A Novel Active Phase Compensated Inverting Amplifier

Ein neuer aktiver phasenkompensierter invertierender Verstärker

By Ahmed M. Soliman (Senior Member IEEE)*)

Abstract:

A new active phase compensation method for inverting amplifiers is given. The proposed circuit uses 2 op-amps and 4 resistors. Three special cases are discussed and the results are summarized in a table. It is shown that to minimize the phase and the magnitude errors and to provide for a maximum bandwidth only a single additional op-amp is necessary for the phase compensation of an inverting weighted summer. This new proposed wide bandwidth inverting weighted summer is considered to be the most economical phase compensated weighted summer available up to date.

Übersicht:

Es wird eine neue aktive Phasenkompensation für invertierende Verstärker angegeben. Die vorgeschlagene Schaltung enthält zwei Operationsverstärker und vier Widerstände. Es werden drei Spezialfälle diskutiert; die Ergebnisse sind tabellarisch zusammengefaßt. Um Phasen- und Amplitudenfehler klein zu halten und um eine große Bandbreite zu erreichen, ist lediglich ein zusätzlicher Operationsverstärker zur Phasenkompensation eines invertierenden Summierverstärkers notwendig. Dieser Breitbandverstärker zeichnet sich damit durch eine besonders wirtschaftliche Phasenkompensation aus.

Für die Dokumentation:
Breitbandverstärker / Operationsverstärker / Phasenkompensation

1. Introduction

The inverting weighted summer which includes the inverting voltage controlled voltage source (VCVS) as a special case is a very useful building block in active *RC* networks. It is well known that the performance of the inverting VCVS depends on the realizable gain and the used op-amp. Let the open loop gain of the op-amp be represented by the one pole model

$$A(s) \simeq \frac{\omega_t}{s} \tag{1}$$

with ω_t being the unity gain bandwidth of the op-amp.

For the uncompensated inverting VCVS shown in **Fig. 1a,** the phase and magnitude errors contributed by the finite ω_t of the op-amp are summarized in **Table 1** [1, 2]. It is clear that the inverting VCVS structures require only phase compensation. Recently Soliman and Ismail [3] have discussed the advantages of active compensation over passive compensation [2] and have proposed a generalized active compensation method which may be used with inverting amplifiers as shown in **Fig. 1b.**

The purpose of this paper is to introduce a new active *R* building block which uses 2 op-amps and 4 resistors and is suitable for realizing phase compensated inverting amplifiers. The proposed circuit does not require matched op-amps. Three special cases are discussed. In one case the circuit is equivalent to that shown in Fig. 1b. An interesting special circuit is arrived at which requires only 2 op-amps and 2 resistors and has smaller phase and magnitude errors and a wider bandwidth than the other two special circuits. This circuit is equivalent to Reddy's [4] inverting VCVS shown in **Fig. 1c** when adjusted for phase compensation, but uses two resistors less.

2. The active compensated inverting VCVS

The new generalized active phase compensated inverting VCVS is shown in **Fig. 2a.** By direct analysis using eqn. (1) the network transfer function is given by

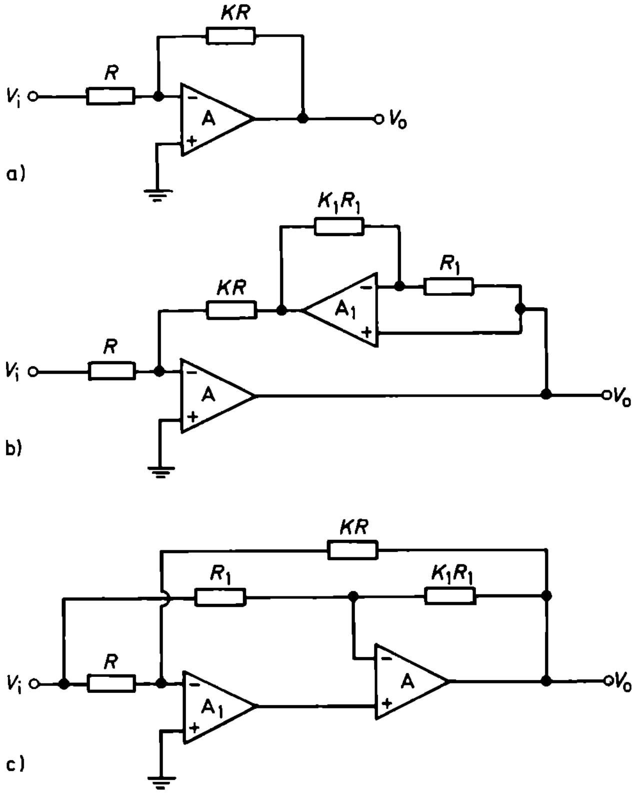

Fig. 1:
- a) The uncompensated inverting VCVS
- b) The Soliman-Ismail active phase compensated inverting VCVS [3]
- c) Reddy's compensated inverting VCVS [4]

---

*) The author is with the Electrical Engineering Department, Florida Atlantic University, Boca Raton, Florida 33431.

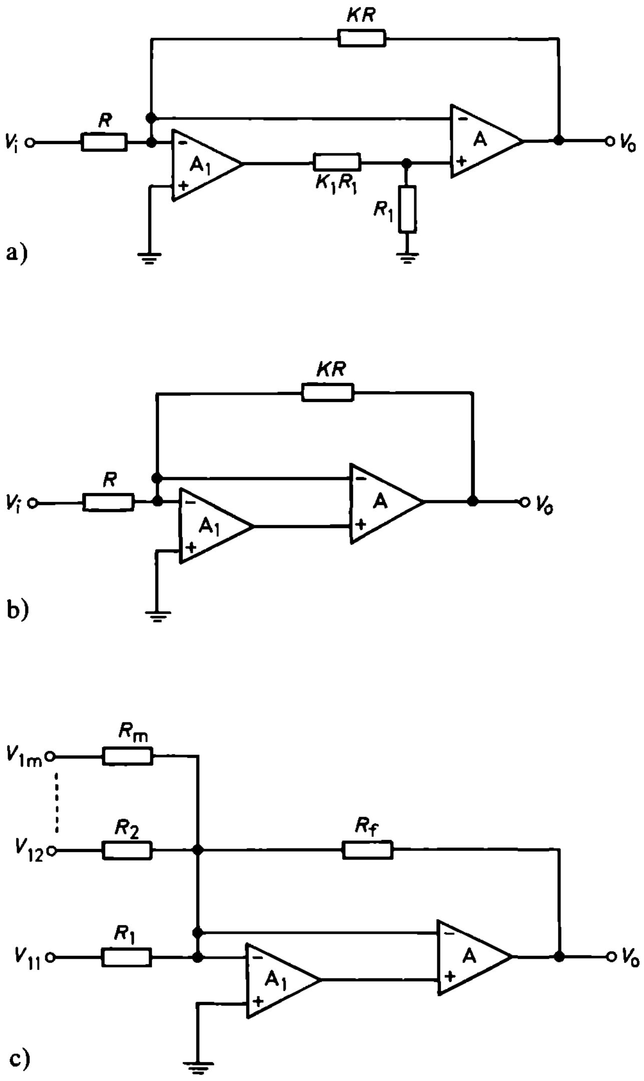

Fig. 2:
a) The proposed generalized phase compensated inverting VCVS
b) The novel economical 2 op-amps + 2 R phase compensated inverting VCVS
c) The proposed phase compensated inverting weighted summer

$$\frac{V_0}{V_i} = -K\,\varepsilon(s) \tag{2}$$

where

$$\varepsilon(s) = \frac{1 + s\tau_1}{1 + s\tau_1 + s^2\tau\tau_1} \tag{3}$$

and

$$\tau = \frac{K+1}{\omega_t}, \quad \tau_1 = \frac{K_1+1}{\omega_{t_1}}. \tag{4}$$

$\varepsilon(s)$ is the remaining error function of the compensated circuit. Examining the above error function it is seen that the remaining phase and magnitude errors are given by

$$\left.\begin{aligned} \Phi &\equiv \arg[\varepsilon(j\omega)] \simeq -\omega^3\tau\tau_1^2 \\ \gamma &\equiv |\varepsilon(j\omega)| - 1 \simeq \omega^2\tau\tau_1 \end{aligned}\right\} \begin{aligned} \omega\tau &\ll 1, \\ \omega\tau_1 &\ll 1. \end{aligned} \tag{5}$$

It is clear that this relatively negligible phase error is obtained even if mismatched op-amps are used. This is one of the advantages of the proposed circuit. The 3 dB bandwidth of the compensated VCVS is given by

$$BW = \frac{1}{\tau}\sqrt{\left(\frac{1}{2} + \frac{\tau}{\tau_1}\right) + \sqrt{\frac{1}{4} + \frac{\tau}{\tau_1} + 2\left(\frac{\tau}{\tau_1}\right)^2}}\,. \tag{6}$$

From the above analysis it is seen that the resistor KR controls the gain of the VCVS and the resistor K_1R_1 controls the compensated response. Assuming that matched op-amps are used, the following special cases are discussed next.

1) $K_1 = K$: in this case the circuit is equivalent to the recently proposed circuit shown in Fig. 1b, (assuming $K = K_1$ and $A = A_1$). The normalized bandwidth in this case is given by

$$BW_n \equiv \frac{BW}{\omega_t} = \frac{1}{(K+1)}\sqrt{\frac{3+\sqrt{13}}{2}} = \frac{1.817}{(K+1)} \tag{7}$$

2) $K_1 = K - 1$: the results in this case are given in Table 1. It is seen that the magnitude error is identical to that obtained using the recently described passive compensated circuit [5], however the phase error here is smaller.

Table 1: Approximate phase and magnitude errors obtained for the uncompensated and the proposed phase compensated inverting VCVS, where

$$\tau = \frac{K+1}{\omega_t}, \quad \tau_c = \frac{K}{\omega_t}, \quad \tau_0 = \frac{1}{\omega_t} \quad \text{and} \quad \omega\tau \ll 1$$

		Error Function $\varepsilon(s)$	Approximate Phase Error	Approximate Magnitude Error
The uncompensated inverting VCVS 2, Fig. 1a		$\frac{1}{1+s\tau}$	$-\omega\tau$	$-\frac{(\omega\tau)^2}{2}$
The Compensated	1) $K_1 = K$	$\frac{1+s\tau}{1+s\tau+s^2\tau^2}$	$-(\omega\tau)^3$	$(\omega\tau)^2$
VCVS Fig. 2a	2) $K_1 = K - 1$	$\frac{1+s\tau_c}{1+s\tau_c+s^2\tau\tau_c}$	$-\left[\frac{K}{K+1}\right]^2(\omega\tau)^3$	$\left[\frac{K}{K+1}\right](\omega\tau)^2$
	3) $K_1 = 0$ Fig. 2b	$\frac{1+s\tau_0}{1+s\tau_0+s^2\tau\tau_0}$	$-\left[\frac{1}{K+1}\right]^2(\omega\tau)^3$	$\left[\frac{1}{K+1}\right](\omega\tau)^2$

3) $K_1=0$: this is the optimum design for minimum phase and magnitude errors and a maximum bandwidth. Setting $K_1=0$ however implies that the transfer function becomes independent of R_1, thus R_1 is taken as open circuit and the circuit of **Fig. 2b** is obtained. In this case the normalized bandwidth is given by

$$BW_n=\frac{1}{(K+1)}\sqrt{\left(K+\frac{3}{2}\right)+\sqrt{\left(K+\frac{5}{4}\right)+2\,(K+1)^2}}\,. \quad (8)$$

It is worth noting that this inverting VCVS has the same error function as the noninverting VCVS described recently by the author [6]. The proposed 2 op-amps + 2 R inverting VCVS may be generated from Reddy's VCVS shown in Fig. 1c when adjusted for phase compensation ($K_1=K$). The feedforward technique employed in the circuit of Fig. 2b has been used before for active compensation of integrators [7].

Although the circuit in Fig. 2b is the optimum circuit, the reason for providing that in Fig. 2a is to demonstrate the analogy to some of the known methods of passive [2, 5] and active [3, 4] compensation.*)

3. Active compensation of the inverting weighted summer

Fig. 2c represents the new active phase compensated inverting weighted summer which requires only a single additional op-amp. By direct analysis to the circuit assuming matched op-amps are used, the output voltage is obtained as:

$$V_0=-R_f\left[\sum_{i=1}^{m}\frac{V_{1i}}{R_i}\right]\varepsilon_0(s)\,, \quad (9)$$

where

$$\varepsilon_0(s)=\frac{1+s\tau_0}{1+s\tau_0+s^2\tau\tau_0}\,, \quad (10)$$

$$\tau=\frac{K+1}{\omega_t}\,,\quad \tau_0=\frac{1}{\omega_t} \quad (11)$$

and

$$K=R_f\left[\sum_{i=1}^{m}\frac{1}{R_i}\right]. \quad (12)$$

4. Conclusions

A novel active compensation method for the inverting weighted summer is proposed. It is shown that only a single additional op-amp is required to reduce the phase error of the inverting weighted summer to a negligible level. Detailed analysis which includes the phase error, magnitude error and realizable bandwidth is given. The circuit for the inverting VCVS has identical error function as the noninverting VCVS described recently by the author [6].

---

*) A detailed stability analysis based on taking the effect of the second pole ω_2 of the op-amp into consideration indicates that the potential divider used in Fig 2a is necessary to stabilize the VCVS if the used op-amps have $\frac{\omega_2}{\omega_t}<\left[2-\frac{1}{2(K+1)}\right]$ (assuming matched op-amps are used) The necessary condition for the stability of the circuit in Fig 2a is given by $\frac{\omega_2}{\omega_t}>\left[\frac{2}{K_1+1}-\frac{1}{2(K+1)}\right]$ For a specified gain and a given $\left(\frac{\omega_2}{\omega_t}\right)$ the design value for K_1 is determined from the above inequality

References:

[1] Budak, A.; Peterela, D. M.: Frequency limitations of active filters using operational amplifiers. IEEE Trans. Circuit Theory CT-19 (1972) 7, pp. 322—328.
[2] Wilson, G.: Compensation of some operational amplifier based RC active networks. IEEE Trans. Circuits and Systems CAS-23 (1976) 7, pp. 443—446.
[3] Soliman, A. M.; Ismail, M.: Active compensation of op-amps. IEEE Trans. Circuits and Systems CAS-26 (1972) 2, pp. 112—117.
[4] Reddy, M. A.: Operational amplifier circuits with variable phase shift and their application to high Q active RC filters and RC oscillators. IEEE Trans. Circuits and Systems CAS-23 (1976) 6, pp. 384—389.
[5] Soliman, A. M.; Ismail, M.: Passive compensation of op-amp VCVS and weighted summer building blocks. IEEE Trans. Circuits and Systems CAS-26 (1979) 10, pp. 898—900.
[6] Soliman, A. M.: A generalized active compensated noninverting VCVS with reduced phase error and wide bandwidth. Proceedings IEEE 67 (1979) 6, pp. 963—965.
[7] Brackett, P. O.; Sedra, A. S.: Active compensation for high frequency effects in op-amp circuits with applications to active RC filters. IEEE Trans. Circuits and Systems CAS-23 (1976) 2, pp. 68—72.

Dr. Ahmed M. Soliman, 1908 N.W. 4th Ave. Apt. 217, Boca Raton, Florida 33432, USA

(Received on August 2, 1979)

Der aktuelle Tagungsbericht

NTG-Fachtagung „Richtfunk" vom 23. bis 25. April 1980 in München

Die Fachtagung „Richtfunk" wurde vom NTG-Fachausschuß 15 „Funktechnik" zusammen mit den NTG-Fachausschüssen 13 „Antennen", 14 „Wellenausbreitung" und 16 „Mikrowellentechnik" mit dem Ziel veranstaltet, konzentriert auf den deutschsprachigen Raum den gegenwärtigen Stand und die abzusehenden Entwicklungstendenzen aufzuzeigen. Die Tagung wurde vom Leiter des Fachausschusses 15, G. Strunz, und dem wissenschaftlichen Tagungsleiter H. Rupp eröffnet.

H. Willenberg (FTZ Darmstadt) zeigte in seinem Eröffnungsvortrag „Richtfunk heute und morgen" den gegenwärtigen nationalen und internationalen Stand der Richtfunktechnik auf und erlauterte dann den von der DBP vorgesehenen Übergang zur digitalen Richtfunktechnik.

In der ersten Vortragsgruppe „Systemplanung und Systemtechnik", in die H. Willenberg einführte, wurden insbesondere im Hinblick auf den Übergang zur digitalen Richtfunktechnik grundlegende Planungsprobleme angesprochen. G. Wöhlbier (FTZ) berichtete einleitend über die Ergebnisse der weltweiten Funkverwaltungskonferenz 1979, soweit der Richtfunk davon betroffen ist Von besonderer Bedeutung ist hier, daß nunmehr praktisch alle wichtigen Richtfunkfrequenzbänder von den Satellitenfunkdiensten mitbenutzt werden können. H. Brodhage und W. Noack (Siemens München) zeigten die grundsätzlichen Unterschiede in der Planung analoger und digitaler Richtfunksysteme hinsichtlich Übertragungsqualität, Bandbreitenbedarf und Entkopplungsbedingungen auf. H D. Brudy (SEL Pforzheim) zeigte wichtige Prinzipien und Randbedingungen des digitalen Richtfunks auf und führte in bandbreitensparende Modulationsverfahren für Digitalsignale ein. W. Schreitmüller (AEG-Telefunken Backnang) verglich verschiedene dieser bandbreitensparenden Modulationsverfahren für Digitalsignale unter den Randbedingungen einer Satellitenübertragungsstrecke H Mahner (Siemens Munchen) zeigte auf, welche Anforderungen an die Filter und die Amplitudenlinearität von digitalen Richtfunksystemen bei bandbreitensparenden Modulationsverfahren zu