Active Compensation of the Voltage Follower

Aktive Kompensation des Spannungsfolgers

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Abstract:

It is shown that is not possible to realize an infinite input impedance active compensated voltage follower using two or three opamps and having compensation conditions independent of the gain bandwidth of the opamps. Several novel active compensated voltage followers using two or three opamps are proposed. The properties of the compensated voltage followers are summarized in tables.

Übersicht:

Es wird gezeigt, daß es nicht möglich ist, einen unendlich großen Eingangswiderstand für einen aktiv kompensierten Spannungsfolger zu realisieren, der aus zwei oder drei Operationsverstärkern besteht und der vom Verstärkungs-Bandbreite-Produkt unabhängige Kompensationseigenschaften hat. Es werden einige neue aktiv kompensierte Spannungsfolger mit zwei oder drei Operationsverstärkern vorgeschlagen. Ihre Eigenschaften sind in Tabellen zusammengefaßt.

Für die Dokumentation:

Spannungsfolger / aktive Kompensation / Operationsverstärker

1. Introduction

It is well known that the single operational amplifier (opamp) voltage follower is suitable only for applications at low frequencies due to the finite and complex open loop gain nature of the opamp. The active phase compensated voltage follower shown in **Fig. 1** has been introduced recently [1–3]. This attractive two opamps voltage follower may also be obtained as a special case from several phase compensated noninverting voltage controlled voltage source (VCVS) structures [4–6], and it requires the two opamps to be matched. Even in integrated circuit technology the gain bandwidth of the two opamps may be slightly different [6].

The purpose of this paper is to propose and discuss active compensation methods of the voltage follower using two or three opamps not necessarily being matched. It is assumed that the opamps considered here are all internally compensated with zero ouptput and infinite input impedances, infinite common-mode rejection ratio and with a voltage gain function that can be approximated by [7]:

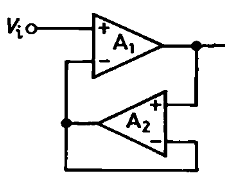

Fig. 1: The active compensated voltage follower using two opamps [1—3]

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

where ω_t is the unity gain bandwidth of the opamp.

2. Class 1—Two Opamps Voltage Followers

Recently the noninverting VCVS structures have been classified into two major classes [4]. In the class 1—VCVS networks the phase compensation condition is independent of ω_t of the opamps. The main result of this section is summarized in the form of a theorem.

Theorem:

For a class 1 active phase compensated voltage follower using two opamps, the input impedance must be finite.

Proof:

For a class 1 two opamps noninverting VCVS, the basic circuit equations are given by [4]

$$\begin{bmatrix} \frac{V_{01}}{A_1} \\ \frac{V_{02}}{A_2} \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} V_i + \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & 0 \end{bmatrix} \begin{bmatrix} V_{01} \\ V_{02} \end{bmatrix} \tag{2}$$

where a_i and b_{ij} are real coefficients having magnitudes ≤ 1, and V_{01} represents the output of the VCVS.

Using equation (1) thus the transfer function of the VCVS is given by

$$T(s) \equiv \frac{V_{01}}{V_i} = \left[\frac{-a_2}{b_{21}}\right] \frac{1 + \left[\frac{a_1}{a_2 b_{12}}\right] \frac{s}{\omega_{t2}}}{1 + \left[\frac{b_{11}}{b_{12} b_{21}}\right] \frac{s}{\omega_{t2}} + \left[\frac{-1}{b_{12} b_{21}}\right] \frac{s^2}{\omega_{t1}\omega_{t2}}}. \tag{3}$$

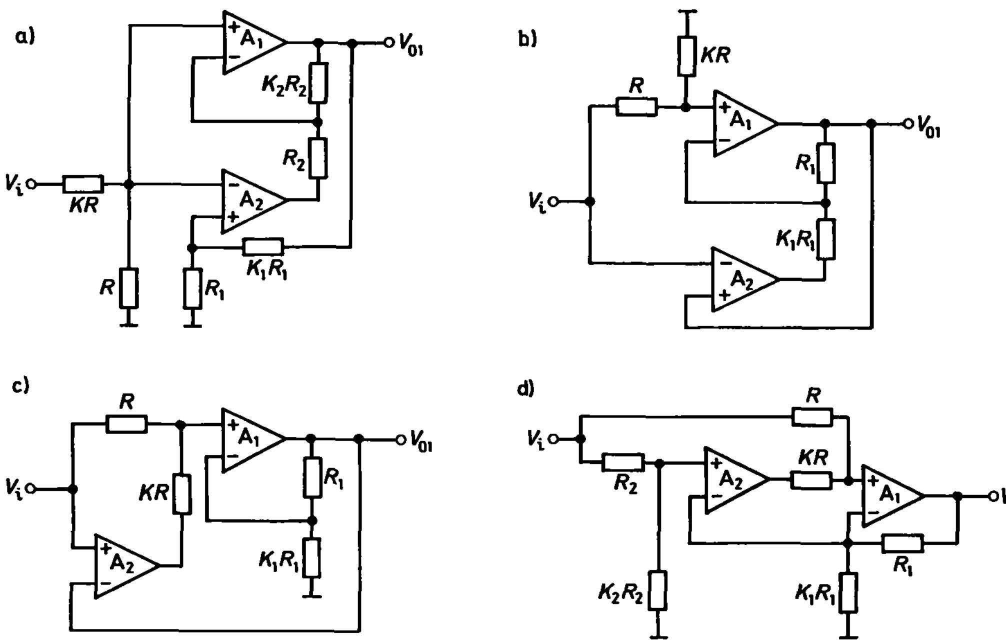

Fig. 2: Class 1 two opamps active compensated voltage followers

Voltage Follower: Fig.	Voltage Follower: Number of Resistors	Transfer Function	Necessary Condition for: Unity Gain	Necessary Condition for: Phase Compensation	Q_p	ω_p	Approximate Errors: Phase	Approximate Errors: Magnitude
2(a)	6	$\frac{K_1+1}{K+1}\cdot\frac{1+\frac{(K_2+1)}{K_2}\frac{s}{\omega_{t2}}}{1+\frac{K_1+1}{K_2}\frac{s}{\omega_{t2}}+\frac{(K_1+1)(K_2+1)}{K_2}\frac{s^2}{\omega_{t1}\omega_{t2}}}$	$K_1=K$	$K_2=K_1$	$\sqrt{\frac{K\omega_{t2}}{\omega_{t1}}}$	$\frac{\sqrt{K\omega_{t1}\omega_{t2}}}{K+1}$	$\frac{(K+1)^3}{K^2}\frac{\omega^3}{\omega_{t1}\omega_{t2}^2}$	$\frac{(K+1)^2}{K}\frac{\omega^2}{\omega_{t1}\omega_{t2}}$
2(b)	4	$\frac{1+\frac{K(K_1+1)}{K+1}\frac{s}{\omega_{t2}}}{1+K_1\frac{s}{\omega_{t2}}+(K_1+1)\frac{s^2}{\omega_{t1}\omega_{t2}}}$	——	$K=K_1$	$\frac{\sqrt{(K+1)\frac{\omega_{t2}}{\omega_{t1}}}}{K}$	$\sqrt{\frac{\omega_{t1}\omega_{t2}}{K_1+1}}$	$-K(K+1)\frac{\omega^3}{\omega_{t1}\omega_{t2}^2}$	$(K+1)\frac{\omega^2}{\omega_{t1}\omega_{t2}}$
2(c)	4	$\frac{1+K\frac{s}{\omega_{t2}}}{1+\frac{K_1(K+1)}{K_1+1}\frac{s}{\omega_{t2}}+(K+1)\frac{s^2}{\omega_{t1}\omega_{t2}}}$						
2(d)	6	$\frac{K_2(K_1+1)}{K_1(K_2+1)}\cdot\frac{1+\frac{K(K_2+1)}{K_2}\frac{s}{\omega_{t2}}}{1+(K+1)\frac{s}{\omega_{t2}}+\frac{(K+1)(K_1+1)}{K_1}\frac{s^2}{\omega_{t1}\omega_{t2}}}$	$K_2=K_1$	$K_2=K$	$\sqrt{\frac{\omega_{t2}}{K\omega_{t1}}}$	$\frac{\sqrt{K\omega_{t1}\omega_{t2}}}{K+1}$	$\frac{(K+1)^3}{K}\frac{\omega^3}{\omega_{t1}\omega_{t2}^2}$	$\frac{(K+1)^2}{K}\frac{\omega^2}{\omega_{t1}\omega_{t2}}$
3(a) 3(b) 3(c)	2	$\frac{1+(K+1)\frac{s}{\omega_{t2}}}{1+\frac{s}{\omega_{t1}}+(K+1)\frac{s^2}{\omega_{t1}\omega_{t2}}}$	——	$\frac{\omega_{t2}}{\omega_{t1}}=K+1$	1	ω_{t1}	$-\left(\frac{\omega}{\omega_{t1}}\right)^3$	$\left(\frac{\omega}{\omega_{t1}}\right)^2$
3(d)	4	$\frac{K_1+1}{K+1}\cdot\frac{1+(K+1)\frac{s}{\omega_{t2}}}{1+\frac{K_1+1}{K+1}\frac{s}{\omega_{t1}}+(K_1+1)\frac{s^2}{\omega_{t1}\omega_{t2}}}$	$K_1=K$					

Table 1: The properties of the two opamps voltage followers

For an infinite input impedance, it is necessary to have $a_i=\pm 1$ or zero. From equation (3) it is clear that a_i cannot be zero ($i=1,2$).

The necessary conditions for a unity DC gain and phase compensation are given respectively by

$$a_2=-b_{21} \quad \text{and} \quad \frac{a_1}{a_2}=\frac{b_{11}}{b_{21}}. \tag{4}$$

Thus the circuit equations for a class 1 — phase compensated voltage follower can be written as

$$\begin{bmatrix} \frac{V_{01}}{A_1} \\ \frac{V_{02}}{A_2} \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} V_i + \begin{bmatrix} -a_1 & b_{12} \\ -a_2 & 0 \end{bmatrix} \begin{bmatrix} V_{01} \\ V_{02} \end{bmatrix} \tag{5}$$

Note that the coefficient a_1 is positive, whereas the coefficients a_2 and b_{12} can both be negative (type A) or positive (type B) [4].

For a type A—follower, since both b_{11} and b_{12} are negative, the inverting input terminal of the opamp A_1 must be connected to a voltage divider between V_{01} and V_{02}. Thus, the coefficient b_{11} ($a_i = |b_{11}|$) must be < 1, which implies that the input impedance must be finite.

For a type B—follower, since b_{12} is positive, the noninverting input terminal of A_1 must be connected to a voltage divider between V_i and V_{02}, thus a_1 cannot be 1, which implies that the input impedance must be finite.

Q.E.D.

A type A—follower with a finite input impedance is shown in **Fig. 2** (a). This circuit has been described by Geiger [8], which is a modified version of the Reddy noninverting VCVS [9] using a voltage divider at the input. The transfer function, the necessary conditions for unity gain and for phase compensation, the pole Q, the pole radian frequency ω_p, as well as the approximate phase and magnitude errors of this circuit are given in **Table 1.**

A novel type A—follower which employes two resistors less than that of Fig. 2 (a) is shown in Fig. 2 (b). The trasfer function as well as the properties of this new follower are given in Table 1.

Fig. 2 (c) represents a new type B—follower. It is interesting to note that it has identical properties as the type A—follower of Fig. 2 (b). Another type B—follower is shown in Fig. 2 (d). Note that this circuit may be used also as a noninverting VCVS with an adjustable DC gain.

3. Class 2—Two Opamps Voltage Followers

In this class the phase compensation condition depends on the gain bandwidth of both opamps. **Fig. 3** represents four different circuits, having identical properties. The followers of Fig. 3 (a) and (b) are special cases from the noninverting VCVS networks reported in References [1–2]. The follower of Fig. 3 (c) has been reported in [6], and Fig. 3 (d) has appeared in [4].

It is worth noting that if the two opamps are matched, the phase compensation condition for the circuits of Fig. 3 (a), (b) and (c) reduces to $K=0$ and the circuits simplies to that of Fig. 1. If the two opamps are not identical however, it is necessary to use the opamp with the larger gain bandwidth for A_2. In this case the resistor KR adjusts the network for phase compensation.

4. Three Opamps Voltage Followers

For the generalized three opamps active compensated network shown in **Fig. 4,** the basic circuit equations can be written as

$$\begin{bmatrix} \frac{V_{01}}{A_1} \\ \frac{V_{02}}{A_2} \\ \frac{V_{03}}{A_3} \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} V_i + \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} V_{01} \\ V_{02} \\ V_{03} \end{bmatrix} \quad (6)$$

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

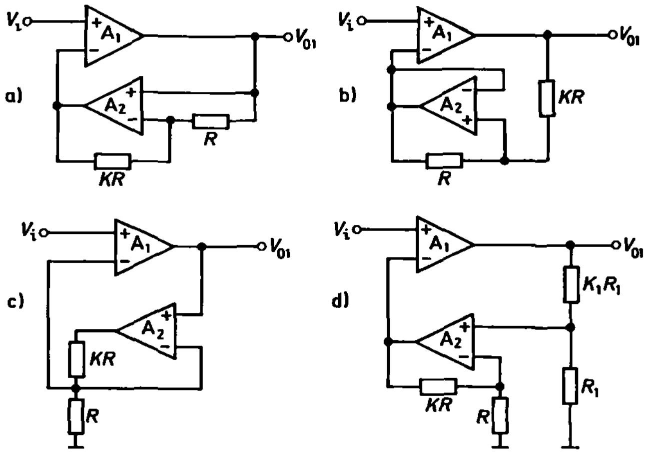

Fig. 3: Class 2 two opamps active compensated voltage followers

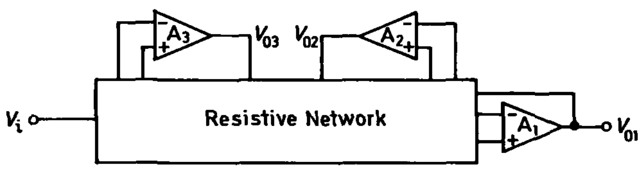

Fig. 4: A generalized three opamps active compensated network

Following similar analysis to that given in section 2, it can be proved that it is impossible to realize an infinite input impedance active compensated voltage follower with compensation conditions independent of ω_{ti} $(i=1,2,3)$. The proof is omitted to limit the length of the paper.

Recently an active compensated noninverting VCVS which employes 3 opamps and 7 resistors has been introduced [10]. As mentioned in [10] if the opamps are matched then 3 opamps and 2 resistors are only necessary for the realization of the voltage follower. On the other hand if the opamps are not matched, then 3 opamps and 5 resistors are required for the voltage follower realization given in [10].

In this section, three new active compensated voltage followers using three opamps and with infinite input impedance are described. It is also shown that if the opamps employed are not matched then only four resistors are required for the follower realization, that is one resistor less than the realization given in [10].

For an infinite input impedance, the coefficients a_i must be ± 1 or zero. From the generalized expression of the transfer function which is obtainable from equation (6), it is found that a_1 must be 1. In the class of followers considered here, it is desirable to achieve compensation with the least possible number of the coefficients a_i, b_{ij} being nonzero. Examining the generalized expression of the transfer function, it is found that it is possible to take the coefficients a_2, a_3, b_{11}, b_{13}, b_{31} and b_{22} as zeros. In this case and using equation (1), the transfer function of the network simplifies to

$$T(s) \equiv \frac{V_{01}}{V_i} = \left[\frac{-b_{23}b_{32}}{b_{33}b_{12}b_{21}}\right] \varepsilon(s) \quad (7)$$

where $\varepsilon(s)$ is the third order compensated error function which is given by

$$\varepsilon(s)=\frac{1+\frac{b_{33}}{b_{23}b_{32}}\frac{s}{\omega_{t2}}+\frac{-1}{b_{23}b_{32}}\frac{s^2}{\omega_{t2}\omega_{t3}}}{1+\frac{-b_{23}b_{32}}{b_{33}b_{12}b_{21}}\frac{s}{\omega_{t1}}+\frac{-1}{b_{33}}\frac{s}{\omega_{t3}}+\frac{-1}{b_{12}b_{21}}\frac{s^2}{\omega_{t1}\omega_{t2}}+\frac{1}{b_{33}b_{12}b_{21}}\frac{s^3}{\omega_{t1}\omega_{t2}\omega_{t3}}}. \quad (8)$$

From the above equation, to ensure the stability of the network the coefficient b_{33} and the products $b_{12}b_{21}$ and $b_{23}b_{32}$ must be negative. Examining further the coefficient signs, it is found that b_{12} must be negative, thus b_{21} is positive. Also b_{32} must be positive, hence b_{23} is negative. From equation (8), the necessary conditions for phase compensation are given by

$$\omega_{t1}=\frac{b_{23}b_{32}}{b_{12}b_{21}}\,\omega_{t3}, \quad (9)$$

$$\omega_{t2}=\frac{b_{33}^2}{-2b_{23}b_{32}}\,\omega_{t3}. \quad (10)$$

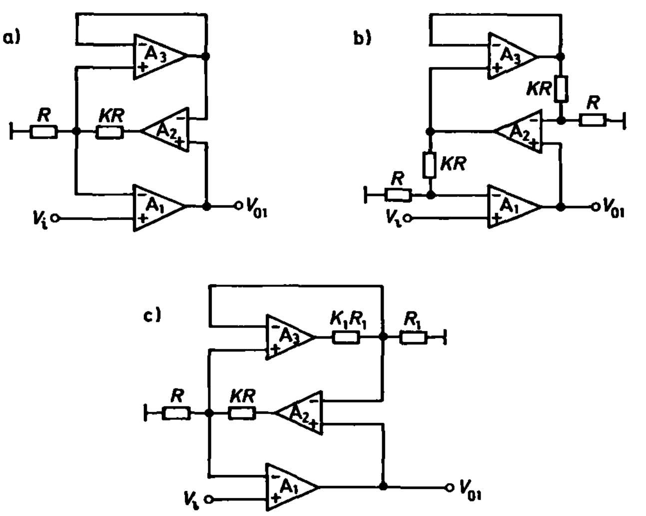

Fig. 5: Novel three opamps active compensated voltage followers

For a unity DC gain, and from equation (7) it follows that

$$b_{33}=-\frac{b_{23}b_{32}}{b_{12}b_{21}}. \quad (11)$$

Fig. 5 represents three new followers which belong to this class. The circuit matrices, the transfer functions and the compensation conditions are given in **Table 2.**

The followers of Fig. 5 (a) and (b) are equivalent. The circuit of Fig. 5 (a) however uses two resistors less than that of Fig. 5 (b). For both followers, it is necessary to have matched opamps for A_1 and A_3. If the three opamps are matched, the parameter K should be taken as unity. Fig. 5 (c) is a generalized follower to that of Fig. 5 (a) and is suitable for use if the three opamps are all different. In this case, the opamp A_3 must have a larger gain bandwidth than the opamp A_1.

It is worth noting that, setting $K=0$ in the circuit of Fig. 5 (a) and taking R as open circuit, result in three opamps resistorless follower, which requires matched opamps for A_1 and A_3 and a different opamp for A_2 with half the gain bandwidth of the opamp A_1 or A_3.

5. Conclusions

It is proved that it is impossible to realize an infinite input impedance active compensated voltage follower using two or three opamps and with compensation conditions independent of ω_t of the opamps. Novel voltage followers are generated in this paper. It is worth noting that the 3 opamps followers of Fig. 5 belong to another class than the follower reported in [10] in which the coefficients b_{22} and b_{13} are nonzero.

Voltage Follower		Circuit Matrices		Compensated Transfer Function	Compensation Conditions
Fig.	Number of Resistors	[a]	[b]		
5(a)	2		$\begin{bmatrix}0 & -\frac{1}{K+1} & 0\\ 1 & 0 & -1\\ 0 & \frac{1}{K+1} & -1\end{bmatrix}$	$\dfrac{1+(K+1)\frac{s}{\omega_{t2}}+(K+1)\frac{s^2}{\omega_{t2}\omega_{t3}}}{1+\frac{s}{\omega_{t1}}+\frac{s}{\omega_{t3}}+(K+1)\frac{s^2}{\omega_{t1}\omega_{t2}}+(K+1)\frac{s^3}{\omega_{t1}\omega_{t2}\omega_{t3}}}$	$\omega_{t1}=\frac{2}{(K+1)}$, $\omega_{t2}=\omega_{t3}$
5(b)	4	$\begin{bmatrix}1\\ 0\\ 0\end{bmatrix}$	$\begin{bmatrix}0 & -\frac{1}{K+1} & 0\\ 1 & 0 & -\frac{1}{K+1}\\ 0 & 1 & -1\end{bmatrix}$		
5(c)	4		$\begin{bmatrix}0 & -\frac{1}{K+1} & 0\\ 1 & 0 & -\frac{1}{K_1+1}\\ 0 & \frac{1}{K+1} & -\frac{1}{K_1+1}\end{bmatrix}$	$\dfrac{1+(K+1)\frac{s}{\omega_{t2}}+(K+1)(K_1+1)\frac{s^2}{\omega_{t2}\omega_{t3}}}{1+\frac{s}{\omega_{t1}}+(K_1+1)\frac{s}{\omega_{t3}}+(K+1)\frac{s^2}{\omega_{t1}\omega_{t2}}+(K+1)(K_1+1)\frac{s^3}{\omega_{t1}\omega_{t2}\omega_{t3}}}$	$\omega_{t1}=\frac{2}{(K+1)}$, $\omega_{t2}=\frac{1}{(K_1+1)}\omega_{t3}$

Table 2: The properties of the three opamps voltage followers

If the three opamps employed are all different then the circuit of Fig. 5 (c) is superior to that described in [10] since it uses one resistor less.

More follower circuits may be generated and are not included here to limit the length of the paper. Generalization of the networks given here using three opamps to realize noninverting amplifiers of arbitrary gain is possible.

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Berechnung der Quantisierungsverzerrung und der pegelabhängigen Dämpfungsverzerrung bei PCM für selektive und breitbandige Messung

Calculation of Quantizing Distortion and Variation of Gain with Input Level for PCM According to Selective and Wideband Measurement

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Übersicht:
Zur Berechnung der Quantisierungsverzerrung und der pegelabhängigen Dämpfungsverzerrung werden allgemeine Formeln hergeleitet, die für selektive und breitbandige Messung gelten. Die für eine 13-Segment-Codierungskennlinie („A-Gesetz") berechneten Kurven der Dämpfungsverzerrung bei Sinus- und Rauschsignalen werden für beide Meßmethoden dargestellt und mit den Werten nach der bisher üblichen Berechnungsmethode verglichen. Bei kleiner Aussteuerung ergeben sich Unterschiede bis zu 4 dB.

Abstract:
General formulas are derived to evaluate the quantizing distortion and the variation of gain with input level in accordance with selective and wideband measurement. Calculated curves for a 13-segment encoding law ("A-law") for sine-wave and noise signals corresponding to both methods of measurement are shown, and compared to the results obtained by the method, that was usually employed up to now. At low input levels differences up to 4 dB were observed.

Für die Dokumentation:
Quantisierungsverzerrung / pegelabhängige Dämpfungsverzerrung / PCM / selektive Messung / Breitbandmessung

Die Berechnung der Quantisierungsverzerrung und der pegelabhängigen Dämpfungsverzerrung (Restdämpfungsänderung) von PCM-Codecs ist bekannt [1–3]. Bei den Formeln für die Dämpfungsverzerrung läßt sich jedoch nicht ohne weiteres erkennen, ob sie einer selektiven oder einer breitbandigen Messung entsprechen. Dies gilt sowohl bei Messungen mit Sinus- als auch mit Rauschsignalen. Im folgenden werden auf etwas andere Art als in [1–3] Formeln hergeleitet, aus denen die Dämpfungsverzerrung sowohl für den selektiven als auch für den breitbandigen Fall berechnet werden kann.

Bild 1 zeigt ein Blockschaltbild zur Bestimmung der verschiedenen Komponenten der Quantisierungsverzerrung. P_1 ist die Leistung des analogen Eingangssignals, P_2 die Leistung des quantisierten Ausgangssignals, P_0 die

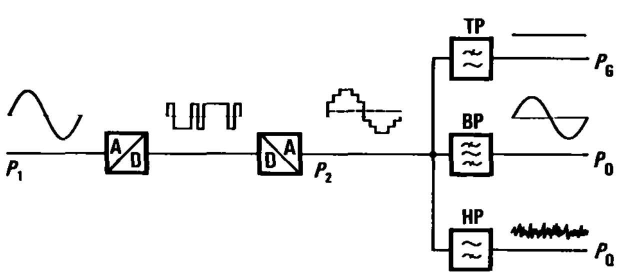

Bild 1: Blockschaltbild zur Bestimmung der verschiedenen Komponenten der Quantisierungsverzerrung
A/D Analog-Digital-Umsetzer
D/A Digital-Analog-Umsetzer
TP Tiefpaß
BP Bandpaß
HP Hochpaß