gentlich gewünscht werden, lassen sich durch geeignetes Zusammenschalten von Richtkopplern mit unterschiedlichen Übertragungscharakteristiken aufbauen. Schaltungstechnisch bedingen hier FRK aus gleichen bzw. ungleichen Fasern unterschiedliche Strukturen. Wegen der quasiperiodischen Übertragungscharakteristik von FRK aus gleichen Fasern ist eine Kombination von Parallel- und Serienschaltungen erforderlich. Der Abgleich einer solchen komplexen Richtkopplerschaltung gestaltet sich jedoch aus zweierlei Gründen als sehr schwierig. Einerseits liegen Nullstellen und Maxima weder im Frequenzbereich noch im Wellenlängenbereich äquidistant, andererseits ist eine ausreichende Sperrdämpfung nur in einem sehr schmalen Frequenzbereich gegeben. Angesichts dessen ist die praktische Realisierbarkeit derartiger Vielkanalsysteme sogar in Frage zu stellen.

Erheblich günstiger ist die Verwendung von FRK aus ungleichen Fasern. Wegen der Bandpaßcharakteristik mit ausgedehnten Bereichen hoher Sperrdämpfung erfolgt der Aufbau einer Vielkanalstruktur durch eine einfache Serienschaltung. Da schmalbandige FRK aus ungleichen Fasern auch sehr geringe Verluste aufweisen [13], bleibt die Gesamteinfügungsdämpfung einer solchen Struktur in vertretbaren Grenzen. Nicht zuletzt hat eine reine Serienschaltungsstruktur den Systemvorteil einfacher nachträglicher Erweiterbarkeit.

Frequenzselektive FRK aus ungleichen Fasern lassen sich somit vorteilhaft als Multiplex- und Demultiplex-Komponenten in einwelligen optischen Frequenzmultiplex-Übertragungssystemen mit Kanalabständen von wenigen THz einsetzen.

[1] Rocks, M.; Kersten, R. Th.: Optische Multiplex-Systeme in der optischen Nachrichtentechnik. Frequenz 36 (1982) 12, S.319—327.
[2] Winzer, G.: Wavelength multiplexing components – a review of single-mode devices and their applications. J. Lightwave Technol. LT-2 (1984) 4, S.369—378.
[3] Snyder, A.; Love, J.: Optical Waveguide Theory. London: Chapman and Hall, 1983.
[4] Parriaux, O.; Gidon, S.; Kuznetsov, A.: Distributed coupling on polished single-mode optical fibers. Appl. Optics 20 (1981) 14, S.2420—2423.
[5] Digonnet, M.; Shaw, H.: Wavelength multiplexing in single-mode fiber couplers. Appl. Optics 22 (1983) 3, S.484—491.
[6] Köster, W.: Wellenlängenmultiplex mit Monomodefasern durch Energietransfer zwischen den Mantelfeldern. Frequenz 38 (1984) 11, S.273—277.
[7] Parriaux, O.; Bernoux, F.; Chartier, G.: Wavelength selective distributed coupling between single mode optical-fibers for multiplexing. J. Optical Commun. 2 (1981) 3, S.105—109.
[8] Zengerle, R.; Leminger, O.: Wavelength-selective directional coupler made of nonidentical single-mode fibers. J. Lightwave Technol. LT-4 (1986) 7, S.823—827.
[9] Whalen, M.; Walker, K.: In-line optical-fibre filter for wavelength multiplexing. Electron. Lett. 21 (1985) 17, S.724—725.
[10] Zengerle, R.; Leminger, O.: Narrowband wavelength-selective directional couplers made of dissimilar single-mode fibers. OFC-IOOC Conference, Reno/Nevada, 1987, S.192.
[11] Leminger, O.; Zengerle, R.: Bandwidth of directional-coupler wavelength filters made of dissimilar optical fibers. Electron. Lett. 23 (1987) 5, S.241—242.
[12] Zengerle, R.; Leminger, O.: Tunable wavelength-selective asymmetrical single-mode fibre directional couplers with an intermediate layer. Opt. Quant. Electronics 18 (1986) 6, S.365—373.
[13] Zengerle, R.: Optische Richtkoppler für Multiplexanwendungen. Kolloquiumsvortrag am FTZ Darmstadt, Oktober 1985.

Dr.-Ing. R. Zengerle, Birkenweg 3, 6101 Fischbachtal
Dr.-Ing. O. Leminger, Gagernstraße 6, 6100 Darmstadt

(Eingegangen am 3.6.1987)

Generation of Actively Compensated Noninverting Amplifiers

Entwurf von aktiv-kompensierten, nicht-invertierenden Verstärkern

By Ahmed M. Soliman*

Abstract:

A general method for generating actively compensated noninverting voltage controlled voltage source (VCVS) building blocks using three operational amplifiers (op amps) is given. Several novel actively compensated noninverting VCVS structures are reported. The proposed compensated amplifiers have negligible phase and magnitude errors over a prescibed frequency band. The compensation conditions, the compensated phase and magnitude errors and the design equations are summarized in tables.

Übersicht:

Ein allgemeines Verfahren zur Bildung einer aktiv-kompensierten, nicht-invertierenden spannungsgesteuerten Spannungsquelle (VCVS) durch Zusammenschaltung dreier Operationsverstärker wird angegeben.
Es wird über mehrere neue nicht-invertierende VCVS-Strukturen berichtet. Die vorgeschlagenen kompensierten Verstärker besitzen vernachlässigbare Phasen- und Amplitudenfehler in einem vorgegebenen Frequenzbereich. Die Kompensationsbedingungen, die Phasen- und Amplitudenfehler der kompensierten Schaltung und die Entwurfsgleichungen sind in Tabellen zusammengefaßt.

Für die Dokumentation:
Aktive Kompensation / Nicht-invertierender Verstärker

1. Introduction

The noninverting voltage controlled voltage source (VCVS) is a basic building block in active RC filters and oscillators. Unfortunately with the exception of some very low frequency applications, the assumption of ideality cannot always be sustained and in particular the complex nature of the voltage gain must be counted for. It is well known that the finite gain bandwidth product of the operational amplifier (op amp) degrades both the phase and magnitude of the conventional VCVS building block [1]. Most recently actively compensated VCVS networks using two and three op amps have been reported in the literature [2–10].

* Professor and Chairman Electrical Engineering Department, Faculty of Engineering, United Arab Emirates University. Al-Ain, United Arab Emirates

The purpose of this paper is to present a method for generating the generalized active compensated noninverting VCVS structures employing three op amps. Several novel actively compensated VCVS networks are given. The proposed compensated noninverting amplifiers have negligible phase and magnitude errors up to an extended frequency range.

2. Analysis

Fig. 1 represents the generalized active compensated noninverting amplifier employing three op amps. The basic circuit equations are represented by the following matrix equation:

$$\begin{bmatrix} \dfrac{V_{01}}{A_1} \\ \dfrac{V_{02}}{A_2} \\ \dfrac{V_{03}}{A_3} \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} V_i + \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} V_{01} \\ V_{02} \\ V_{03} \end{bmatrix} \tag{1}$$

where a_i and b_{ij} are real coefficients having magnitudes ≤ 1.

A_i is the open loop gain of the amp which for all practical applications is represented by the single pole model [11]:

$$A_i(s) \cong \frac{\omega_{ti}}{s} \quad (i=1,2,3) \tag{2}$$

where ω_t is the gain-bandwidth product of the op amp and s the complex frequency. Without any loss of generality let V_{01} represent the output of the compensated noninverting amplifier as shown in Fig. 1. From (1), the generalized expression for the transfer function of the circuit is given by

$$T(s) \equiv \frac{V_{01}}{V_i} = \frac{N(s)}{D(s)} \tag{3}$$

where

$$N(s) = a_1 B_{11} + a_2 B_{21} + a_3 B_{31} + \frac{(a_3 b_{13} - a_1 b_{33})}{A_2} + \frac{(a_2 b_{12} - a_1 b_{22})}{A_3} + \frac{a_1}{A_2 A_3}, \tag{4}$$

and

$$D(s) = -b_{11} B_{11} - b_{21} B_{21} - b_{31} B_{31} + \frac{B_{11}}{A_1} + \frac{B_{22}}{A_2} + \frac{B_{33}}{A_3} - \frac{b_{11}}{A_2 A_3} - \frac{b_{22}}{A_1 A_3} - \frac{b_{33}}{A_1 A_2} + \frac{1}{A_1 A_2 A_3} \tag{5}$$

with

$$B_{11} = b_{22} b_{33} - b_{23} b_{32}, \tag{6}$$

$$B_{21} = b_{13} b_{32} - b_{12} b_{33}, \tag{7}$$

$$B_{31} = b_{12} b_{23} - b_{13} b_{22}, \tag{8}$$

$$B_{22} = b_{11} b_{33} - b_{13} b_{31}, \tag{9}$$

$$B_{33} = b_{11} b_{22} - b_{12} b_{21}. \tag{10}$$

From equations (2), (3), (4) and (5) the transfer function of the circuit can be written as

$$T(s) = \frac{C}{B} \varepsilon(s) \tag{11}$$

where

$$C = a_1 B_{11} + a_2 B_{21} + a_3 B_{31}, \tag{12}$$

$$B = -(b_{11} B_{11} + b_{21} B_{21} + b_{31} B_{31}), \tag{13}$$

$$\varepsilon(s) = \frac{1 + \dfrac{1}{C}\left[\left(\dfrac{a_3 b_{13} - a_1 b_{33}}{\omega_{t2}} + \dfrac{a_2 b_{12} - a_1 b_{22}}{\omega_{t3}}\right) s + \dfrac{a_1}{\omega_{t2}\omega_{t3}} s^2\right]}{1 + \dfrac{1}{B}\left[\left(\dfrac{B_{11}}{\omega_{t1}} + \dfrac{B_{22}}{\omega_{t2}} + \dfrac{B_{33}}{\omega_{t3}}\right) s - \left(\dfrac{b_{11}}{\omega_{t2}\omega_{t3}} + \dfrac{b_{22}}{\omega_{t1}\omega_{t3}} + \dfrac{b_{33}}{\omega_{t1}\omega_{t2}}\right) s^2 + \dfrac{1}{\omega_{t1}\omega_{t2}\omega_{t3}} s^3\right]}. \tag{14}$$

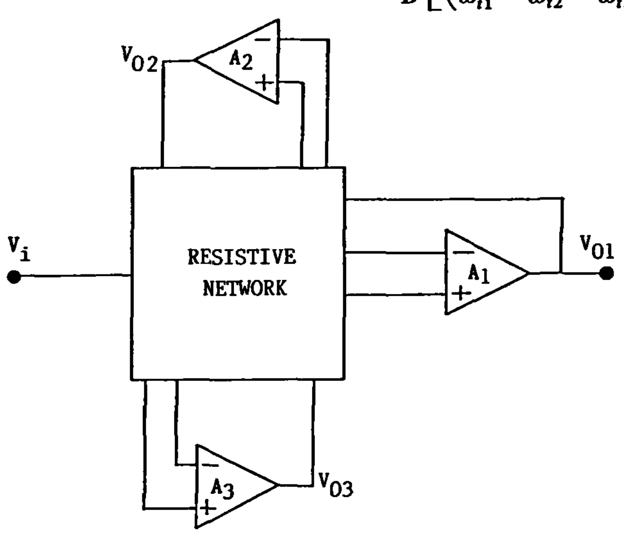

Fig. 1: The generalized compensated noninverting amplifier using 3 op amps

$\varepsilon(s)$ is the error function. Ideally it must have a unity magnitude and a zero phase. It is well known that in order to reduce the phase and magnitude errors to negligible limits, the coefficients of the s and s^2 terms in the numerator and the denominator must be identical [8–10].

In the next sections the phase compensated noninverting amplifiers are classified according to the coefficient signs of a_i and b_{ij} $(i, j = 1, 2, 3)$.

3. Class 1 – Noninverting Amplifiers

In this class the compensation conditions are independent of the gain-bandwidth of the three op amps employed in the circuit. From (14) it is seen that for the compensation conditions to be independent of ω_{ti} $(i = 1, 2, 3)$, one must have

$$B_{11} = 0, \tag{15}$$

$$b_{22} = b_{33} = 0. \tag{16}$$

Table 1: The coefficients a_i, b_{ij} signs

Class	a_1	a_2	a_3	b_{11}	b_{12}	b_{13}	b_{21}	b_{22}	b_{23}	b_{31}	b_{32}	b_{33}
1-A	+	−	−	−	−	−	+	O	+	+	O	O
1-B	+	O	−	−	−	−	O	O	+	+	O	O
2-A	+	O	O	O	−	O	+	O	−	O	+	−
2-B	+	O	O	O	−	O	+	O	+	O	−	−
2-C	+	O	O	O	−	−	+	−	−	O	+	−
3	+	O	O	O	−	O	+	−	−	−	+	O

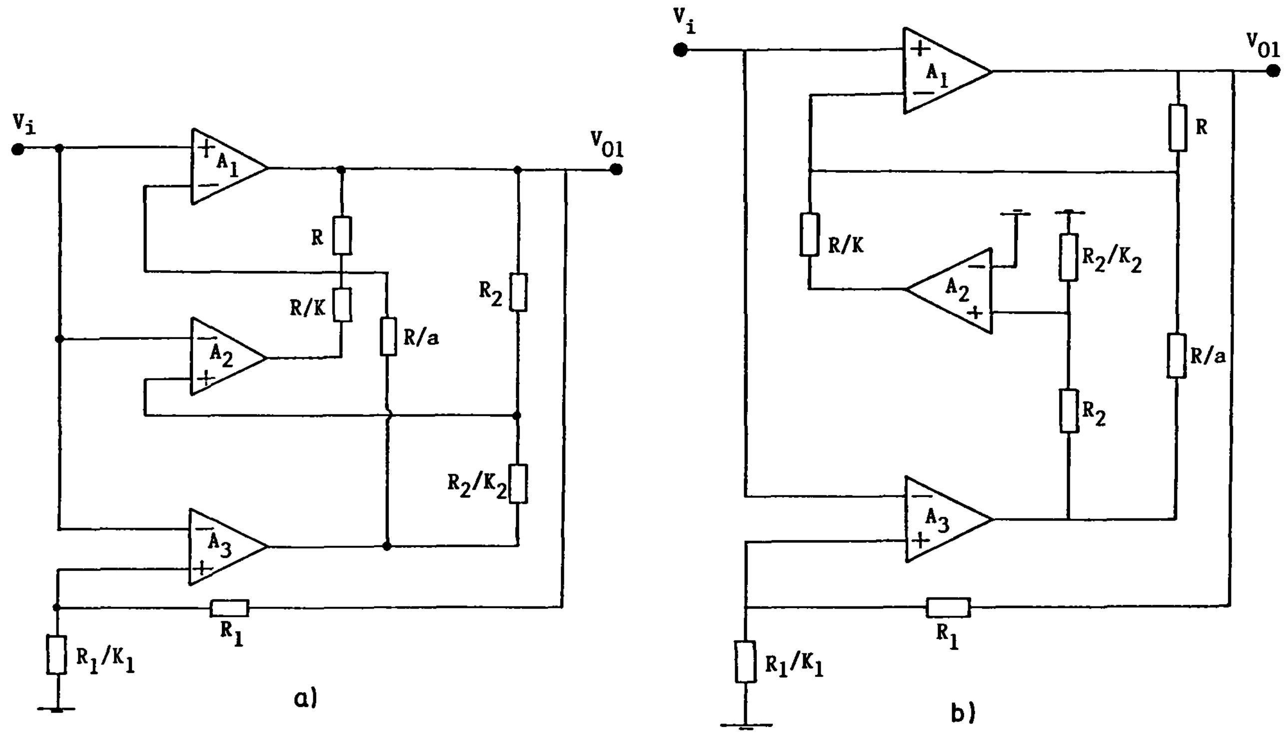

Fig. 2: Class 1-A amplifier (a) and Class 1-B amplifier (b)

From (6), (15) and (16), thus

$$b_{23} b_{32} = 0. \tag{17}$$

From the above equation and examining the transfer function, it is seen that either b_{23} or b_{32} must be zero. Without any loss of generality, take

$$b_{32} = 0, \quad b_{23} \neq 0. \tag{18}$$

From (11), (15), (16) and (18) the transfer function in this case reduces to

$$T(s) = \frac{-a_3}{b_{31}} \cdot \frac{1 + \frac{b_{13}}{b_{12} b_{23}} \frac{s}{\omega_{t2}} + \frac{a_2}{a_3 b_{23}} \frac{s}{\omega_{t3}} + \frac{a_1}{a_3 b_{12} b_{23}} \frac{s^2}{\omega_{t2}\omega_{t3}}}{1 + \frac{b_{13}}{b_{12} b_{23}} \frac{s}{\omega_{t2}} + \frac{b_{21}}{b_{23} b_{31}} \frac{s}{\omega_{t3}} + \frac{b_{11}}{b_{12} b_{23} b_{31}} \frac{s^2}{\omega_{t2}\omega_{t3}} + \frac{-1}{b_{12} b_{23} b_{31}} \frac{s^3}{\omega_{t1}\omega_{t2}\omega_{t3}}} \tag{19}$$

The compensation conditions are given by

$$\frac{a_1}{b_{11}} = \frac{a_2}{b_{21}} = \frac{a_3}{b_{31}}. \tag{20}$$

Thus it is seen that it is not necessary to use matched op amps with this class of amplifiers. From (19) and for a positive DC gain, the coefficients a_3 and b_{31} must have opposite signs. From (20), therefore the coefficiente a_i, b_{i1} must also have opposite signs ($i = 1, 2$). From the coefficients of s^2 and s^3 in the denominator of (19), one must have a negative b_{11}, (since the product $b_{12} b_{23} b_{31}$ must be negative and $b_{11}/b_{12} b_{23} b_{31}$ must be positive). A negative b_{11} implies that a_1 must be positive, and for infinite input impedance a_1 must be $+1$, b_{12} and b_{13} must be negative. From the coefficient of s/ω_{t2} in the denominator of (19), and since b_{12}, b_{13} are both negative, then b_{23} must be positive. Again for infinite input impedance b_{21} must be positive and a_2 must be -1. (Of course it is possible to have $a_2 = b_{21} = 0$ as a special case as will be discussed later).

From the coefficient of s^2 in the numerator of (19), thus a_3 must be negative and of course equals -1 (again for infinite input impedance). Finally b_{31} must be positive. The coefficient signs are summarized in **Table 1**. From the coefficient signs the following circuit is generated.

Table 2: The circuit matrices

Noninverting Amplifier circuit				Circuit matrices			
Class	Type	Fig.	Ref.	[a]	[b]		
				1	$-\frac{1}{(K+a+1)}$	$-\frac{K}{(K+a+1)}$	$-\frac{a}{(K+a+1)}$
1	A	2a	8	−1	$\frac{1}{(K_2+1)}$	0	$\frac{K_2}{(K_2+1)}$
				−1	$\frac{1}{(K_1+1)}$	0	0
				1	$-\frac{1}{(K+a+1)}$	$-\frac{K}{(K+a+1)}$	$-\frac{a}{(K+a+1)}$
1	*B*	2b	8	0	0	0	$\frac{1}{(K_2+1)}$
				−1	$\frac{1}{(K_1+1)}$	0	0
				1	0	−1	0
2	A	3a	—	0	$\frac{1}{(K_1+1)}$	0	$-\frac{1}{(K_2+1)}$
				0	0	$\frac{1}{(K_3+1)}$	$-\frac{1}{(K_3+1)}$
				1	0	−1	0
2	A	3b	—	0	$\frac{1}{(K_1+1)}$	0	$-\frac{1}{(K_2+1)}$
				0	0	$\frac{1}{(K_3+1)}$	$-\frac{1}{(K_3+1)}$
				1	0	$-\frac{1}{(K_2+1)}$	0
2	A	3c	9	0	$\frac{1}{(K_1+1)}$	0	$-\frac{1}{(K_3+1)}$
				0	0	$\frac{1}{(K_2+1)}$	$-\frac{1}{(K_3+1)}$
				1	0	$-\frac{1}{(K_2+1)}$	0
2	A	3d	—	0	$\frac{1}{(K_1+1)}$	0	−1
				0	0	$\frac{1}{(K_2+1)}$	$-\frac{1}{(K_3+1)}$
				1	0	−1	0
2	A	3e	10	0	$\frac{1}{(K_1+1)}$	0	−1
				0	0	$\frac{1}{[1+K(a+1)]}$	$-\frac{(K+1)}{[1+K(a+1)}$
				1	0	$-\frac{1}{(K_1+1)}$	0
2	A	3f	10	0	1	0	−1
				0	0	$\frac{1}{[1+K(a+1)}$	$-\frac{(K+1)}{[1+K(a+1)]}$

(to be continued on the next page)

Noninverting Amplifier circuit				Circuit matrices			
Class	Type	Fig.	Ref.	[a]	[b]		
				1	0	$-\frac{1}{(K_1+1)}$	0
2	B	4	—	0	$\frac{1}{(K_2+1)}$	0	$\frac{K_2}{(K_2+1)}$
				0	0	$-\frac{K_3}{(K_3+1)}$	$-\frac{1}{(K_3+1)}$
				1	0	$-\frac{a_1}{(a_1+a_2+a_3)}$	$-\frac{a_2}{(a_1+a_2+a_3)}$
2	C	5	6	0	$\frac{1}{(K_1+1)}$	$-\frac{a_1}{(a_1+a_2+a_3)}$	$-\frac{a_2}{(a_1+a_2+a_3)}$
				0	0	$\frac{1}{(K_2+1)}-\frac{a_1}{(a_1+a_2+a_3)}$	$-\frac{a_2}{(a_1+a_2+a_3)}$
				1	0	$-\frac{1}{(K_2+1)}$	0
3	—	6	—	0	$\frac{1}{(K_1+1)}$	$-\frac{1}{(K_3+1)}$	$-\frac{K_3}{(K_3+1)}$
				0	$-\frac{1}{(K_1+1)}$	$\frac{1}{(K_2+1)}$	0

Fig. 2a represents a class 1-A noninverting amplifier which uses three op amps and seven resistors. This circuit is a special case from the Geiger-Budak zero second derivative finite gain amplifier [8] after removing one resistor and was also reported in [12]. **Table 2** includes the circuit matrices and the corresponding transfer function. **Table 3** includes the compensation conditions, the approximate phase and magnitude errors assuming matched op amps are used.

Fig. 2b represents a class 1-B noninverting amplifier, which is generated from the coefficient signs given in Table 1 [8], where $a_2=b_{21}=0$.

4. Class 2 – Noninverting amplifiers

Here

$$a_1=1 \quad \text{and} \quad a_2=a_3=b_{11}=b_{13}=b_{31}=b_{22}=0 \tag{21}$$

and equation (11) reduces to

$$T_2(s)=\frac{-b_{23}b_{32}}{b_{12}b_{21}b_{33}}\,\varepsilon_2(s) \tag{22}$$

where

$$\varepsilon_2(s)=\frac{1+\frac{b_{33}}{b_{23}b_{32}}\frac{s}{\omega_{t2}}+\frac{-1}{b_{23}b_{32}}\frac{s^2}{\omega_{t2}\omega_{t3}}}{1+\frac{-b_{23}b_{32}}{b_{12}b_{21}b_{33}}\frac{s}{\omega_{t1}}+\frac{-1}{b_{33}}\frac{s}{\omega_{t3}}+\frac{-1}{b_{12}b_{21}}\frac{s^2}{\omega_{t1}\omega_{t2}}+\frac{1}{b_{12}b_{21}b_{33}}\frac{s^3}{\omega_{t1}\omega_{t2}\omega_{t3}}}. \tag{23}$$

As seen from the above equation the compensation conditions depend on the gain bandwidth of the three op amps and are given by

$$\frac{b_{23}b_{32}}{b_{12}b_{21}}\frac{1}{\omega_{t1}}=\frac{-b_{33}^2}{2b_{23}b_{32}}\frac{1}{\omega_{t2}}=\frac{1}{\omega_{t3}}. \tag{24}$$

From equations (22), (23) and (24) the compensated transfer function for this class can be written as

$$T_{2c}(s)=P_2\frac{1+2P_2\frac{s}{\omega_{t1}}+2P_2^2\left(\frac{s}{\omega_{t1}}\right)^2}{1+2P_2\frac{s}{\omega_{t1}}+2P_2^2\left(\frac{s}{\omega_{t1}}\right)^2+2P_2^3\left(\frac{s}{\omega_{t1}}\right)^3} \tag{25}$$

where

$$P_2=\frac{-b_{23}b_{32}}{b_{12}b_{21}b_{33}}. \tag{26}$$

From the coefficient of s^2 in the numerator of equation (23) it is clear that the product $b_{23}b_{32}$ must have a negative sign. Thus two types of amplifiers may be defined. Type A in which b_{23} is negative and b_{32} is positive, and type B in which b_{23} is positive and b_{32} is negative as given in Table 1. Several circuits may be generated which belong to the class 2-A. Six of these circuits are shown in **Fig. 3**. Tables 2 and 3 include the properties of these circuits. **Fig. 4** represents a class 2-B amplifier which is generated from the coefficient signs given in Table 1. It is worth noting that the circuit of **Fig. 5** which was reported in [7] belongs to a different class which is defined here as a class 2-C.

5. Class 3 – Noninverting amplifiers

Fig. 6 represents a class 3 amplifier. The properties of this new circuit are given in Tables 2 and 3.

Conclusion

A general method for generating actively compensated noninverting amplifiers is given. Several novel compen-

Table 3: The transfer functions, the compensation conditions, the stability conditions, the phase and the magnitude errors,

where $\tau_i = \frac{K_i+1}{\omega_{ti}}$ $(i=1,2,3)$.

In the expressions for the phase and the magnitude errors it is assumed that $\omega_{t1}=\omega_{t2}=\omega_{t3}=\omega_t$ and $\omega \ll \omega_t$.

Fig.	$T(s)$	Compensation Conditions	Stability Condition	Phase Error $\phi(\omega)$	Magnitude Error $\gamma(\omega)$
2a	$(K_1+1)\dfrac{1+\frac{a(K_2+1)s}{KK_2\omega_{t2}}+\frac{(K_2+1)s}{K_2\omega_{t3}}+\frac{(K+a+1)(K_2+1)s^2}{KK_2\omega_{t2}\omega_{t3}}}{1+\frac{a(K_2+1)s}{KK_2\omega_{t2}}+\frac{(K_1+1)s}{K_2\omega_{t3}}+\frac{(K_1+1)(K_2+1)s^2}{KK_2\omega_{t2}\omega_{t3}}+\frac{(K+a+1)(K_1+1)(K_2+1)s^3}{KK_2\omega_{t1}\omega_{t2}\omega_{t3}}}$	$K_1=K_2=K+a$	$\frac{a}{K}>K_2\frac{\omega_{t2}}{\omega_{t1}}-\frac{\omega_{t2}}{\omega_{t3}}$	$\frac{(K_1+1)^3}{KK_1}\left(\frac{\omega}{\omega_t}\right)^3$	$\frac{(K_1+1)^4}{K^2K_1}\left(\frac{\omega}{\omega_t}\right)^4$
2b	$(K_1+1)\dfrac{1+\frac{a(K_2+1)s}{K\omega_{t2}}+\frac{(K+a+1)(K_2+1)s^2}{K\omega_{t2}\omega_{t3}}}{1+\frac{a(K_2+1)s}{K\omega_{t2}}+\frac{(K_1+1)(K_2+1)s^2}{K\omega_{t2}\omega_{t3}}+\frac{(K+a+1)(K_1+1)(K_2+1)s^3}{K\omega_{t1}\omega_{t2}\omega_{t3}}}$	$K_1=K+a$	$\frac{a}{K}>\frac{(K_1+1)\omega_{t2}}{(K_2+1)\omega_{t1}}$	$\frac{(K_1+1)^2(K_2+1)}{K}\left(\frac{\omega}{\omega_t}\right)^3$	$\frac{(K_1+1)^2(K_2+1)^2a}{K^2}\left(\frac{\omega}{\omega_t}\right)^4$
3a & 3b	$\frac{(K_1+1)}{(K_2+1)}\cdot\dfrac{1+s\tau_2+s^2\tau_2\tau_3}{1+s\left(\tau_3+\frac{\tau_1}{(K_2+1)}\right)+\frac{s^2\tau_1\tau_2}{(K_2+1)}+\frac{s^3\tau_1\tau_2\tau_3}{(K_2+1)}}$	$\frac{\tau_1}{(K_2+1)}=\frac{\tau_2}{2}=\tau_3$	—	$2\left[\frac{\omega\tau_1}{(K_2+1)}\right]^3$	$4\left[\frac{\omega\tau_1}{(K_2+1)}\right]^4$
3c	$(K_1+1)\left[\dfrac{1+s\tau_2+s^2\tau_2\tau_3}{1+s(\tau_1+\tau_3)+s^2\tau_1\tau_2+s^3\tau_1\tau_2\tau_3}\right]$	$\tau_1=\frac{\tau_2}{2}=\tau_3$	—	$2(\omega\tau_1)^3$	$4(\omega\tau_1)^4$
3d	$(K_1+1)(K_3+1)\dfrac{1+\frac{s\tau_2}{(K_3+1)}+\frac{s^2\tau_2\tau_3}{(K_3+1)}}{1+s\{\tau_1(K_3+1)+\tau_3\}+s^2\tau_1\tau_2+s^3\tau_1\tau_2\tau_3}$	$\tau_1(K_3+1)=\frac{\tau_2}{2(K_3+1)}=\tau_3$	—	$2[\omega\tau_1(K_3+1)]^3$	$4[\omega\tau_1(K_3+1)]^4$
3e & 3f	$\frac{(K_1+1)}{(K+1)}\dfrac{1+\frac{s(K+1)}{\omega_{t2}}+\frac{s^2\{1+K(a+1)\}}{\omega_{t2}\omega_{t3}}}{1+\frac{s}{(K+1)}\left\{\tau_1+\frac{1+K(a+1)}{\omega_{t3}}\right\}+\frac{s^2\tau_1}{\omega_{t2}}+\frac{s^3\tau_1[1+K(a+1)]}{(K+1)\omega_{t2}\omega_{t3}}}$	$\tau_1=\frac{(K+1)^2}{2\omega_{t2}}=\frac{1+K(a+1)}{\omega_{t3}}$	—	$2\left[\frac{\omega\tau_1}{(K+1)}\right]^3$	$4\left[\frac{\omega\tau_1}{(K+1)}\right]^4$
4	$(K_1+1)K_2K_3\dfrac{1+\frac{s\tau_2}{K_2K_3}+\frac{s^2\tau_2\tau_3}{K_2K_3}}{1+s\{\tau_1K_2K_3+\tau_3\}+s^2\tau_1\tau_2+s^3\tau_1\tau_2\tau_3}$	$\tau_1K_2K_3=\frac{\tau_2}{2K_2K_3}=\tau_3$	—	$2[\omega\tau_1K_2K_3]^3$	$4[\omega\tau_1K_2K_3]^4$
5	$(K_1+1)\dfrac{1+s\left\{\tau_2+\frac{a_1}{a_2}\frac{(K_2+1)}{\omega_{t3}}\right\}+s^2\tau_2\frac{(a_1+a_2+a_3)}{a_2\omega_{t3}}}{1+s\left\{\tau_1+\frac{a_1}{a_2}\frac{(K_2+1)}{\omega_{t3}}\right\}+s^2\left\{\frac{a_1}{a_2}\tau_1\frac{(K_2+1)}{\omega_{t3}}+\tau_1\tau_2\right\}+s^3\tau_1\tau_2\frac{(a_1+a_2+a_3)}{a_2\omega_{t3}}}$	$\tau_1=\tau_2=\frac{a_1+a_2+a_3}{a_1\omega_{t2}+a_2\omega_{t3}}$	—	$(K_1+1)^3\left(1+\frac{a_1}{a_2}\right)\left(\frac{\omega}{\omega_t}\right)^3$	$(K_1+1)^4\left(1+\frac{a_1}{a_2}\right)^2\left(\frac{\omega}{\omega_t}\right)^4$
6	$(K_1+1)\dfrac{1+\frac{s(K_2+1)}{K_3\omega_{t3}}+\frac{s^2\tau_2\tau_3}{K_3}}{1+s\left\{\tau_1+\frac{\tau_3}{K_3}\right\}+\frac{s^2\tau_1(K_2+1)}{K_3\omega_{t3}}+\frac{s^3\tau_1\tau_2\tau_3}{K_3}}$	$\tau_1=\frac{\tau_2(K_3+1)}{(K_2+1)}=\tau_3\frac{(K_2-K_3)}{K_3(K_3+1)}$	—	$\frac{(K_1+1)^4}{K_1}\left(\frac{\omega}{\omega_t}\right)^3$	$\frac{(K_1+1)^6}{K_1^2}\left(\frac{\omega}{\omega_t}\right)^4$

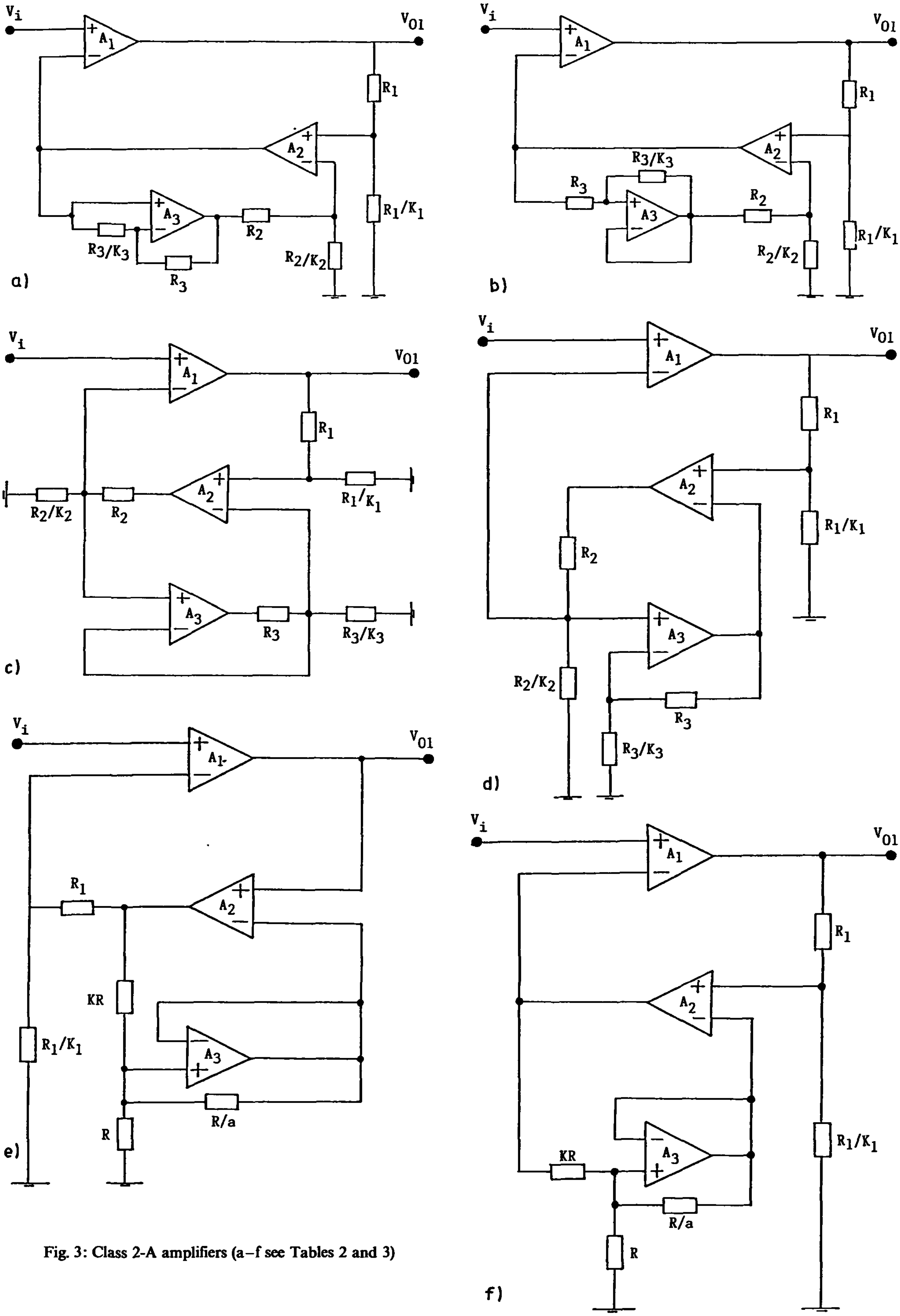

Fig. 3: Class 2-A amplifiers (a–f see Tables 2 and 3)

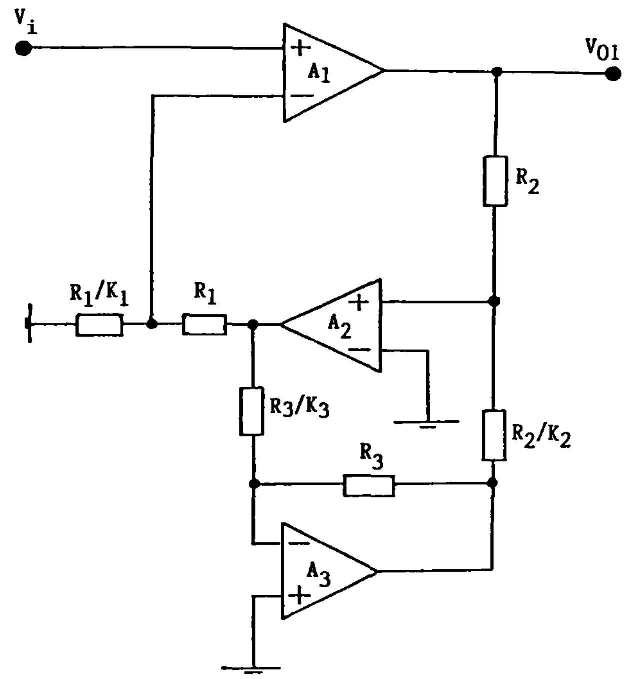

Fig. 4: Class 2-B amplifier

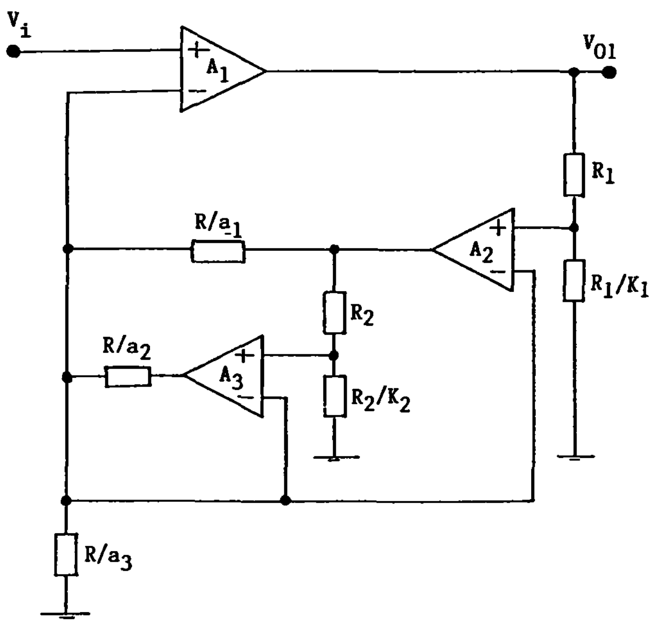

Fig. 5: Class 2-C amplifier

sated amplifiers are given here. It is worth noting that the circuits reported in [12] do not belong to either class 2 or 3 defined in this paper. The properties of the compensated amplifiers are given in Tables 1, 2 and 3.

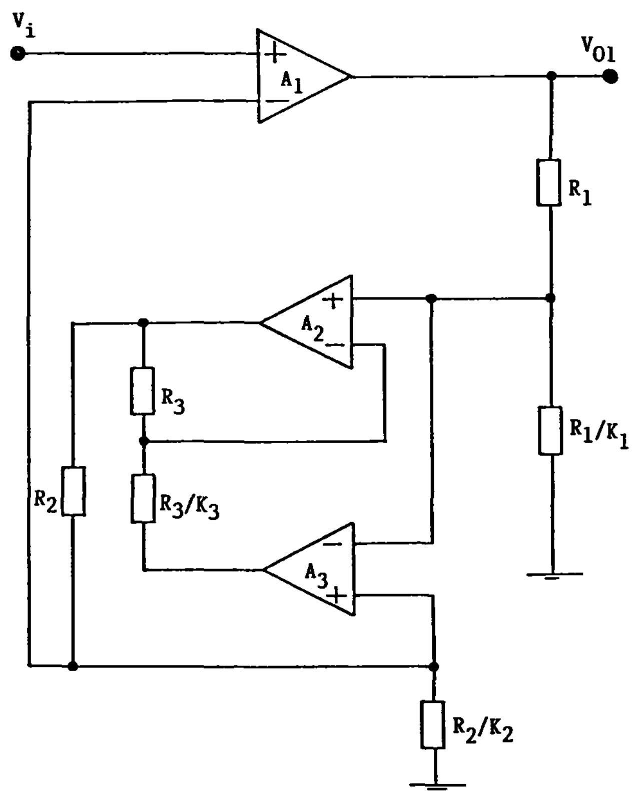

Fig. 6: Class 3 amplifier

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] Soliman, A.M.; Ismail, M.: Active compensation of op-amps. IEEE Trans. Circuits and Systems CAS-26 (1979) 2, pp. 112—117.
[3] 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.
[4] Soliman, A.M.: A generalized active compensated noninverting VCVS with reduced phase error and wide bandwidth. Proc. IEEE 67 (1979) 6, pp. 963—965.
[5] Soliman, A.M.: Classification and generation of active compensated noninverting VCVC building blocks. Int. J. of Circuit Theory and Applications 8 (1980) pp. 395—405.
[6] Natarajan, S., Bhattacharyya, B.B.: Design and some applications of extended bandwidth finite gain amplifiers. J. Franklin Institute 305 (1978) pp. 321—341.
[7] Natarajan, S.; Bhattacharyya, B.B.: Design of actively compensated finite gain amplifiers for high frequency applications. IEEE Trans. Circuits and Systems CAS-27 (1980) 12, pp. 1133—1139.
[8] Geiger, R.; Budak, A.: Design of active filters independent of first and second order operational amplifier time constant effects. IEEE Trans. Circuits and Systems CAS-28 (1981) pp. 749—757.
[9] Soliman, A.M.: Design of high frequency amplifiers. IEEE Circuits and Systems Magazine 5 (1983) pp. 9—11.
[10] Soliman, A.M.: Novel phase and magnitude compensated noninverting voltage amplifiers. Frequenz 40 (1986) 3, pp. 71—72.
[11] Budak, A.: Passive and active network analysis and synthesis. Boston, MA.: Houghton Mifflin, 1974, p. 204.
[12] Bhattacharyya, B.B.; Lopes, P.B.: Classification, generation and evaluation of actively compensated noninverting finite gain amplifiers. IEEE Proc. Vol. 131 (1984) Oct., pp. 177—189.

Professor Dr. Ahmed M. Soliman, The United Arab Emirates University, Faculty of Engineering, POB 15551, Al-Ain, United Arab Emirates

(Received on August 28, 1986)