New Single VDCC-based Explicit Current-Mode SRCO Employing All Grounded Passive Components

Dinesh Prasad, D. R. Bhaskar and Mayank Srivastava

Abstract—**This paper proposes a new single resistance controlled sinusoidal oscillator (SRCO) which employs only one voltage differencing current conveyor (VDCC), two grounded resistors and two grounded capacitors. The presented circuit configuration offers the following advantageous features (i) explicit current-mode output with independent control of condition of oscillation (CO) and frequency of oscillation (FO) (ii) low active and passive sensitivities and (iii) a very good frequency stability. The proposed structure can also be configured as (a) trans-admittance low pass filter and band pass filter and (b) quadrature oscillator. The validity of the proposed SRCO, quadrature oscillator and trans-admittance low pass filter and band pass filter has been verified by PSPICE simulations using TSMC CMOS 0.18μm process model parameters.**

Index Terms—**VDCC, SRCO, current mode, filter.**

Original Research Paper
DOI: 10.7251/ELS1418081P

I. Introduction

Recently, attention is being given to single active element/ active building block (ABB) based SRCOs [1]-[12] and in particular explicit current-mode (CM) SRCOs [13]–[18] and the references cited therein. The use of single ABB has the advantageous features like small chip area, low power dissipation and manufacturing cost as compared to two or more ABBs. The CM operation has received much attention over voltage-mode (VM) operation due to its wider bandwidth and high linearity [19]. The usefulness of explict CM SRCO is well defined in [20]. The VDCC provides electronically tunable transconductance gain in addition to transferring both current and voltage in its relevant terminals [21]. The application of VDCC as positive/ negative lossy/ lossless grounded inductance simulation circuits and a floating inductance simulation circuit using single VDCC have been described in [22]-[23]. Therefore, the purpose of this article is to present a new explicit CM SRCO, quadrature oscillator and trans-admittance low pass filter and band pass filter using single VDCC and with bare minimum passive components. The performance of the various modes both in time-domain and frequency-domain has been verified by PSPICE simulation.

The paper is organized as follows: Proposed circuit is described in section 2. Section 3 includes non ideal analysis and sensitivity performance of the circuit. Frequency stability of the proposed circuit is presented in section 4. Sections 5 and 6 represent the simulation results and conclusion of the paper.

II. Proposed Circuit Configuration

The symbolic notation of recently proposed six- terminals active building block namely, VDCC is shown in Fig. 1, where P and N are input terminals and Z, X, W_P and W_N are output terminals. All terminals of VDCC exhibit high impedance, except the X terminal [22]. The ideal terminal characteristics of VDCC can be defined by the hybrid matrix as given by equation (1). The proposed configuration is shown in Fig. 2

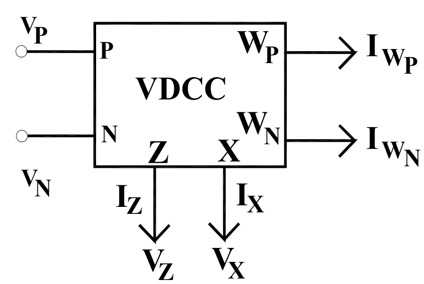


Fig. 1. The symbolic notation of VDCC.

$$\begin{bmatrix} I_N \\ I_P \\ I_Z \\ V_X \\ I_{W_P} \\ I_{W_N} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ g_m & -g_m & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} V_P \\ V_N \\ V_Z \\ I_X \end{bmatrix} \tag{1}$$

Manuscript received 14 August 2014. Received in revised form 19 December 2014. Accepted for publication 25 December 2014.

D. Prasad is with the Faculty of Engineering & Technology, Jamia Millia Islamia, New Delhi, India (phone: +91-11-26981284, e-mail: dprasad@jmi.ac.in)

D. R. Bhaskar is with Faculty of Engineering & Technology, Jamia Millia Islamia, New Delhi, India (e-mail: dbhaskar@jmi.ac.in).

M. Srivastava is with the Amity School of Engineering & Technology, Amity University, Noida, U.P., (e-mail: mayank2780@gmail.com).

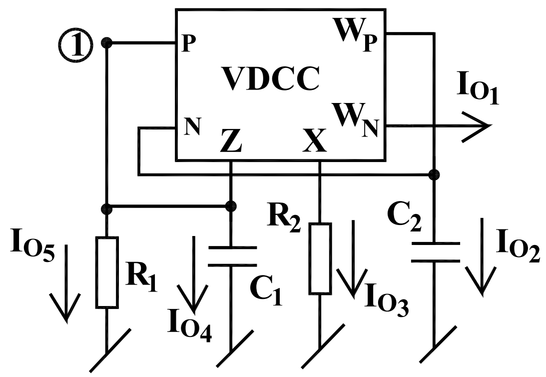


Fig. 2. The proposed circuit topology.

The characteristic equation of the proposed SRCO as shown in Fig. 2, can be derived using routine circuit analysis as:

$$s^2 + s\frac{1}{C_1}\left(\frac{1}{R_1} - g_m\right) + \frac{g_m}{R_2 C_1 C_2} = 0 \tag{2}$$

Thus, from equation (2), it is clear that the CO and FO are obtained as:

$$\left(\frac{1}{R_1} - g_m\right) \le 0 \tag{3}$$

and

$$\omega_0 = \sqrt{\frac{g_m}{R_2 C_1 C_2}} \tag{4}$$

From equations (3) and (4), CO can be established by R_1 and FO is controlled by R_2. Hence, both CO and FO are independently controllable.

With the feedback link broken at node '1' and considering the 'P' terminal of VDCC as the input, the two open loop transfer functions realized by the proposed circuit are given by:

$$\frac{I_{0_1}}{V_{in}} = \frac{s\left(\frac{C_2 g_m}{R_2}\right)}{s^2 + s\left(\frac{1}{R_1 C_1}\right) + \frac{g_m}{R_2 C_1 C_2}} \tag{5}$$

$$\frac{I_{o_4}}{V_{in}} = \frac{s^2 g_m}{s^2 + s\left(\frac{1}{R_1 C_1}\right) + \frac{g_m}{R_2 C_1 C_2}} \tag{6}$$

Thus, in this mode, the same configuration can also be used to realize trans-admittance band pass and high pass filters simultaneously. From equations (5) and (6), the natural frequency (ω0) and bandwidth (BW) are given by

$$\omega_0 = \sqrt{\frac{g_m}{R_2 C_1 C_2}} \tag{7}$$

$$BW = \frac{1}{R_1 C_1} \tag{8}$$

Thus, it is seen that and BW are independently tunable.

In the third mode of operation, the various current transfer functions obtained from Fig. 2 are

$$\frac{I_{o_1}(s)}{I_{o_4}(s)} = -\frac{1}{sR_2C_1} \tag{9}$$

$$\frac{I_{o_2}(s)}{I_{o_4}(s)} = \frac{1}{sR_2C_1} \tag{10}$$

$$\frac{I_{o_3}(s)}{I_{o_4}(s)} = \frac{1}{sR_2C_1} \tag{11}$$

$$\frac{I_{o_5}(s)}{I_{o_4}(s)} = \frac{1}{sR_1C_1} \tag{12}$$

For sinusoidal steady state, Equations (9), (10), (11) and (12) become

$$\frac{I_{o_1}(j\omega)}{I_{o_4}(j\omega)} = \frac{1}{\omega R_2 C_1} e^{j90^0} \tag{13}$$

$$\frac{I_{o_2}(j\omega)}{I_{o_4}(j\omega)} = \frac{1}{\omega R_2 C_1} e^{-j90^0} \tag{14}$$

$$\frac{I_{o_3}(j\omega)}{I_{o_4}(j\omega)} = \frac{1}{\omega R_2 C_1} e^{-j90^0} \tag{15}$$

$$\frac{I_{o_5}(j\omega)}{I_{o_4}(j\omega)} = \frac{1}{\omega R_1 C_1} e^{-j90^0} \tag{16}$$

Thus, the phase difference between (I_{o1} and I_{o4}) is 90^0 and between (I_{o2} and I_{o4}), (I_{o3} and I_{o4}) and (I_{o5} and I_{o4}) is -90^0

Hence, the currents (I_{o1} and I_{o4}), (I_{o2} and I_{o4}), (I_{o3} and I_{o4}) and (I_{o5} and I_{o4}) are in the quadrature form. Thus, in this mode of operation, the circuit works as quadrature oscillator.

III. NON –IDEAL PERFORMANCE AND SENSITIVITY ANALYSIS

Considering the various parasitics of VDCC i.e. the X-terminal impedance consisting of a resistance R_x in series with inductance L_x, the impedance at the W_P-terminal consisting of a resistance R_p in parallel with capacitance C_p, the impedance at the W_N-terminal consisting of a resistance R_n in parallel with capacitance C_n and the impedance at the Z-terminal consisting of a resistance R_z, the FO and CO for the circuit shown in Fig. 2 are given as:

FO:

$$\omega_0=\sqrt{\frac{\dfrac{R_x}{R_P}+\dfrac{R_2}{R_P}+\dfrac{R_xR_1}{R_PR_z}+\dfrac{R_1R_2}{R_PR_z}+\dfrac{R_xR_1g_m}{R_P}-\dfrac{R_2R_1g_m}{R_P}+g_mR_1}{C_1C_2R_1(R_x+R_2)+C_1C_pR_1(R_x+R_2)+C_2L_x\left(1+\dfrac{R_1}{R_z}-R_1g_m\right)+C_pL_x\left(1+\dfrac{R_1}{R_z}\right)+\dfrac{C_1L_xR_1}{R_p}-C_pL_xR_1g_m}} \tag{17}$$

and CO:

$$\begin{aligned}&\left[C_2(R_x+R_2)(1-R_1g_m)+\left\{\begin{matrix}(R_x+R_2)\left(\dfrac{C_1R_1}{R_P}+C_p+\dfrac{C_pR_1}{R_z}\right)+\\ C_2R_1\left(\dfrac{R_x}{R_P}+\dfrac{R_2}{R_z}\right)+\dfrac{L_x}{R_pR_z}(R_1+R_z-R_2R_1g_m)-\\ C_pR_1g_m(R_x+R_2)\end{matrix}\right\}\right]\\ &\left[\begin{matrix}L_x\{R_z(C_1R_1+C_2R_p+C_pR_p)+R_P(C_2R_1+C_pR_1)-R_1R_pR_z(C_2+C_p)\}+\\ C_1R_1R_pR_z(R_x+R_2)(C_2+C_p)\end{matrix}\right]-\\ &\left[L_xC_1R_1(C_2+C_p)\left\{\frac{R_x}{R_P}+\frac{R_2}{R_P}+\frac{R_xR_1}{R_PR_z}+\frac{R_1R_2}{R_PR_z}+\frac{R_xR_1g_m}{R_P}-\frac{R_2R_1g_m}{R_P}+g_mR_1\right\}\right]\le 0\end{aligned} \tag{18}$$

The sensitivities of ω_0 with respect to active and passive components are given as:

$$S_{R_1}^{\omega_0}=\frac{\left[\dfrac{2}{R_p}R_xg_mL_x(C_2+C_P)+g_mL_x(C_2+C_P)-\dfrac{C_1L_x(R_2+R_x)}{R_p^2}-\dfrac{C_1(R_x+R_2)^2(C_2+C_p)}{R_p}\right]}{X}R_1$$

$$S_{R_2}^{\omega_0}=\frac{\left[\left\{\dfrac{1}{R_P}+\dfrac{R_1}{R_PR_z}-\dfrac{R_1g_m}{R_P}\right\}Z-\dfrac{2C_1C_2R_1^2R_2g_m}{R_P}-\dfrac{2C_1C_pR_1^2R_2g_m}{R_P}-C_1C_2R_1^2g_m-C_1C_pR_1^2g_m\right]}{X}R_2$$

$$S_{C_1}^{\omega_0}=-\frac{\left[C_1R_1(R_x+R_2)(C_2+C_p)+\dfrac{C_1L_xR_1}{R_P}\right]}{Y}$$

$$S_{C_2}^{\omega_0}=-\frac{\left[C_1C_2R_1(R_x+R_2)+C_2L_x\left(1+\dfrac{R_1}{R_z}-R_1g_m\right)\right]}{Y}$$

$$S_{R_x}^{\omega_0}=\frac{\left[\left\{\dfrac{1}{R_P}+\dfrac{R_1}{R_PR_z}+\dfrac{R_1g_m}{R_P}\right\}Z+\dfrac{2C_1C_2R_1^2R_2g_m}{R_P}+\dfrac{2C_1C_pR_1^2R_2g_m}{R_P}-C_1C_2R_1^2g_m-C_1C_pR_1^2g_m\right]}{X}R_x$$

$$S_{R_p}^{\omega_0}=\frac{\left[\{C_1C_2R_1(R_x+R_2)+C_1C_pR_1(R_x+R_2)+Z\}\left\{-\dfrac{R_x}{R_P}-\dfrac{R_2}{R_P}-\dfrac{R_xR_1}{R_PR_z}-\dfrac{R_1R_2}{R_PR_z}-\dfrac{R_xR_1g_m}{R_P}+\dfrac{R_2R_1g_m}{R_P}\right\}+\left(\dfrac{C_1L_xR_1}{R_p}\right)W\right]}{X}$$

$$S_{R_z}^{\omega_0}=\frac{\left[\{C_1C_2R_1(R_x+R_2)+C_1C_pR_1(R_x+R_2)+Z\}\left\{-\dfrac{R_1R_2}{R_PR_z}-\dfrac{R_1R_x}{R_PR_z}\right\}+\left\{\dfrac{C_2L_xR_1}{R_z}+\dfrac{C_pL_xR_1}{R_z}\right\}W\right]}{X}$$

$$S_{C_P}^{\omega_0} = -\frac{\left[C_p C_1 R_1 (R_x + R_2) + C_p L_x \left(1 + \frac{R_1}{R_z}\right) - C_p L_x R_1 g_m\right]}{Y}$$

$$S_{g_m}^{\omega_0} = \frac{\left[\begin{array}{l} \left\{C_1 C_2 R_1 (R_x + R_2) + C_1 C_p R_1 (R_x + R_2) + Z\right\}\left\{\frac{R_1 R_x}{R_P} - \frac{R_1 R_2}{R_P} + R_1\right\} + \\ \left\{C_2 L_x R_1 + C_p L_x R_1\right\}\left\{\frac{R_x}{R_P} + \frac{R_2}{R_P} + \frac{R_x R_1}{R_P R_z} + \frac{R_1 R_2}{R_P R_z} + \frac{R_x R_1 g_m}{R_P} - \frac{R_2 R_1 g_m}{R_P} + g_m R_1\right\} \end{array}\right]}{X} g_m$$

Where

$$X = 2\left[\left\{\begin{array}{l} C_1 C_2 R_1 (R_x + R_2) + C_1 C_p R_1 (R_x + R_2) + C_2 L_x \left(1 + \frac{R_1}{R_z} - R_1 g_m\right) + \\ C_p L_x \left(1 + \frac{R_1}{R_z}\right) + \frac{C_1 L_x R_1}{R_p} - C_p L_x R_1 g_m \end{array}\right\}\left\{\frac{R_x}{R_P} + \frac{R_2}{R_P} + \frac{R_x R_1}{R_P R_z} + \frac{R_1 R_2}{R_P R_z} + \frac{R_x R_1 g_m}{R_P} - \frac{R_2 R_1 g_m}{R_P} + g_m R_1\right\}\right],$$

$$Y = 2\left[C_1 C_2 R_1 (R_x + R_2) + C_1 C_p R_1 (R_x + R_2) + C_2 L_x \left(1 + \frac{R_1}{R_z} - R_1 g_m\right) + C_p L_x \left(1 + \frac{R_1}{R_z}\right) + \frac{C_1 L_x R_1}{R_p} - C_p L_x R_1 g_m\right],$$

$$Z = \left\{C_2 L_x \left(1 + \frac{R_1}{R_z} - R_1 g_m\right) + C_p L_x \left(1 + \frac{R_1}{R_z}\right) + \frac{C_1 L_x R_1}{R_p} - C_p L_x R_1 g_m\right\} \text{ and}$$

$$W = \left\{\frac{R_x}{R_P} + \frac{R_2}{R_P} + \frac{R_x R_1}{R_P R_z} + \frac{R_1 R_2}{R_P R_z} + \frac{R_x R_1 g_m}{R_P} - \frac{R_2 R_1 g_m}{R_P} + g_m R_1\right\} \quad (19)$$

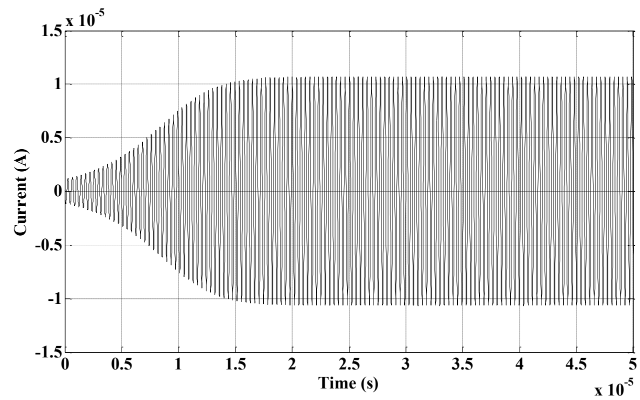
Taking $C_1 = C_2 = 0.01$nF, $C_p = C_n = 0$, $R_z = R_p = R_n = \infty$, $R_x = 0$, $L_x = 0$, $R_1 = 3.675$kΩ and $R_2 = 10$kΩ, these sensitivities are found to be (0, -1/2, 0, 0, 0, -1/2, -1/2, 0, 1/2) for equations (19). Thus, all the passive and active sensitivities of natural frequency (ω_0) are low.

IV. Frequency Stability

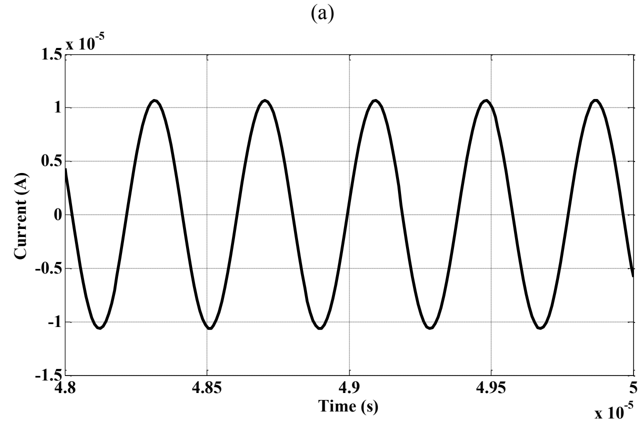
Using the definition of the frequency stability factor S^F as given in [4] $S^F = \left(\frac{d\phi(u)}{du}\right)\Big|_{u=1}$ (where $u = \frac{\omega}{\omega_0}$ is the normalized frequency and $\phi(u)$ represents the phase of the open-loop transfer function of the oscillator circuit), with $C_1 = C_2 = C$, $g_m = \frac{1}{R_1}$ and $g_2 = \frac{1}{R_2} = n g_m$, the S^F of the proposed oscillator is found to be $2\sqrt{n}$. Therefore, very good frequency stability is obtainable by selecting larger value of n.

V. Simulation Results

To verify the theoretical analysis, the proposed circuit was simulated using CMOS VDCC [22]. The passive components were selected as $C_1 = C_2 = 0.01$nF, $R_1 = 3.675$kΩ and $R_2 = 10$kΩ. The transconductance of the VDCC is taken as 277.83µA/V. PSPICE generated output waveforms indicating transient and steady state responses are shown in Fig. 3(a) and 3(b) respectively. These results, thus, confirm the validity of the proposed configuration. Fig. 4 shows the output spectrum, where the frequency of the generated wave is 2.654MHz and the total harmonic distortion (THD) is found to be 1.584%.



(a)



(b)

Fig. 3. (a) Transient output waveform, (b) Steady state response of the output.

Fig. 5 shows the frequency response of Transadmittance band pass and high pass filters.

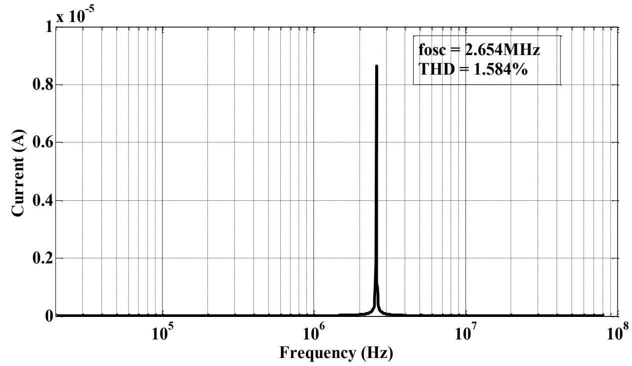


Fig. 4. Simulation result of the output spectrum.

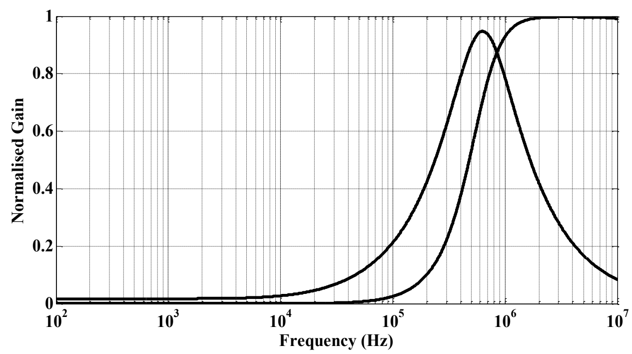


Fig. 5. Frequency response of the simulated filter.

Fig. 6 shows the transient response and steady state response (considering all five currents).

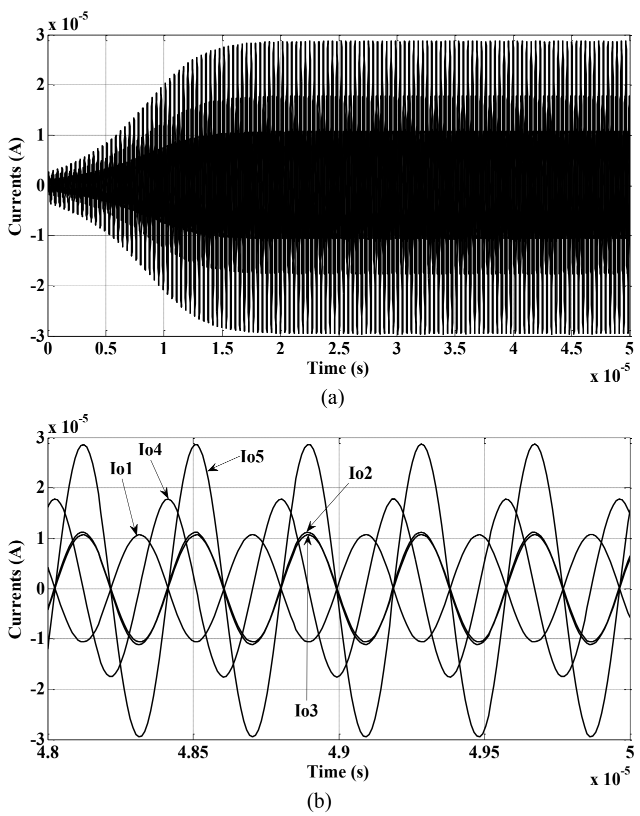


Fig. 6. (a) Transient output waveform, (b) Steady state response of the output.

From Fig. 7 it is clear that the two currents are in quadrature and the measured value of phase shift between two waveforms is $= 89.59^0$.

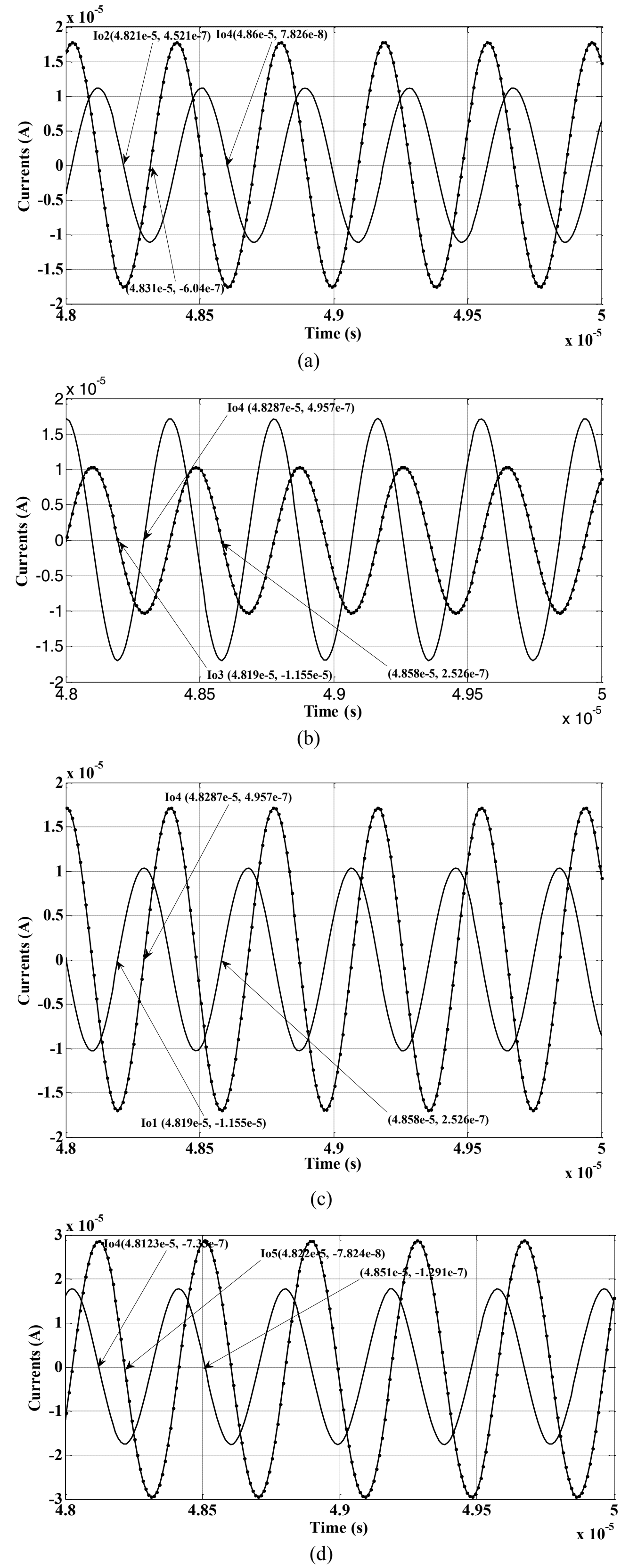


Fig. 7. Currents showing quadrature wave forms.

Fig. 8 shows the transient response of output waveform of Fig. 2 to achieve $S^F = 2$. The circuit of Fig 2 has been checked for robustness using Monte-Carlo simulations, the sample result has been shown in Fig. 9, which confirms that for ±10% variations in the value of R_1, the value of oscillation frequency remain close to its normal value of 2.654MHz and hence almost unaffected by change in R_1. The circuit is re- simulated for larger value of n (n = 100) and the transient response is shown in Fig. 10. Fig. 11 shows the variation of frequency of output with respect to resistance R_2. Fig. 12 represents the variation of S^F with n. A comparison with other previously known explicit CM SRCOs using single ABB has been given in Table 1. These results, thus, confirm the validity of the proposed configuration.

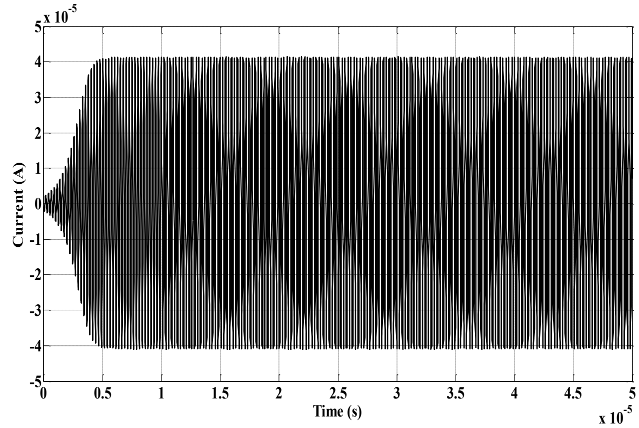


Fig. 8. Transient output waveform for $S^F = 2$.

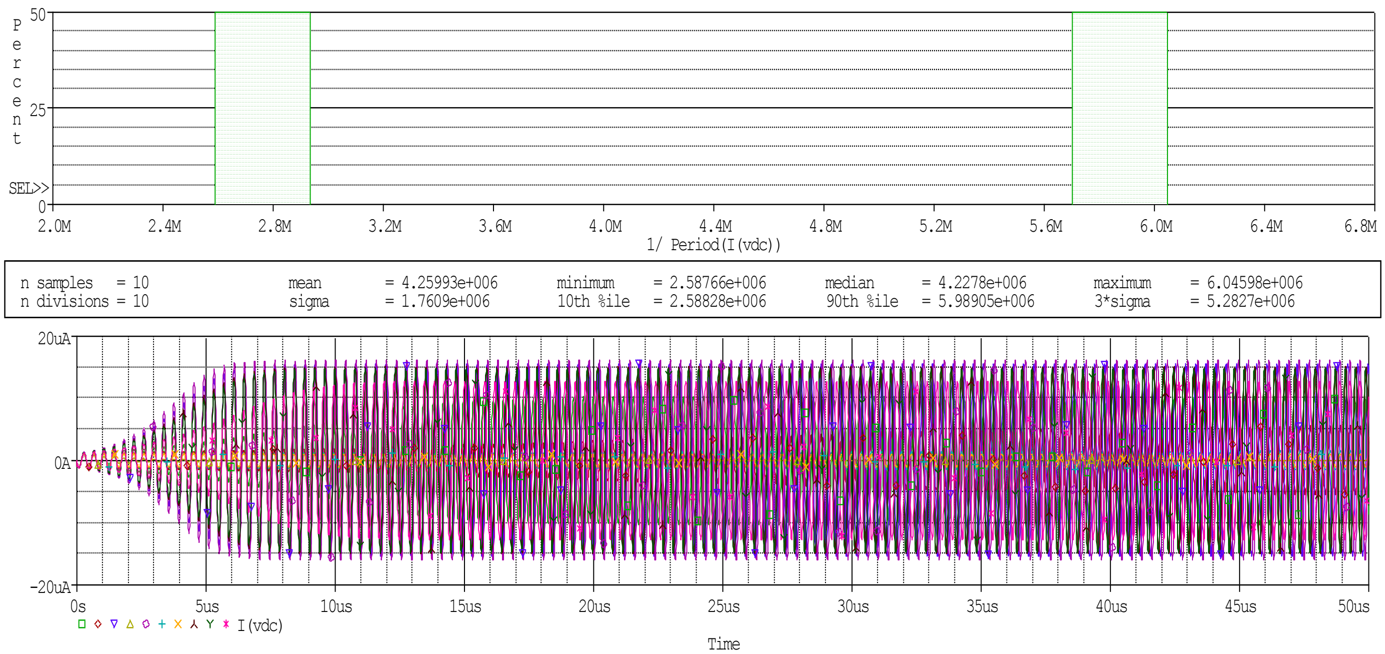


Fig. 9. Result of Monte-Carlo Simulation of oscillator circuit of Fig. 2.

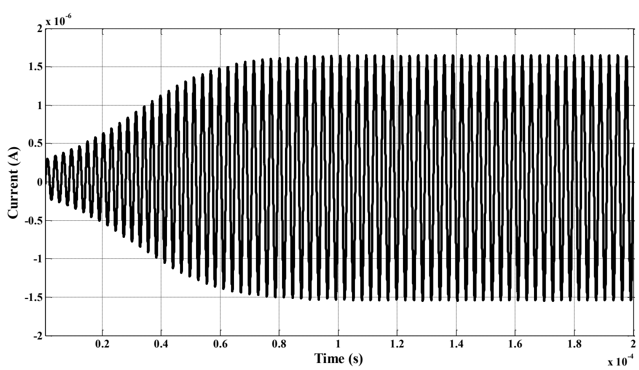


Fig. 10. Transient output waveform for n = 100.

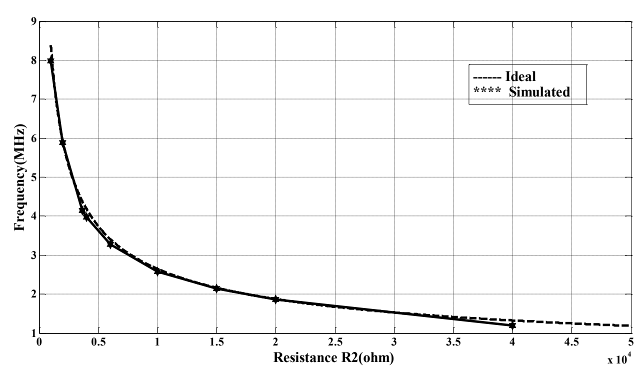


Fig. 11. Variation of frequency with Resistance R_2.

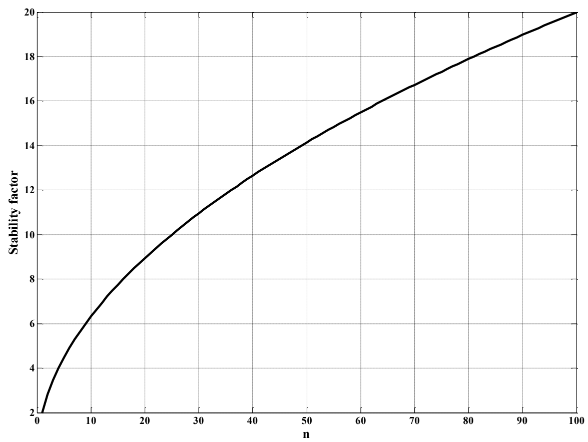


Fig. 12. Variation of S^F with respect to n.

VI. Conclusion

A new SRCO has been proposed using a recently introduced VDCC. The proposed circuit employs four grounded passive components (two grounded resistors and two grounded capacitors) and yet offers independent control of FO through the resistor R_2 and CO through the resistance R_1, low active and passive sensitivities, realizes two trans-admittance filters (Band Pass and Low Pass) and a very good frequency stability. The performance of the proposed configuration in all three modes has been confirmed by PSPICE simulations.

TABLE 1
COMPARASION OF PROPOSED SRCO WITH OTHER PREVIOUSLY KNOWN SAME TYPE OF SRCOs

Reference	Active Component	Capacitors		Resistors	Availability of Explict current-mode output/	Independent controllability of CO and FO through grounded resistors
		Grounded	Floating			
[14]	1 FTFN	Case I				
		3	0	5	YES	NO
		3	0	5	YES	NO
		Case II				NO
		1	1	3	YES	NO
		0	2	4	YES	NO
		0	2	4	YES	NO
		1	1	4	YES	NO
		Case III				NO
		2	1	4	YES	NO
		1	2	4	YES	NO
		1	2	4	YES	NO
		2	1	4	YES	NO
		Case IV				NO
		1	2	4	YES	NO
		1	2	4	YES	NO
		1	2	4	YES	NO
		2	1	4	YES	NO
[15]	1 DVCCC	2	0	3	YES	NO
[16]	1 FDCCII	2	0	3	YES	YES
[17]	1 CFOA	0	3	3	YES	NO
		1	2	3	YES	NO
[18]	1 DVCCC	2	0	3	YES	NO
Proposed	**1 VDCC**	**2**	**0**	**2**	**YES**	**YES**

References

[1] R. Senani, “New types of sine wave oscillators,” *IEEE Trans. on Instrumentation and Measurement (USA)*, vol. 34, no.3, pp. 461-463, Sept. 1985.

[2] R. Senani and D. R. , Bhaskar, “Single-op-amp Sinusoidal oscillators suitable for generation of very low frequencies,” *IEEE Trans. on Instrumentation and Measurement (USA),* vol. 40, no.4, pp. 777-779, Aug- 1991.

[3] S. Celma, P. A. Martinez and A. Carlosena, “Minimal realisation for single resistor controlled sinusoidal oscillator using single CCII,” *Electron. Letters*, vol. 28, no. 5, pp. 443-444, 1992.

[4] D. R. Bhaskar and R. Senani, “New Current-Conveyor-based Single-resistance- controlled/ voltage-controlled oscillator employing grounded capacitors,” *Electronics Letters,* vol. 29, no. 7, pp. 612-614, 1993.

[5] C. T. Lee and H. Y. Wang, “Minimum realization for FTFN-based SRCO,” *Electronics Letters*, vo. 37, no. 20, pp. 1207-1208, 2001.

[6] D. R. Bhaskar, “Grounded -capacitor SRCO using only one PFTFN,” *Electronics Letters*, vol. 38, no. 20, pp. 1156-1157, 2002.

[7] J. J. Chen, C. C. Chen, H. W. Tsao and S. I. Liu, “Current-mode oscillator using single current follower,” Electronics Letters, vol. 27, no.22, pp. 2056-2059, Oct. 1991.

[8] S. Ozcan, A. Toker, C. Acar, H. Kuntman and O. Cicekoglu, ‘Single resistance-controlled sinusoidal oscillators employing current

differencing buffered amplifier," Microelectronics Journal, vol. 31, pp. 169-174, 2000.

[9] U. Cam, "A Novel Single-Resistance-Controlled Sinusoidal Oscillator Employing Single Operational Transresistance Amplifier," *Analog Integrated Circuits and Signal Processing*, vol. 32, pp. 183-186, 2002.

[10] V. K. Singh, R. K. Sharma, A. K. Singh, D. R. Bhaskar and R. Senani, "Two new canonic single-CFOA oscillators with single resistor controls," *IEEE Trans. on Circuits and Systems II: Express Brief (USA)*, vol. 52, no. 12, pp. 860-864, 2005.

[11] U. Cam, A. Toker, O. Cicekoglu and H. Kuntman, "Current-mode high output impedance sinusoidal oscillator configuration employing single FTFN," A*nalog Integr. Circ. and Sig. Process.*, vol. 24, pp. 231-238, 2000.

[12] D. Prasad, D. R. Bhaskar and A. K. Singh, "Realisation of single–resistance-controlled sinusoidal oscillator: A new application of the CDTA," *WSEAS Trans. Electron*., vol. 6, no. 5, pp. 257-259, 2008.

[13] M. T. Abuelmatti, "Grounded-capacitor current-mode oscillator using single current follower.," IEEE *Trans. on Circuits and Systems I: Funda. Theor. And app*., vol. 39, no. 12, pp. 1018-1020, Dec. 1992.

[14] M. T. Abuelmatti and H. A. Al-Zaher, "Current-mode sinusoidal oscillator using single FTFN," *IEEE Trans. on Circuits and Systems II: Anal. and Dig. Sig. Process*, vol. 46, no. 1, pp. 69-74, Jan. 1999.

[15] S. S. Gupta and R. Senani, "Grounded-capacitor current-mode SRCO: Novel application of DVCCC," *Electronics Letters*, vol. 36, no. 3, pp. 195-196, Feb. 2000.

[16] C. M. Chang, B. M. Ai-Hashimi, H. P. Chen, S. H. Tu and J. A. Wan, "Current-mode single resistance controlled oscillators using only grounded passive components" *Electronics Letters*, vol. 38, no. 19, pp. 1071-1072, 2002.

[17] R. Senani and R. K. Sharma, "Explicit-current-output sinusoidal oscillators employing only a single current-feedback op-amp" *IEICE Electron. Express*, vol. 2, no. 1, pp. 14-18, 2005.

[18] V. Aggarawal, S. Kilinc and U. Cam, "Minimum component SRCO and VFO using a single DVCCC," *Analog Integrated Circuits and Signal Processing*, vo. 49, no. 2, pp. 181-185, 2006.

[19] C. Toumazou, F. J. Lidgey and D. G. Haig, "Analogue IC Design: The current- mode approach" London: Peter Peregrinus Limited, 1990.

[20] D. R. Bhaskar and R. Senani, "New FTFN-based grounded capacitor SRCO with explict current-mode output and reduced number of resistors," *AEU: Int. J. Electron. Commun*., vol. 59, pp. 48-51, 2005.

[21] D. Biolek, R. Senani, V. Biolkova and Z. Kolka, "Active elements for analog signal processing; classification, review and new proposals," *Radioengineering*, vol. 17, no. 4, pp. 15-32, Dec. 2008.

[22] F. Kacar, A. Yesil, S. Minaei and H. Kuntman, "Positive/ negative lossy/ lossless grounded inductance simulators employing single VDCC and only two passive elements," *AEU, Int. J. of Electron. and Comm.*, vol. 68, no. 1, pp. 73-78, Jan. 2014.

[23] D. Prasad and J. Ahmad, "New Electronically-Controllable Lossless Synthetic Floating Inductance Circuit Using Single VDCC" *Circuits and Systems*, vol. 5, no. 1, pp. 13-17, Jan. 2014