Prungsak UTTAPHUT

Suan Sunandha Rajabhat University, Thailand

New Current-mode Multiphase Sinusoidal Oscillators Based on CCCCTA-based Lossy Integrators

***Abstract**. An implementation of current-mode multiphase sinusoidal oscillators is presented. Using CCCCTA-based lossy integrators, odd and odd/even phase systems can be realised with following advantages. The condition of oscillation and frequency of oscillation can be electronically/orthogonally tuned. The high output impedances facilitate easy driving an external load without additional current buffers. The proposed MSOs provide odd or even phase signals that are equally spaced in phase and equal amplitude. The circuit requires one CCCCTA and one grounded capacitor per phase without external resistor and additional current amplifier. The effects of the non-idealities of the CCCCTA-lossy integrator sections were also studied. The results of PSPICE simulations using BJT CCCCTA are included to verify theory.*

***Streszczenie.** Zaprezentowano wielofazowy generator w trybie prądowym. Stosując integrator CCCCTA uzyskuje się przesunięcie fazowe parzyste lub nieparzyste. Układ charakteryzuje się dużą impedancją wyjściową. Zbada no wpływ nieidealnych parametrów integratora. (**Nowy wielofazowy generator sinusoidalny o trybie prądowym wykorzystujący integrator typu CCCCTA**)*

Keywords: multiphase sinusoidal oscillator; current-mode; CCCCTA.
Słowa kluczowe: genersator sinusoidalny, tryb prądowy, CCCCTA.

Introduction

It is well known that multiphase sinusoidal oscillator (MSO) is an important blocks for various applications. For example, in telecommunications it is used for phase modulators, quadrature mixers [1], and single-sideband generators [2]. In measurement systems, MSO is employed for vector generators or selective voltmeters [3]. It can also be utilized in power electronic systems [4]. Recently, current-mode circuits have been receiving considerable attention of due to their potential advantages such as inherently wide bandwidth, lower slew-rate, greater linearity, wider dynamic range, simple circuitry and low power consumption [5]. The interesting active element, called current conveyor transconductance amplifier (CCTA), is introduced to provide new possibilities in the current-mode circuit. This device can operate in both current and voltage modes which provides flexibility and enables a variety of circuit designs. In addition, it can offer advantageous features such as high-slew rate, higher speed, wide bandwidth and simple implementation [6]. However, the CCTA can not control the parasitic resistance at X (R_X) port so when it is used in some circuits, it must unavoidably require some external passive components, especially the resistors. This makes it not appropriate for IC implementation due to occupying more chip area, high power consumption and without electronic controllability. On the other hand, the introduced current-controlled current conveyor transconductance amplifier (CCCCTA) [7] has the advantage of electronic adjustability over the CCTA.

A number of current-mode MSOs using different active building blocks are available in the literature. These include realizations using current follower (CF) [8], CCCII [9]-[10], most recently by CDTA [11]-[13] and CCCCTA [14]-[15]. The CF-based MSO in [8] requires two current followers, one floating resistor, and one floating capacitor for each phase and thus the circuit is not suitable for monolithic integration. Moreover, it cannot be electronically controlled. The CCCII-based MSOs [9]-[10] enjoy high-output impedances and electronic tunability. However, the first one requires a large number of external capacitors. In addition, the oscillation condition can be provided by tuning the capacitance ratio of external capacitors, which is not easy to implement. The second reported circuit requires additional current amplifiers, which makes the circuit more complicated and increases its power consumption. CDTA-based current-mode MSOs in [11] is based on lossy integrators, whereas the circuits in [12] and [13] contain CDTA-based allpass sections. They exhibit good performance in terms of electronic tunability, high-output impedances, and independent control of the oscillation frequency and the oscillation condition. However, MSOs in [11] and [12] require an additional current amplifier, which is implemented by two CDTAs. Moreover, the output currents of the MSO, utilizing the CDTA-based lossy integrators, are of different amplitudes. The MSO employing CDTA-based allpass sections [12] requires two CDTAs in each allpass section, and the circuitry becomes more extensive. While MSO using CDTA-based allpass sections [13] requires floating capacitor. Consequently, it occupies a larger chip area for VLSI design. In addition, its power consumption is also increased. MSOs using CCCCTAs [14]-[15] and CCCDTAs [16] have been proposed. They provide following advantages: electronic tunability, high-output impedances, independent control of the oscillation frequency and the oscillation condition, no use of external current amplifier. However, MSOs in [14]-[16] require external resistor per

Table 1. Comparison between various MSOs

Ref	Design technique	Active element	No. of active element per phase	Additional amplifier	Grounded C only	No. of R+C per phase	Electronic control	CM output
[9]	Losy integrator	CCCII	1	No	Yes	0+2	Yes	Yes
[10]	Losy integrator	CCCII	1	Yes	Yes	1+1	Yes	Yes
[11]	Losy integrator	CDTA	1	Yes	Yes	0+1	Yes	Yes
[12]	Allpass filter	CDTA	2	Yes	No	0+1	Yes	Yes
[13]	Allpass filter	CDTA	1	No	No	2+1	Yes	Yes
[14]	Losy integrator	CCCCTA	1	No	Yes	1+1	Yes	Yes
[15]	Allpass filter	CCCCTA	1	No	Yes	1+1	Yes	Yes
[16]	Allpass filter	CCCDTA	1	No	Yes	1+1	Yes	Yes
Proposed MSOs	Losy integrator	CCCCTA	1	No	Yes	0+1	Yes	Yes

phase. The proposed MSOs are compared with previously published MSOs of [9-16] and the results are shown in Table 1.

The purpose of this study is to introduce a new current-mode multiphase sinusoidal oscillator. The features of the proposed circuit are the following: (I) Use of grounded capacitors and identical circuit configuration for each section in the MSO topology which are suitable for integration. (II) The electronic tunability of oscillation condition and oscillation frequency. (II) High-impedance current outputs. (IV) The possibility of generating multi-phase signals for both an even and odd number of equally-spaced in phases. (V) Independent tuning of the oscillation frequency and the oscillation condition. (VI) Equality of amplitudes of each phase due to utilizing identical sections. (VII) Requirement for only one CCCCTA as the active element for each phase without any additional current amplifiers and external resistors.

Theory and Principle

Basic Concept of CCCCTA

Since the proposed circuit is based on CCCCTA, a brief review of CCCCTA is given in this section. The characteristics of the ideal CCCCTA are represented by the following hybrid matrix [17]:

(1) $$\begin{bmatrix} I_y \\ V_x \\ I_z \\ I_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ R_x & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & \pm g_m & 0 \end{bmatrix} \begin{bmatrix} I_x \\ V_y \\ V_z \\ V_o \end{bmatrix}.$$

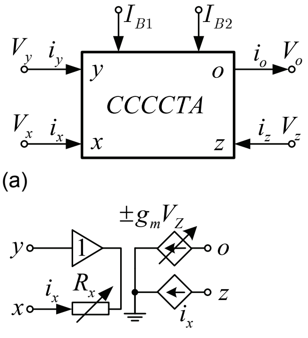
For a BJT CCCCTA, the parasitic resistance at x port (R_x) and the transconductance (g_m) can be expressed to be

(2) $$R_x = \frac{V_T}{2I_{B1}},$$

and

(3) $$g_m = \frac{I_{B2}}{2V_T}.$$

V_T is the thermal voltage. I_{B1} and I_{B2} are the bias currents used to control the parasitic resistances and transconductance, respectively. The symbol and the equivalent circuit of the CCCCTA are illustrated in Figs. 1(a) and (b), respectively. In general, CCCCTA can contain an arbitrary number of o terminals, providing current I_o of both directions.



(b)

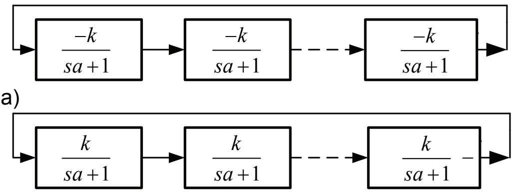
Fig.1. CCCCTA (a) Symbol (b) Equivalent circuit

Implementation of n-cascaded Lossy Integrator-based Multiphase Sinusoidal Oscillator

The generalized structure of MSO by cascading the n identical stages (n≥3) is shown in Fig. 2 which contains the lossy integrator (first order low pass filter) for each phase. The output of the n^th stage is fed back to the input of the first stage, and the signal of the last section is non-inverted for odd phase system and inverted for odd or even phase system. It is found in Fig. 2 that the system can provide one phase per one lossy integrator without any additional external amplifier. The system loop gain for odd phase system can be written as follows [18]:

(4) $$L(s) = \left(\frac{-k}{sa+1}\right)^n,$$

where the symbols *k* is the current gain and the constant *a* denotes the time constant of each integrator section. At the oscillation frequency $\omega_{osc} = 2\pi f_{osc}$, the Barkhausen's condition can be written as



(b)

Fig.2. MSO block diagram for (a) odd phase (b) odd/even phase

(5) $$L(j\omega_{osc}) = \left(\frac{-k}{j\omega_{osc}a+1}\right)^n = 1,$$

or

(6) $$\left(j\omega_{osc}a+1\right)^n + (-1)^{n+1}\left(k\right)^n = 0.$$

Considering in Eq. (5) for $n = 3,5,7,...$, the frequency of oscillation (FO) and condition of oscillation (CO) are expressed as [18]

(7) $$\text{FO: } \omega_{osc} = \frac{1}{a}\tan\frac{\pi}{n},$$

and

(8) $$\text{CO: } k \geq \sec\frac{\pi}{n}.$$

Considering Eqs. (7) and (8), the oscillation condition can be controlled independently of the oscillation frequency by the gain *k*, while the oscillation frequency can be changed by the time constant *a*.

For odd or even phase system, the system loop gain for odd phase system can be written as follows [18]:

(9) $$L(s) = -\left(\frac{k}{sa+1}\right)^n.$$

At the oscillation frequency $\omega_{osc} = 2\pi f_{osc}$, the Barkhausen's condition can be written as

(10) $$\left(j\omega_{osc}a+1\right)^n + \left(k\right)^n = 0$$

Considering in Eq. (10) for $n \geq 3$, the frequency of oscillation (FO) and condition of oscillation (CO) are expressed as [19]

(11) $$\text{FO: } \omega_{osc} = \frac{1}{a}\tan\frac{\pi}{n},$$

and

(12) $$\text{CO: } k \geq \sec\frac{\pi}{n}.$$

Similar to odd phase system, for even or odd phase system, the oscillation condition can be controlled independently of the oscillation frequency by the gain *k*, while the oscillation frequency can be changed by the time constant *a* as shown in Eqs. (11) and (12). It is also found from Eqs. (7) and (11) that both frequency of oscillations for odd phase and odd/even phase are same.

Proposed n-cascaded Lossy Integrator-based Multiphase Sinusoidal Oscillators

As mentioned in the above section, the proposed MSO is based on identical lossy integrator sections. A prospective CCCCTA-based implementation is shown in Fig. 3. It is seen that proposed lossy integrator circuit consists of 1 CCCCTA and 1 grounded capacitor. The current transfer function can be written as follows:

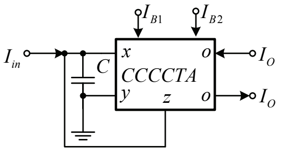


Fig.3. CCCCTA-based current-mode lossy integrator

$$\frac{I_O(s)}{I_{in}(s)} = \pm\frac{\frac{g_m R_x}{2}}{s\frac{CR_x}{2}+1}. \tag{13}$$

According to Eqs. (7) and (8), the oscillation condition and oscillation frequency for odd phase system are as follows:

(14) FO: $\omega_{osc} = \frac{2}{CR_x}\tan\frac{\pi}{n}$,

and

(15) CO: $\frac{g_m R_x}{2} \geq \sec\frac{\pi}{n}$.

Also, the oscillation condition for odd or even phase system is as follows:

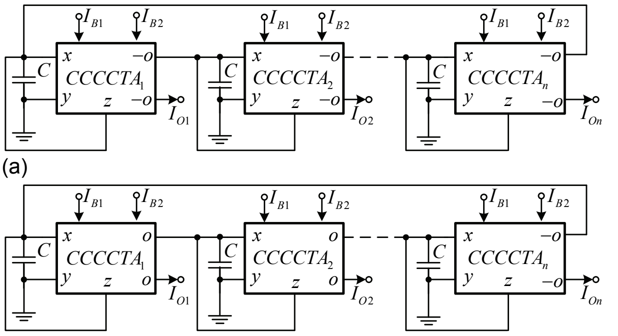
$$\frac{g_m R_x}{2} \geq \sec\frac{\pi}{n}. \tag{16}$$

If $R_x = V_T / 2I_{B1}$ and $g_m = I_{B2} / 2V_T$, the FO and CO from Eqs. (14)-(16) are written as

(17) OF: $\omega_{osc} = \frac{4I_{B1}}{CV_T}\tan\frac{\pi}{n}$,

(18) CO: $\frac{I_{B2}}{8I_{B1}} \geq \sec\frac{\pi}{n}$,

From Eq. (17), it can be seen that the CO can be adjusted electronically/independently from the FO by varying I_{B2} while the oscillation frequency can be electronically adjusted by I_{B1}. The resulting current-mode MSOs are shown in Fig. 4(a) and (b) for odd and odd/even phase system, respectively. It is found from Figs. 5 and 6 that the current mirrors are required to split the bias currents I_{B1} and I_{B2} to each lossy integrator section. In addition, it can be seen that the proposed MSOs enjoy high-output impedances which facilitate easy driving an external load without additional current buffers [20]-[21].



(a)

(b)

Fig.4. Proposed current-mode MSO (a) odd phase (b) odd/even phase

Analysis of Non-ideal Case

For a complete analysis of the circuit, it is necessary to take into account the following non-idealities of CCCCTA,

- Current transfer gains

(19) $V_x = I_x R_x + \beta V_y; I_z = \alpha I_x; I_o = \gamma g_m V_z$,

where α is the parasitic current transfer gain from x terminal to z terminal: β is the parasitic voltage transfer gain from y terminal to x terminal: γ is the parasitic current gain associated with copies of the current from o terminal.

- The parasitic resistances and capacitances appear between the high-impedance z (C_z and R_z) and o (C_o and R_o) terminals of the CCCCTA and ground.

Considering the non-ideal effects, if $R_o, R_z >> R_x$, the current transfer function for the lossy integrator shown in Fig. 3 gets modified to

$$\frac{I_O(s)}{I_{in}(s)} = \pm\frac{\frac{\gamma g_m R_x}{(\alpha+1)}}{s\frac{(C+C_z+C_o)R_x}{(\alpha+1)}+1}. \tag{20}$$

Then the oscillation frequency and oscillation condition of the proposed MSO from Eqs.(14)-(16) become

(21) FO: $\omega_{osc} = \frac{\alpha+1}{(C+C_z+C_x)R_x}\tan\frac{\pi}{n}$,

(22) CO: $\frac{\gamma g_m R_x}{(\alpha+1)} \geq \sec\frac{\pi}{n}$,

It is found that non-ideal parameters will affect both oscillation condition and oscillation frequency. These parameters are dependent on temperature variations. Consequently, these errors affect the sensitivity to temperature and the high frequency response of the proposed circuit, the CCCCTA should be carefully designed to minimize these errors. Moreover, the stray/parasitic capacitance at terminal z and o can be absorbed into the external grounded capacitors as they appear in shunt with them.

Simulation Results

To prove the performances of the proposed MSOs, the PSpice simulation program was used for the examination. The PNP and NPN transistors employed in the proposed circuit were simulated by using the parameters of the PR200N and NR200N bipolar transistors of ALA400 transistor array from AT&T [22] with parameters tabulated in Table 2. Internal construction of CCCCTA used in simulation is shown in Fig. 5 [17]. The circuit was biased with ±2V supply voltages. Firstly, an odd three-phase sinusoidal oscillator (n=3) based on the structure in Fig. 2(a) has been designed on the basis of Fig. 4(a). The component values are as follows: I_{B1}=50μA, I_{B2}=780μA, C=0.4nF. The simulated output waveforms, I_{O1}, I_{O2} and I_{O3} are shown in Fig. 6 and 7. The frequency of oscillation achieved was 4.387MHz against the calculated value of 5.303MHz having frequency error of 17.273%. This error stems from the non-ideal parameters as depicted in Eq. (22). The frequency spectrum of output currents are shown in Fig. 8. The total harmonic distortion is about 0.479%.

Table 2. Parameters of the transistors

```
  .model PX PNP
+RB=327  IRB=0  RBM=24.55  RC=50  RE=3
+IS=73.5E-18  EG=1.206  XTI=1.7  XTB=1.866  BF=110
+IKF=2.359E-3  NF=1  VAF=51.8  ISE=25.1E-16  NE=1.650
+BR=0.4745  IKR=6.478E-3  NR=1  VAR=9.96  ISC=0  NC=2
+TF=0.610E-9  TR=0.610E-8  CJE=0.180E-12  VJE=0.5
+MJE=0.28  CJC=0.164E-12  VJC=0.8  MJC=0.4  XCJC=0.037
+CJS=1.03E-12  VJS=0.55  MJS=0.35  FC=0.5

  .model NX NPN
+RB=524.6  IRB=0  RBM=25  RC=50  RE=1
+IS=121E-18  EG=1.206  XTI=2  XTB=1.538  BF=137.5
+IKF=6.974E-3  NF=1  VAF=159.4  ISE=36E-16  NE=1.713
+BR=0.7258  IKR=2.198E-3  NR=1  VAR=10.73  ISC=0  NC=2
+TF=0.425E-9  TR=0.425E-8  CJE=0.214E-12  VJE=0.5
+MJE=0.28  CJC=0.983E-13  VJC=0.5  MJC=0.3  XCJC=0.034
+CJS=0.913E-12  VJS=0.64  MJS=0.4  FC=0.5
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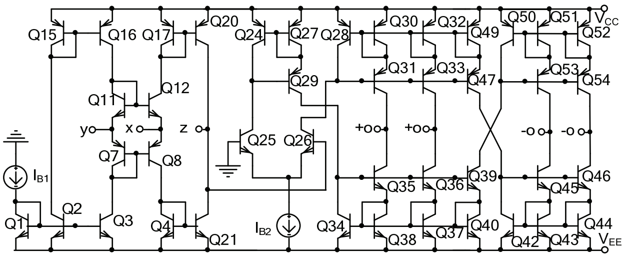

Fig.5. Internal construction of CCCCTA

Secondly, an even four-phase sinusoidal oscillator (n=4) based on the structure in Fig. 2(b) has been designed on the basis of Fig. 4(b). The component values are same to previous investigation. The simulated output waveforms, I_{O1}, I_{O2}, I_{O3} and I_{O4} are shown in Figs. 9 and 10. The frequency of oscillation achieved was 2.575MHz while calculated value of this parameter from Eq. (22) is 3.062Hz (deviated by 15.904%). This error stems from the non-ideal parameters as depicted in Eq. (22). The frequency spectrum of output currents are shown in Fig. 11. The total harmonic distortion is about 0.798%.

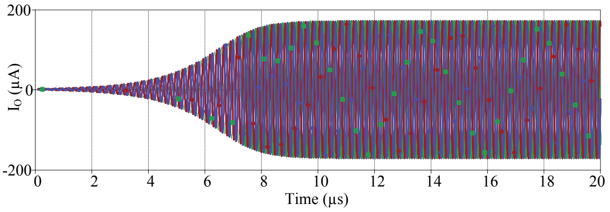

Fig.6. Output waveforms during initial state (n=3)

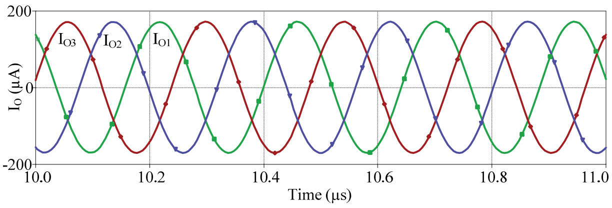

Fig.7. Current outputs of the proposed MSO (n=3)

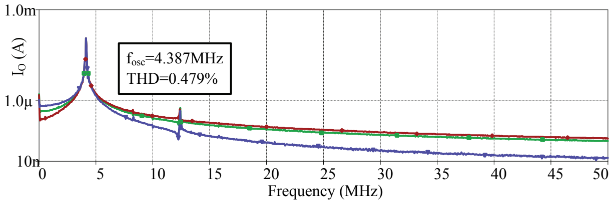

Fig.8. Spectrum of signal in Fig.7

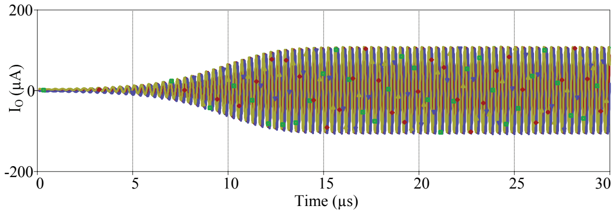

Fig.9. Output waveforms during initial state (n=4)

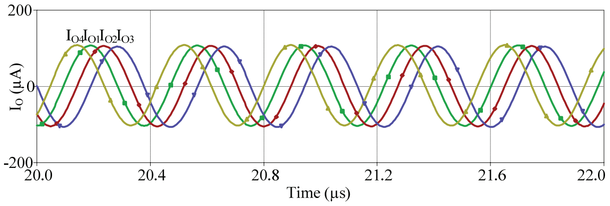

Fig.10. Current outputs of the proposed MSO (n=4)

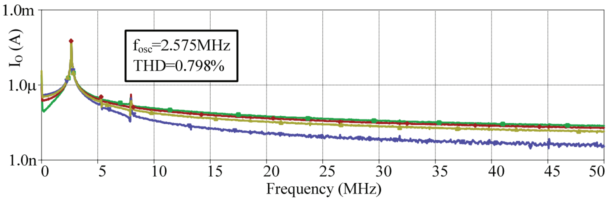

Fig.11. Spectrum of signal in Fig.10

Conclusions

New current-mode multiphase sinusoidal oscillators using CCCCTA-based lossy integrators with grounded capacitors have been presented. The features of the proposed circuit are that: oscillation frequency and oscillation condition can be independently tuned; the proposed oscillator consists of merely 1 CCCCTA and 1 grounded capacitor for each phase and no additional current amplifier and availability of explicit-current outputs from high-output impedance terminals. PSPICE simulation results agree well with the theoretical anticipation.

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Authors*: Prungsak Uttaphut, Department of Electrical Technology, Faculty of Industrial Technology, Suan Sunandha Rajabhat University, Dusit, Bangkok, 10300, Thailand E-mail: prongsaku@hotmail.com.*

The correspondence address is:

e-mail: prongsaku@hotmail.com