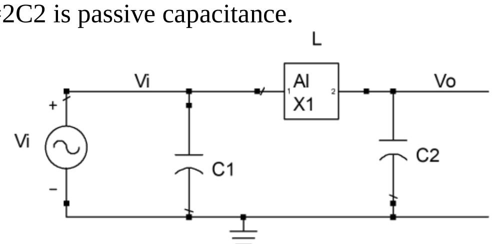

Fig 9: Low-pass Filter

This circuit is simulated for frequency response, having fc=10MHz and $k=9\pi\times10^4$; with circuit components L(AI)=9mH and C1=C2=0.56pF. The frequency response curve of this low pass filter is as shown in fig 10.

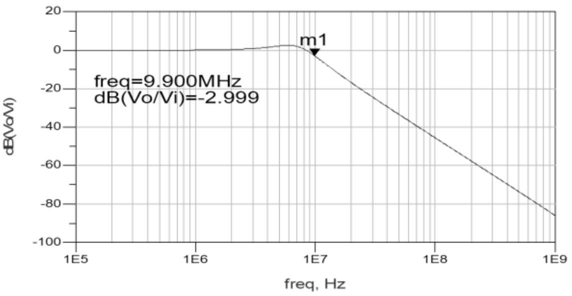

Fig 10: Frequency Response of low-pass filter

From this frequency response, following points were observed.

- -3dB Cut-off frequency = 9.9MHz
- Roll of rate is -42.2dB/decade.
- Peak gain overshoots of 2.5dB@6.2MHz.
- Frequency Range for gain overshoots is 1.1MHz to 8.4MHz.

C. *Band Pass Filter*

The circuit shown in fig 11 is parallel LC resonance band-pass filter using AI (Active Inductance). This circuit has centre frequency $fc=\frac{1}{2\pi\sqrt{LC}}$[23]; where L is effective Inductance of AI and C is passive capacitance.

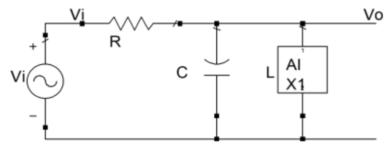

Fig 11: Band-pass Filter

This circuit is simulated for fc = 5.3MHz; with circuit components L(AI)=9mH, C=0.1pF and different values of R. The frequency response curve of this band pass filter with R=300KΩ is as shown in fig 12. Also, frequency response for different values of R is compiled in Table-2.

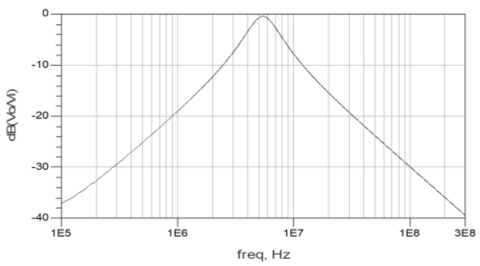

Fig 5: Frequency Response of Band-pass filter

From this frequency Response, following points were observed.

- For lower value of R: Gain at F_c approaches to 0dB but wider bandwidth.
- For higher value of R: Gain at F_c drops below 0dB but narrow bandwidth

TABLE II. FREQUENCY RESPONSE FO BAND-PASS FILTER

Sr. No	R in KΩ	Centre Freq. F_c in MHz	Gain at F_c in dB	Bandwidth	
				F_L in MHz	*F_H in MHz*
1	100	5.44	-0.087	1.74	17.4
2	300	5.44	-0.253	3.44	8.58
3	500	5.44	-0.418	4.12	7.13
4	1000	5.44	-0.817	4.75	6.16

D. *Band Stop Filter*

The circuit shown in fig 13 is series LC resonance band-stop filter using AI (Active Inductance). This circuit has centre frequency $fc=\frac{1}{2\pi\sqrt{LC}}$ [23]; where L is effective Inductance of AI and C is passive capacitance.

This circuit is simulated for f_c = 5.3MHz; with circuit components L(AI)=9mH, C=0.1pF and different values of R. The frequency response curve of this band stop filter with R=500KΩ is as shown in fig 14, Also, frequency response for different values of R is compiled in Table-3.

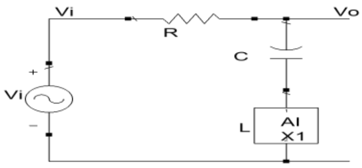

Fig 63: Band-stop filter

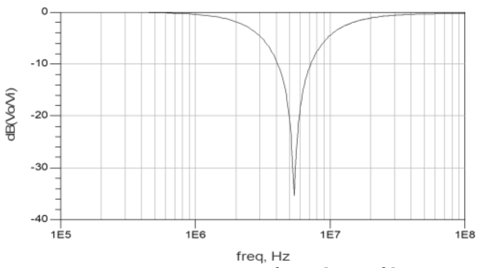

Fig 7: Frequency Response of Band-stop filter

TABLE III. FREQUENCY RESPONSE FO BAND-STOP FILTER

Sr. No	R in KΩ	Centre Freq. Fc in MHz	Attenuation at Fc in dB	Bandwidth	
				F_L in MHz	*F_H in MHz*
1	100	5.4	-22.03	4.51	6.49
2	300	5.4	-31.11	3.28	9.21
3	500	5.4	-35.44	2.48	12.5
4	1000	5.4	-41.39	1.46	20.97

From this frequency response, following points were observed.

- For lower value of R: Bandwidth is narrow but attenuation is less.
- For higher value of R: Attenuation is better but bandwidth is wider.

V. Conclusion

The Variable Gain DVCC is best suitable for floating Impedance converter. The proposed Active Inductance simulated using VG-DVCC based Impedance converter has effective inductance within ±2.5% of its theoretical values. The impedance of Proposed Active Inductance is linear or remains proportional to frequency over 4 decade of frequencies. Though, the value of effective inductance is theoretically independent on frequency but while designing or selecting L of Active inductance, frequency range of a particular application plays a vital role.

The magnetic interference free high order filters are easily developed using proposed Active Inductance. Constant k-prototype LC high-pass and low-pass filter designed using Active Inductance has better roll-off rate in stop band, constant gain in pass band but suffers from gain overshoots in transition band which is similar to passive filters. The performance of RLC resonance filters using proposed Active Inductance is similar to passive inductor based filters.

VI. Referances

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Author Profile

Ramkrishna V Yenkar received his B.E in Industrial Electronics from SSGMCE, Shegaon, India and M. Tech. in Electronics from VNIT, Nagpur, India. He has more than 31 years of experience in teaching, administration and research. He has published 19 research papers in national and international conferences and Journals. His field of interest includes Educational Technology, Analog / Digital systems, Current Conveyor and chaotic in nonlinear systems.

Dr. Manoj Kumar Nigam received the B.E. and ME degree in Electrical Engineering from MITS Gwalior, M.P., India and Ph.D. in Electrical Engineering from R.K.D.F University, Bhopal (M.P), India. He has more than 18 years of experience in teaching and research. He has published 35 research papers in national and international conferences and Journals. His current research focuses on Distributed generation, power electronics drives, current conveyors and power quality Issues in the Power System.