# Current Conveyor Based Sinusoidal Oscillators Employing Quartz Crystal Resonators Behaving as Inductors

Ivailo Milanov Pandiev, Todor Georgiev Todorov,
Peter Ivanov Yakimov and Doycho Dimitrov Doychev

*Abstract* - **In this paper two new sinusoidal crystal oscillators, using single and dual composite current conveyor (CC) are proposed. The LC tank of the proposed circuits includes a capacitive network and crystal resonator that behaves as an inductor. The crystal oscillators are the results of a systematic circuit synthesis and can relatively easily be derived from the classical Pierce oscillator, realized with discrete transistors. The created circuits provide the following advantages: (1) the insignificant influence of the load over the parameters of the oscillators, (2) ability for independent fine tuning of oscillation frequency and oscillation condition, (3) low output impedance, and (4) good frequency stability. Some recommendations for designing this kind of analog circuits are given based on symbol analysis of the characteristic equations. Experimental results that confirm the theoretical analysis are included.**

*Keywords* – **Analog circuits, Oscillators, Crystal resonators, Current conveyors.**

## I. INTRODUCTION

The quartz crystal oscillators have been found useful in many applications, such as analogue signal processing, telecommunications and measurement systems. Additionally, the principals of oscillation can be extended to construct other types of oscillators, such as quartz crystal resonator sensors, voltage controlled crystal oscillators, chaotic oscillators, etc. [1-3].

Over the past two decades several current conveyor- and current-feedback amplifier (CFA)- based sinusoidal oscillators [4-13] are proposed in the literature. Each of the current conveyor-based oscillator circuit uses one (two or three) second-generation current-conveyors (CCII) and a small number of resistors and capacitors. In most cases the oscillation condition and the oscillation frequency is tuned by grounded resistors and capacitors. Only the circuit presented in [4] use one floating resistor for controlling frequency of oscillation. The CFA-based sinusoidal oscillators in comparison with the CC circuits have small output impedance and larger bandwidth. However, the majority of published RC or LC oscillators usually generate sinusoidal signal with frequency up to $10MHz$ and the load, connected to the output, can have significant influence on the oscillation condition. Additionally the frequency stability is insufficient of the oscillators given in Ref. [4, 5, 10] and Ref. [12, 13] above the oscillation frequency $200...300kHz$ and $1MHz$, respectively. The frequency stability factor of these circuits comparatively difficult can be arranged to remain greater than 5...10 over the entire tuning frequency range [16]. The oscillator circuits given in [12] and [13] consist of several passive RLC elements and a single CFA and a composite CC, respectively. The main drawbacks of the circuit presented in Ref. [12] are the relatively difficult tuning of the oscillation condition and the insufficient frequency stability. The oscillators given in Ref. [13] are improved variants of the circuit given in Ref. [12], but the frequency stability factor and amplitude stability is small over the exploring frequency range ($0{,}1...100MHz$).

This paper proposes two new crystal oscillators using single and dual composite current conveyors, small group of passive RLC elements and quartz crystal resonator. The oscillation condition and oscillation frequency of the created circuits can be controlled through a single grounded resistor and a trimmer-capacitor, respectively. The proposed oscillators can be obtained from the classical Pierce structure of the Colpitts oscillator [15, 16]. In fact, the circuits, presented in this paper can be considered, as improved circuit variants of the oscillators given in [12] and [13].

## II. CIRCUITS DESCRIPTION

The proposed circuits of the crystal oscillators are shown in Fig. 1 and Fig. 2. The first circuit (LCO1) is with a single composite CC and capacitive positive feedback. The second circuit (LCO2) is also with capacitive feedback, but here the positive feedback is closed through additional composite CC with voltage gain higher than unity. In this case the frequency stability factor can be obtained with higher value, since the equivalent Q-factor of the equivalent LC tank is higher.

### *A. Sinusoidal crystal oscillator using single composite CC*

The basic part of the circuit, shown in Fig. 1, is a composite CC, which is a cascade structure of positive second-generation current conveyor (CCII+) and additional voltage follower, similar to the current-feedback amplifiers (CFAs). The CCII+ can be viewed as *ideal transistors*. Like transistors, they have three terminals – a high impedance input (*B – base*), a low-impedance input/output (*E – emitter*), and the current output (*C – collector*). The op amps

I. Pandiev is with the Department of Electronics, Technical University - Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: ipandiev@tu-sofia.bg

T. Todorov is with the Department of Electronics, Technical University - Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: ttodorov@tu-sofia.bg

P. Yakimov is with the Department of Electronics, Technical University - Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: pij@tu-sofia.bg

D. Doychev is with the Department of Electronics, Technical University - Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: dddoychev@tu-sofia.bg

AD844 (from Analog Dev.), OPA860, OPA615 (from Texas I.) and MAX436 (from Maxim) are typical representatives of the monolithic composite CCs.

The linear macromodel of the composite CC, presented in Fig. 3, reflects the ac behavior of the real device. The -model includes the following elements: input and output buffers (voltage followers); $i_e$ – controlled current source; $r_b$ and $C_b$ – resistance and capacitance of the non-inverting input; $r_c$ and $C_c$ – output resistance and capacitance.

For this composite current conveyor the general relation between input and output voltages and currents can be given by the following hybrid matrix

$$\begin{bmatrix} i_B \\ u_E \\ i_C \\ u_o \end{bmatrix} = \begin{bmatrix} 1/Z_b & 0 & 0 \\ 1 & 1/r_e & 0 \\ 0 & 1 & 1/Z_c \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_B \\ i_E \\ u_C \end{bmatrix}, \qquad (1)$$

where $Z_b = r_b \parallel (1/sC_b)$ and $Z_c = r_c \parallel (1/sC_c)$.

The matrix representation given with Eq. (1) is valid only for the ideal input and output voltage followers.

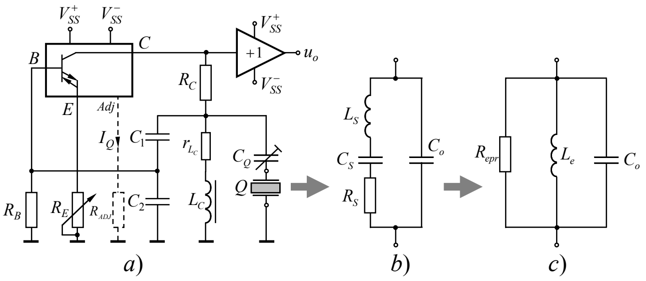

Fig. 1. Proposed capacitive feedback crystal oscillator (LCO1) using single composite CC (*a*); equivalent series-parallel RLC model of the crystal with elements $L_S$ and $C_S$ - motional inductance and capacitance, $R_S$ - series resistance and $C_o$ - holder capacitance (*b*); equivalent parallel RLC model of the crystal with elements $R_{epr}$ - equivalent resistance, $L_e$ - equivalent inductance and $C_o$ - holder capacitance (*c*).

The control of the oscillation condition of the circuit LCO1 is fulfilled by two feedbacks – one *positive* and one *negative*. *The positive feedback* of the circuit is realized with a equivalent parallel LC resonant circuit (LC tank) using a crystal resonator $Q$ and capacitances $C_1$ and $C_2$. In this way the crystal resonator behaves as an equivalent inductor. We want the oscillator to operate as close as possible to the series resonant frequency $f_s$ as this is the frequency which is the closest to the internal electro-mechanical operation of the crystal. Moreover, it is the frequency which is the least dependent on the package and mounting capacitance $C_M$, which is hard to predict. The positive feedback is closed by connecting the intermediate node of the $C_1$ and $C_2$ with *B terminal* of the CCII+. *The negative feedback* of the oscillator is implemented with the grounded resistor $R_E$. This $R_E$ can be a trimmer-potentiometer for tuning of the negative feedback depth (or gain), until the oscillation condition is fulfilled and desired amplitude of the output signal is obtained. When the oscillation condition is fulfilled, the oscillator is generating a sinusoidal signal with a frequency, equal to the resonant frequency of the equivalent LC tank.

Greater amplitude stability of the LCO1 can be achieved with an automatic gain control (AGC) circuit that has a gain control element and a peak detector. The gain control element can be made with JFET, that replaces the resistor $R_E$. Additionally the resistance D – S of the JFET is controlled by the amplitude of the output signal, using peak detector.

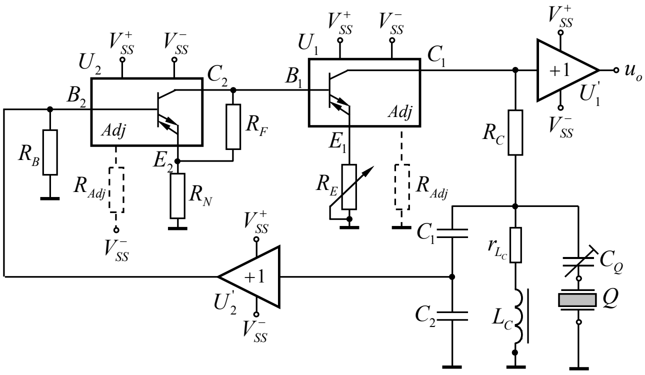

Fig. 2. Proposed capacitive feedback crystal oscillator (LCO2) using dual composite CC.

The small resistor $R_C$ (connected between the *C terminal* of the CCII+ and the equivalent LC tank) and the RF inductor $L_C$ (connected in parallel of the LC tank), are used to keep the CCII+ in a linear mode of operation when the oscillation condition is fulfilled and to define DC current at the *C terminal*. The DC current component at the B terminal of the CCII+ is flowing through the grounded resistor $R_B$. The resistor $R_{ADJ}$ adjusts the transconductance of the CCII+ ($S = 1/r_e$) and allows to optimize the bandwidth $-3dB$ and the quiescent current.

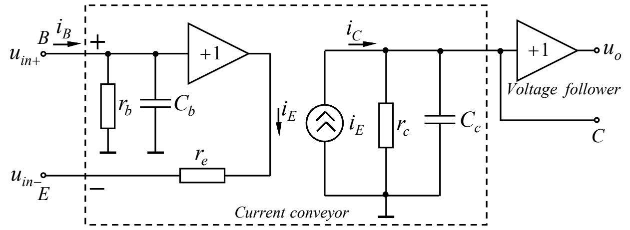

Fig. 3. Linear macromodel of the composite CC.

Using the hybrid matrix given in Eq. (1), which characterizes the composite CC by routine analysis of the LCO1, the characteristic equation is found:

$$s^2 C_1' C_2' L_e' (R_E + r_e) + s\left[ (C_1' + C_2') L_e' \frac{R_E + r_e}{R_{oe}} - C_1' L_e' \right] + $$
$$+ (C_1' + C_2')(R_E + r_e) = 0\,, \qquad (2)$$

where $R_{oe} \approx (R_{epr} + R_C) \parallel R_{L_C} \parallel r_C \parallel (p_C^2 R_B)$ is the equivalent resonance resistance of the circuit, $p_C = (C_1 + C_2)/C_1$, $R_{epr} = \rho^2 / R$ is the equivalent resonance resistance of the

LC tank, $\rho = \sqrt{L_e^{'} / C_{12}^{'}}$ is the characteristic resistance of the LC tank, $L_e^{'} = L_e \| L_C$, $L_e = L(1 - \omega_{S,C_Q}^2 / \omega_o^2)$ is the equivalent inductance of the parallel RLC model of the crystal, $\omega_{S,C_Q} = \omega_S \sqrt{1 + C/(C_o + C_Q)}$ is the radian series resonant frequency, which is defined with trimmer-capacitor $C_Q$, $C_{12}^{'} = C_1^{'} \| C_2^{'} = C_{12} + C_o + C_C + C_M$, $C_{12} = C_1 \| C_2$ and $R_{L_C} \approx (\omega_o L_C)^2 / r_{L_C}$.

The oscillation condition and radian oscillation frequency are given by

$$\underbrace{\frac{C_1^{'}}{C_1^{'} + C_2^{'}}}_{\beta^+} = \underbrace{\frac{R_E + r_e}{R_{oe}}}_{A_U^{-1}} \tag{3}$$

and

$$\omega_o = 1/\sqrt{L_e^{'} C_{12}^{'}} . \tag{4}$$

respectively. Thus, $R_E$ appears only in the expression for oscillation condition and $L_e^{'}$ appears only in the equation for oscillation frequency. Therefore, each one of them can be independently controlled through the grounded resistor $R_E$ and the trimmer-capacitor $C_Q$, serially connected to the crystal behaving as an equivalent inductor $L_e$, respectively.

The passive $\omega_o$ - sensitivities of the LCO1 are low and obtained as

$$S_{C_1}^{\omega_o} = -\frac{1}{2} \frac{C_2^{'}}{C_1^{'} + C_2^{'}} ; \; S_{C_2}^{\omega_o} = -\frac{1}{2} \frac{C_1^{'}}{C_1^{'} + C_2^{'}} ; \; S_{L_e}^{\omega_o} = -0{,}5 .$$

Another notable merit of the proposed oscillator with composite CC is the very good frequency stability property. The frequency stability factor $S_F$ is defined as [4]

$$S_F = \left. \frac{d\Phi(u)}{du} \right|_{u=1} , \tag{5}$$

where $u = \omega / \omega_o$ is the normalized frequency and $\Phi(u)$ represents the phase function of the open loop transfer function (with the feedback loop broken at *B terminal*) of the circuit in Fig. 1.

The frequency stability factor $S_F$ for the proposed circuit is found to be $S_F \approx 2Q_e$ ($Q_e = R_{oe} / \rho$ is the equivalent quality factor (Q-factor) of the phase shift LC network), which is considerable larger than the CC based RC or LC oscillators known previously [4, 5, 10, 12, 13]. The Q-factor of the new circuit can be arranged to remain significantly greater than unity over the large frequency range.

### *B. Sinusoidal crystal oscillator using dual composite CC*

The proposed sinusoidal crystal oscillator (LCO2) with dual composite CC is shown in Fig. 2. The main advantages of the LCO2 in comparison with the LCO1, presented in the previous subsection, is that here the frequency stability factor can be obtained with higher value. Since the equivalent Q-factor of the phase shift network is higher. In the LCO2 the feedback voltage at the common node of the capacitors $C_1$ and $C_2$ is applied to the $B_1$ *terminal* of the CCII+ $U_1$ through additional high impedance ($>1M\Omega$) voltage follower $U_2^{'}$ and composite CC $U_2$, connected as an non-inverting amplifier.

The characteristic equation for the LCO2 can be given as

$$s^2 C_1^{'} C_2^{'} L_e^{'} \frac{1}{A_{U2}} + s \left[ \frac{1}{A_{U2}} \frac{(C_1^{'} + C_2^{'}) L_e^{'}}{R_{oe}} - \right.$$

$$\left. - \frac{C_1^{'} L_e^{'}}{r_e + R_E} \right] + (C_1^{'} + C_2^{'}) \frac{1}{A_{U2}} = 0 , \tag{6}$$

where $R_{oe} \approx (R_{epr} + R_C) \| R_{L_C} \| r_C \| (p_C^2 R_{i,buff})$ is the equivalent resonance resistance, $R_{i,buff}$ is the input resistance of the voltage follower $U_2^{'}$ and $A_{U2} \approx 1 + R_F / 2R_N$ is the voltage amplification of the amplifier with the additional composite CC $U_2$.

The oscillation condition can be obtained as

$$\underbrace{\frac{R_E + r_e}{R_{oe}}}_{A_{U1}^{-1}} \times \underbrace{\frac{1}{1 + \dfrac{R_F}{2R_N}}}_{A_{U2}^{-1}} = \underbrace{\frac{C_1^{'}}{C_1^{'} + C_2^{'}}}_{\beta^+} . \tag{7}$$

The radian frequency of oscillation for this circuit is given by equation (4).

The passive $\omega_o$ - sensitivities of the LCO2 is lower than unity and equal to those obtained for the LCO1.

## III. EXPERIMENTAL RESULTS AND DISCUSSIONS

To verify the theoretical analysis, various circuits of the proposed sinusoidal oscillators, were implemented on a FR4 PCB laminate with SMD components. The oscillator circuits are realized based on the proposed practical approach to design and analysis sinusoidal oscillators, presented in Ref. [14]. The operation of the LCO1 and LCO2 has been analyzed by using single monolithic composite CC OPA860 (from Texas Instruments), biased with $\pm 5V$ supplies and AT-cut crystals (from SJK) with different series resonance frequencies ($0{,}1 ... 100MHz$). The typical value of the crystal quality factors according to the manufacture's data is $10^5$.

Fig. 4 shows a typical output waveform at $f_o = 10MHz$ of Fig. 1 with $C_1 = C_2 = 15pF$, $C_{12}^{'} \approx 20pF$ ($C_{12}^{'} \approx C_L =$, $= 20pF$, where $C_L$ is the equivalent load capacitance specified by the manufacturer for the chosen SJK – quartz crystal), $C_M = 2...4pF$, $L_C = 100\mu H$, $R_C = 50\Omega$, $R_B = 100k\Omega$, $R_{ADJ} = 250\Omega$ (sets approximately $I_Q = 11{,}2mA$ and $r_c = 54k\Omega$, $C_c = 2pF$, $r_b = 455k\Omega$, $C_b = 2{,}1pF$, $r_e = 8\Omega$, $R_{i,buff} = 1M\Omega$ and $R_{o,buff} = 1{,}4\Omega$), and $R_E$ varies from 10 to $50k\Omega$. The parameters of the RLC model of the chosen quartz crystal resonator are: $L_S = 12{,}008mH$, $R_S = 7{,}86\Omega$, $C_S = 21{,}11fF$ and $C_o = 5{,}04pF$. The oscillator is started by tuning the value of the resistor $R_E$. The limit cycle stability is guaranteed by the nonlinear internal mechanism of the used CCII+.

The coefficient of the positive feedback $\beta^+$ is chosen 0,5 for the design frequency, which guarantee the maximal bandwidth of the CCII+ ($A_{U,\min} \ge 1/\beta_1^+$ or $A_{U,\min} \ge 2$, where for the op amp OPA860 the bandwidth $B_{0,7} \approx 470 MHz$ is significantly larger than the chosen oscillation frequency equal to $10 MHz$).

The quality characteristics of the quartz crystal resonator are obtained experimentally using Impedance Analyzer HP4195A.

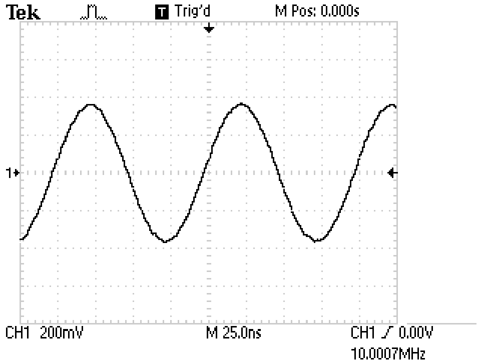

Fig. 4. Typical output waveform of LCO1.

Horizontal scale is $25 ns/div$

Vertical scale is $200 mV/div$ (the attenuation option is $10X$)

The amplitude of the output signal $V_{o,m} = 7{,}2V$ (peak to peak) at $R_L = 500\Omega$, $f_{o,mes} = 10{,}0007 MHz -$ measured output frequency, the DC voltage component of the output signal $V_{o,DC} < 1mV$ and the $THD < 1\%$ were obtained. The spectral oscillator spectrum is shown in Fig. 5. These results prove the feasibility of the proposed oscillator circuit.

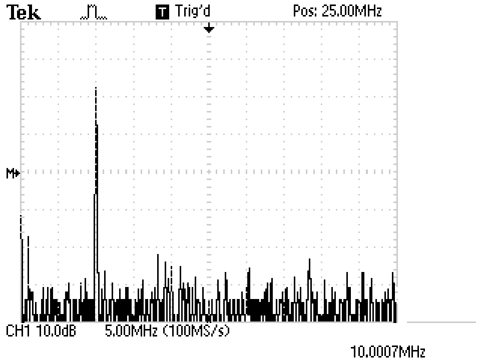

Fig. 5. Oscillator spectrum ($V_{SS}^+ = -V_{SS}^- = 5V$).

## IV. CONCLUSIONS

In this paper two new sinusoidal crystal oscillators using single and dual composite current conveyor with grounded equivalent LC tank have been presented. The oscillation frequency of the proposed oscillators is stabilized with quartz crystal behaving as inductor. The oscillation frequency and oscillation condition of the circuits can be independently controlled by a variable trimmer-capacitor and grounded resistor, respectively. The circuits described are simpler and do not have some of the drawbacks, encountered in previously reported circuits, based on CCII+ and CFAs. The created oscillators have been tested with a monolithic composite CC, obtaining good behavior for low and high frequencies.

## ACKNOWLEDGEMENTS

The OPA860 operational amplifiers, used in this work, were provided by Texas Instruments. This paper is a part of a project under contract № 091ni035-03/2009, which is sponsored by the research programme of the Technical University of Sofia, Bulgaria.

## REFERENCES

[1] M. Ferrari, V. Ferrari, K. Kanazawa. *Dual-harmonic oscillator for quartz crystal resonator sensors*. Sensors and Actuators, vol. 145-146, pp. 131-138, 2008.

[2] W. Sansen. *Analog design essentials*, New York, Springer, 2006.

[3] A. Elwakil, M. Kenndy. *Chaotic oscillators derived from sinusoidal oscillators based on the current feedback op amp*. Analog Integrated Circuits and Signal Processing, vol. 24, pp. 239-251, 2000.

[4] R. Senani, V. Singh. *Single-element-controlled sinusoidal oscillator employing single current conveyor IC*. Electronics Letters, vol. 28, pp. 414-415, 1992.

[5] C.-M. Chang. *Novel current-conveyor-based single-resistance-controlled/voltage-controlled oscillator employing grounded resistors and capacitor*. Electronics Letters, vol. 30, no. 3, pp. 181-182, 1994.

[6] A. M. Soliman, A. S. Elwakil. *Wein oscillators using current conveyors*. Computers and Electrical Engineering, vol. 25, no. 1, pp. 45-55, 1999.

[7] M. T. Abuelma'atti. *New sinusoidal oscillators with fully uncoupled control of oscillation frequency and condition using three CCII.s*. Analog Integrated Circuits and Signal Processing, vol. 24, no. 1, pp. 253-261, 2000.

[8] J.-W. Horng. *Current conveyors based allpass filters and quadrature oscillators employing grounded capacitors and resistors*. Computers and Electrical Engineering, vol. 31, no. 1, pp. 81-92, 2005.

[9] Sh. Liu, Ch. Shin, D. Wu. *Sinusoidal oscillators with single element control using a current-feedback amplifier*. International Journal of Electronics, vol. 77, no. 6, pp. 1007-1013, 1994.

[10] A. Toker, O. Cicekoglu, H. Kuntman. *On the oscillator implementations using a single current feedback op amp*. Computers and Electrical Engineering, vol. 28, pp. 375-389, 2002.

[11] A. Keskin. *Wien Bridge oscillator performances using current and voltage feedback amplifiers*. ICSP 2003, Conference Proceedings, vol. 1, pp. 38-41, 2003.

[12] I. Pandiev. *Analysis and design of LC amplifiers and LC oscillators using current-feedback amplifiers*. International Journal of Electronics, vol. 93, no. 10, pp. 663-677, 2006.

[13] I. Pandiev. *Analysis and design of LC oscillators using composite current conveyors*. ICEST 2009 (in press).

[14] I. Pandiev, T. Todorov, P. Yakimov, D. Doychev. *A practical approach to design and analysis sinusoidal oscillators*. Electronics 2009 (in press).

[15] V. Tietze und Ch. Schenk. *Halbleiterschaltungstechnik*. 12. Auflage. Berlin, Heidelberg, New York. Springer-Verlag, 2002.

[16] M. Seifart. *Analoge Schaltungen*. 6. Auflage. Berlin, Verlag Technik, 2003.