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## LINEARITY ERRORS OF THE PUSH-PULL CURRENT AMPLIFIERS WITH SEPARATE INTERMEDIATE CASCADE

BY

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**Abstract.** Structural and functional schemas of push-pull DC amps (PPDCA) were analysed. It is shown that selective feedback helps to balance operating points in the intermediate stages and significantly decreases linearity error of the transfer characteristic. The analytical expressions for describing the hypothetical and actual static transfer characteristic of the PPDCA were proposed along with the estimation of linearity errors and the curvature measurement.

**Key words:** bidirectional current mirror; linearity error; push-pull DC amplifier; transfers characteristics.

### 1. Introduction

A significant number of DC amps (DCA) use mainly single-cycle structure that has certain disadvantages: low rate of output signal growth, significant THD, especially with increasing amplitude and frequency of the input signal, asymmetric reaction to the input bipolar pulse signal.

The latter two decades are characterized by growing interest in development of analog devices to the push-pull DC amplifier (PPDCA). Their advantages over single-cycle structures in the first place is the high linearity of

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the transfer characteristic and symmetrical fronts of the transient response during the reaction of input bipolar signal boost. A distinctive feature of the push-pull circuit is the wide frequency range of maximum undistorted sinusoidal signal power.

## 2. Actuality

At present, there are several types of PPDCA:

1° PPDCA with integrated push-pull intermediate amplification channels – current conveyors (Sedra *et al.*, 1990);

2° with a single-cycle intermediate amplification stages and parametric operating point specification (Frye, 1976);

3° with a single-cycle stages of intermediate amplification and self-balancing of the operating point due to the introduction of selective feedback (SF).

A common drawback of the first two types of schemes is the complexity of specifying the DC-mode of the intermediate channels of amplification. The advantage of the third type of DCA is an opportunity not to use precision components and balancing small-signal transmission rate in the intermediate cascade built using bipolar transistors of different conductivity type with a large spread of  $\beta$ -values. This, in turn, allows us to construct DCA with high linearity, *i.e.* those in which the linearity error,  $\Delta I_{le}$ , is much smaller than the scale error,  $\Delta I_{se}$ .

Analytical expressions for the small-signal transmission gain of the mentioned devices and static transfer characteristic are considered by Azarov *et al.*, (2011). However, there are no mathematical models of the linearity errors, because they are determined by static transfer characteristic of PPDCA and so the subject of a paper, *Linearity errors of the push-pull current amplifiers with separate intermediate cascade* is relevant.

## 3. Aim of the Research

Improve linearity of the transfer function of push-pull DCA with self-balancing of the working points in separate single-cycle intermediate cascades by setting the appropriate depth of the selective feedback in these stages.

### 3.1. Objectives of Research

1. To analyse alternative circuit and functional organization of the DCA with selective feedback, that can potentially provide high linearity of the transfer characteristic.

2. To obtain analytical expressions that describe the hypothetical and actual static transfer characteristic of DCA with selective feedback in separate single-cycle intermediate cascades with self-balancing of their working points.

3. Evaluate the linearity error of the static transfer characteristic for the proposed schemes of the DCA.
4. Find the coefficient of transmission of specialized current mirror (SpCM), when linearity error in a given range will be minimum.

#### 4. Solution

Consider the generalized structural and functional scheme of a push-pull symmetric DCA (Fig. 1), which implements the method of self-balancing of the working points of intermediate cascades. The method consists in introducing of two integrated circuits of selective feedback in the intermediate stages of amplification, in which counter-phase output currents are balanced, and so it sets the working point of the intermediate gain stages, in spite of transistors of different conductivity type. Displayed amplifier circuit consists of a push-pull input stage, built on transistors VT1 and VT2, two intermediate paths with antiphase gain and transfer ratio  $K_i'$ ,  $K_i''$  and the output stage is implemented with a push-pull specialized current mirror (SpCM). These integrated circuits (dotted) are composed of bi-directional current mirror (BCM) and the current compensators CCI and CCII. This balancing of operating points works by means of the compensation currents  $I'_{CC}$ ,  $I''_{CC}$  and so next equality takes place  $I'_{\text{offset}} = I''_{\text{offset}} = (m-1)I_o$ .

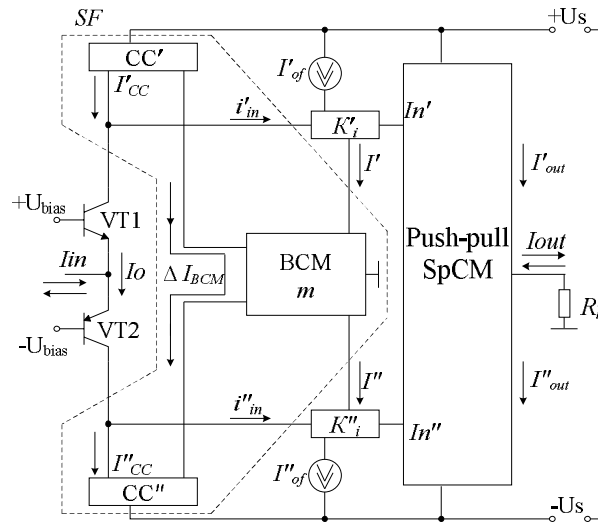


Fig. 1 – Structural-functional scheme of PPDCA with selective feedback.

Selectivity of the feedback loop means its ability to respond only to the disproportionate currents increasing in the intermediate stages of counter-phase amplification and generate the appropriate compensation currents using compensators CCI and CCII. Introduction of the BCM in the structure of an

amplifier allows to form continuous signals about the ratio of  $I'$  and  $I''$ , that gives opportunity to regulate the compensation currents to achieve balance of the scheme in the feedback loops. Possible implementation of BCM is shown in Fig. 2.

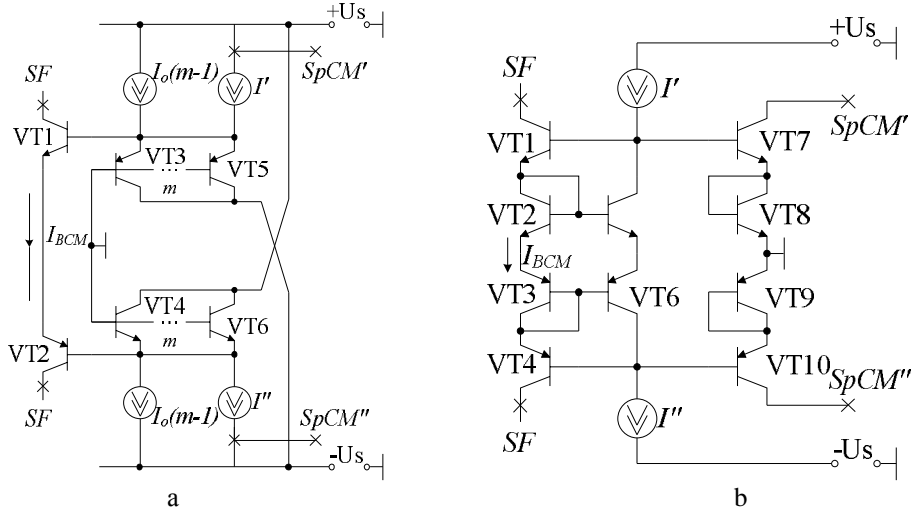


Fig. 2 – BCM circuit organization based on: *a* – complementary stages "common base"; *b* – upgraded push-pull Wilson current mirror (WCM) with an additional amplifying stages.

Effects of feedback results in maintaining the balance value of the scheme

$$I_o = \frac{\sqrt{I'I''}}{m}. \quad (1)$$

In the case of this balance such equality is maintained,  $I'_{cc} \approx I''_{cc} \approx I_o$ , where  $I_o$  – the operating point current.

The parameter  $m$  determines the depth of the feedback of BCM. This feedback allows you to allocate a permanent component of operating current during changes of  $I'$  and  $I''$ . The proportional change in  $I'$  and  $I''$  currents has virtually no effect on the  $I_{BCM}$  current value. In the case when the increase of  $\Delta I'$  and  $\Delta I''$  is not proportional, at the output of BCM appears gain  $\Delta I_{BCM}$  (Azarov *et al.*, 2011):

$$\Delta I_{BCM} = I_{BCM} - I_o = \frac{\sqrt{I'I''}}{m} - I_o = \frac{\sqrt{(I_o + \Delta I')(I_o - \Delta I'')}}{m} - I_o. \quad (2)$$

The dependence  $\Delta I_{BCM}$  vs.  $m$  for the above mentioned BCM schemes (Fig. 2) is shown in Fig. 3.

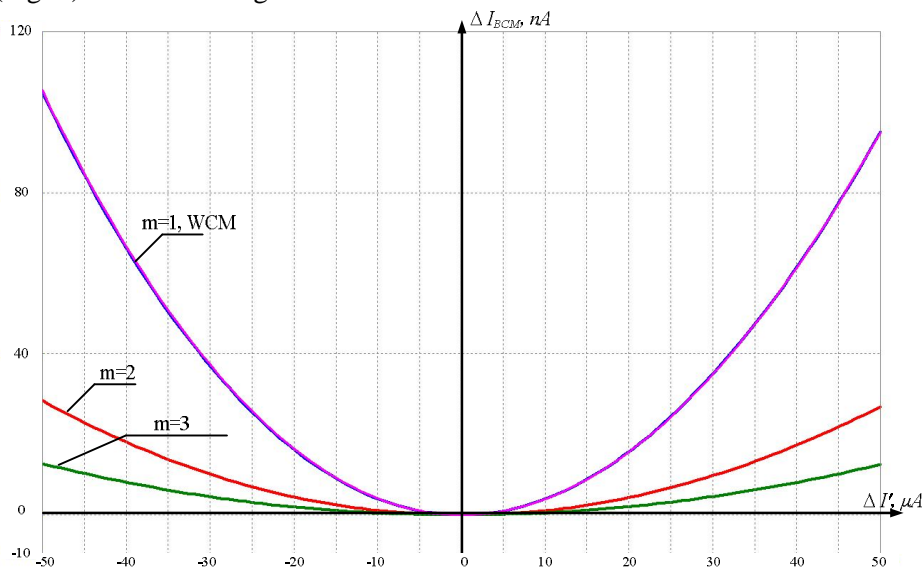


Fig. 3 – Transfer characteristics of the BCM for proportional signals  $I'$  and  $I''$ .

The parameter  $m$ , that is the number of pairs of parallel connected diodes, sets the depth of the selective feedback loop, resulting in reduced current,  $\Delta I_{BCM}$ , and improved linearity of the transfer characteristic and reduced zero bias current.

Considering the physical principle of the amplifier, and the phenomenon in which, when a current flows into the input of the circuit, it flows into its out from the load resistor, for PPDCA, which is shown in Fig. 1, was prepared the general expression of transfer characteristics (Azarov, *et al.*, 2012):

$$\begin{aligned}
 I_{out}(I_{in}) = I'_2 - I''_1 = & \frac{-(I_{in} + I_b)K'K'_{SpCM}}{2} + \\
 & + \frac{\sqrt{[(I_{in} + I_b)K'K''K'_{SpCM}K''_{SpCM}]^2 + 4I_o^2m^2K'K''K'_{SpCM}K''_{SpCM}}}{2K''K''_{SpCM}} - \\
 & - \frac{(I_{in} + I_b)K''K''_{SpCM}}{2} - \\
 & - \frac{\sqrt{[(I_{in} + I_b)K'K''K'_{SpCM}K''_{SpCM}]^2 + 4I_o^2m^2K'K''K'_{SpCM}K''_{SpCM}}}{2K'K'_{SpCM}}.
 \end{aligned} \tag{3}$$

An important feature of the scheme is the presence of nonlinearity in the dependence  $I_{out}$  vs.  $I_{in}$ . In this case, the absolute and relative linearity errors of the PPDCA are determined through currents  $I'$  and  $I''$  by the relations

$$\Delta I_{nl} = |I'_{out}| - |I''_{out}|, \quad (4)$$

$$\delta I_{nl} = \frac{\Delta I_{nl}}{\max(I'_{out}, I''_{out})} \cdot 100\%. \quad (5)$$

Absolute  $\Delta I_{nl}$  or relative  $\delta I_{nl}$  linearity errors must be determined on the edges of the linear range of the transfer characteristic. It should be noted that this approach to the evaluation of these errors corresponds to the worst case, when the amplifier is used without feedback.

Small-signal transfer coefficient,  $K_{i out}$ , can be found through the derivative of eq. (3) of the transfer characteristic in the form

$$K_{i out} = \frac{dI_{out}(I_{in})}{dI_{in}} = -\frac{K''K''_{SpCM}}{2} - \frac{(K'K''K'_{SpCM}K''_{SpCM})^2(I_{in} + I_b)}{2K'K'_{SpCM}\sqrt{[(I_{in} + I_b)K'K''K'_{SpCM}K''_{SpCM}]^2 + 4I_o^2m^2K'K''K'_{SpCM}K''_{SpCM}}} - \frac{K''K''_{SpCM}}{2} + \frac{(K'K''K'_{SpCM}K''_{SpCM})^2(I_{in} + I_b)}{2K''K''_{SpCM}\sqrt{[(I_{in} + I_b)K'K''K'_{SpCM}K''_{SpCM}]^2 + 4I_o^2m^2K'K''K'_{SpCM}K''_{SpCM}}}. \quad (6)$$

An additional criterion for evaluating the linearity of the amplifier transfer characteristic can serve as a curvature that shows how this characteristic deviates from a straight line. This parameter is calculated with the following relation:

$$k = \frac{|I_{out}(I_{in})|}{[1 + I_{out}^2(I_{in})]^{3/2}}. \quad (7)$$

The smaller the absolute value of the curvature, the greater linearity, since the curvature of a straight line at each point is 0.

There are several ways to solve the problem of reducing the linearity error of PPDCA. The first of the ways of its solution is aligning the gains,  $K'_i$  and  $K''_i$ , in the intermediate counter-phase amplifying channels. This should be

used building intermediate stages with  $m$ -fold amplifying transistors connection, or parallel transistor connection in BCM. Another way is to use in each channel of intermediate-stage amplification combinations of n-p-n and p-n-p-transistors. These techniques of reducing the amplifier linearity error are discussed in detail by Azarov *et al.*, (2012).

A third way to reduce linearity error of the PPDCA is the use of specialized push-pull current mirror at the output of an amplifier as shown in Figs. 4 and 4'.

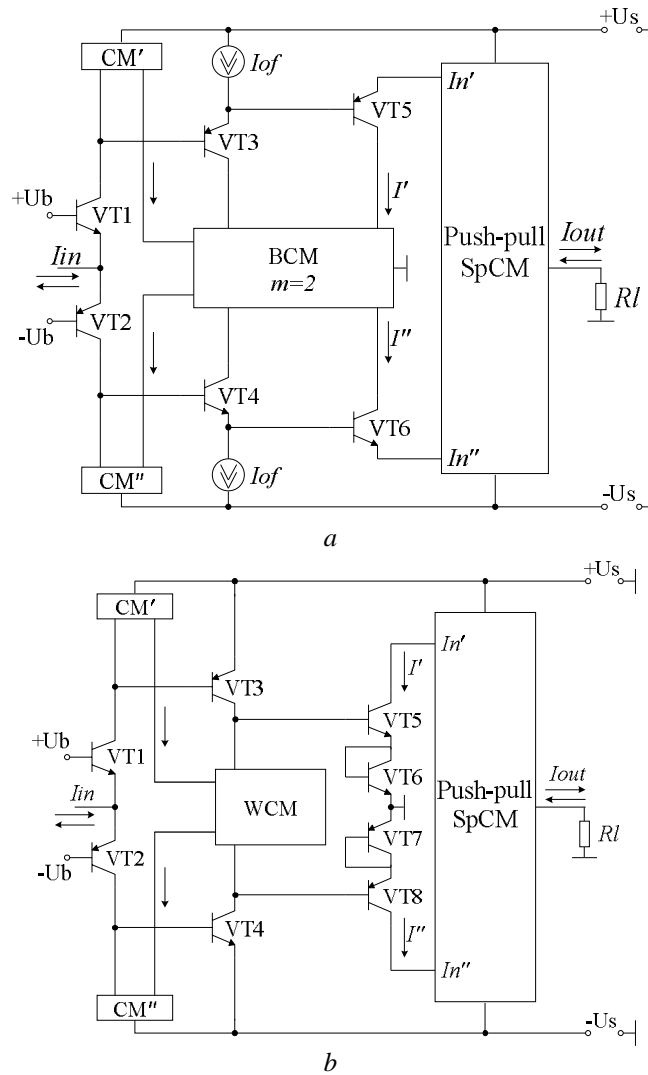


Fig. 4 – Schematic organization of push-pull DC amplifiers with SpCM PPDCA with two-stage intermediate cascades based on: *a* – Darlington transistor pair; *b* – Wilson current mirror and Sziklai transistor pair.

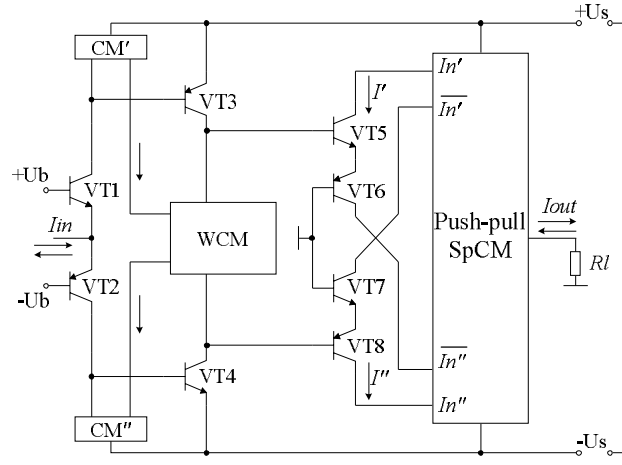


Fig. 4' – Schematic organization of push-pull DC amplifiers with SpCM PPDCA with two-stage intermediate cascades based on Sziklai transistor pair and 4-input specialized current mirror.

It is worth noting that connection configuration of intermediate stages outputs with counter-phased inputs of the SpCM has much importance. Especially critical is when the emitter of the amplifying stage transistor is connected to the input of SpCM. This is due to the fact that the resistances  $r'_{in}$ ,

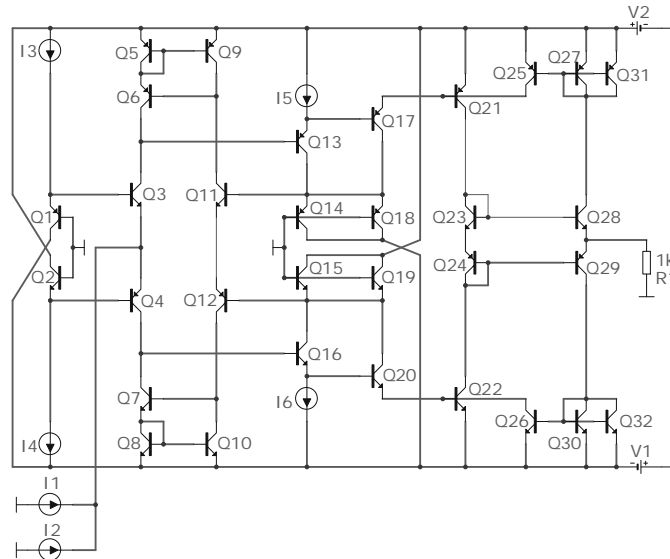


Fig. 5 – Computer simulation of the push-pull DCA schematic diagram of PDCA.



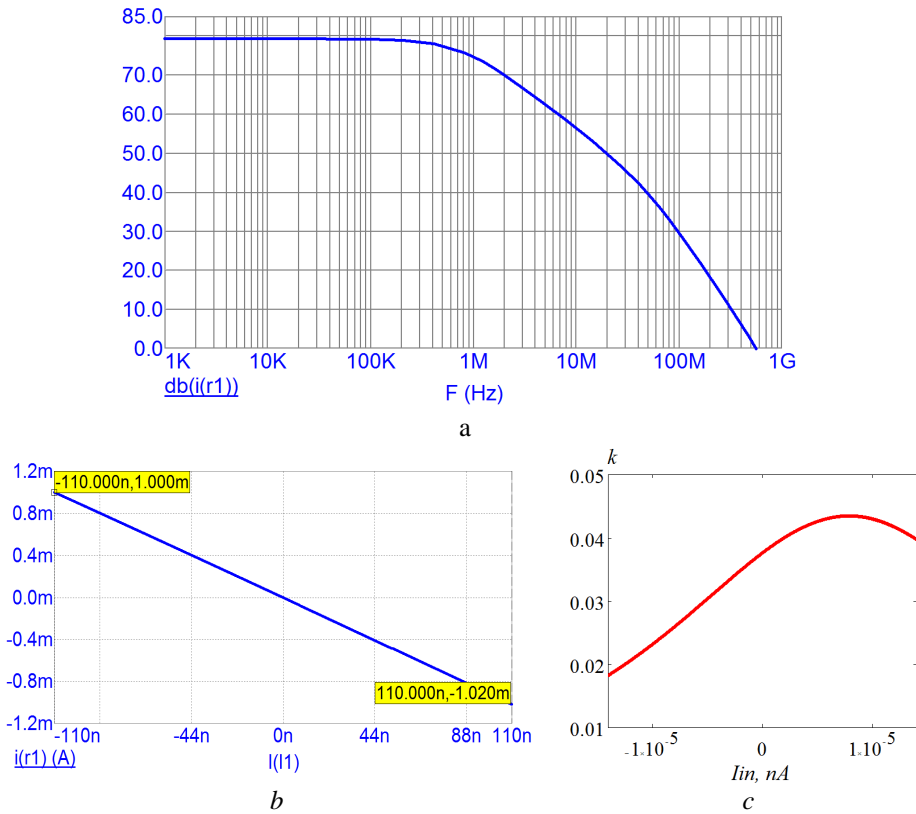


Fig. 5' – Computer simulation of the push-pull DC amplifier: *a* – frequency response; *c* – the transfer characteristic; *d* – curvature of the transfer characteristic.

$r_{in}''$  of the SpCM significantly affect the frequency response of the amplifier. It is more profitable the option when inputs of the SpCM are connected to the collector circles of intermediate amplifying cascade (Walter, 2004).

Schematic diagram, frequency response, transfer characteristic and the curvature graph of the circuit PPDCA from Fig. 4 are shown in Figs. 5 and 5'.

As can be seen from these graphs the gain for the circuit is 79 dB and linearity error,  $\Delta I_{nl}$ , is 20  $\mu$ A. Linearity errors for all considered schemes of amps are shown in Table 1.

**Table 1**  
*Linearity Errors of the PPDCA*

	Circuit 1	Circuit 2	Circuit 3
Gain $K_i$	9,190	12,150	18,000
$\Delta I_{nl}$ , [ $\mu$ A]	20	6	0.7
$\delta I_{nl}$ , [%]	2	0.6	0.07

As we can see from the Table 1 the best results both in gain and linearity shows the third circuit (Fig. 4 c). It should also be noted that the characteristics of PPDCA largely depend on the type of scheme of the specialized current mirror, the simplest implementation of which is shown in Fig. 6.

In this case SpCM transfer coefficient is given by the number of parallel connected diodes in the feedback loop, but a gradual increase in this number increases the linearity error and reduces the bandwidth of the amplifier as a whole. Computer simulation showed that for considered scheme of SpCM optimal transfer coefficient  $\approx 2$ , which occurs when you switch two pairs of diodes.

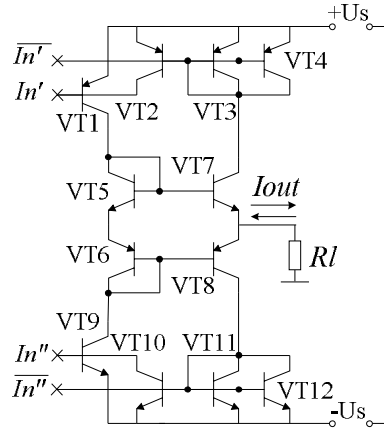


Fig. 6 – 4-input specialized current mirror.

Small-signal input resistance of SpCM can be estimated using analytical expressions

$$r'_{in} = \frac{r_{inVT'}}{1+k'_i} \approx 2.8 \Omega, \quad r''_{in} = \frac{r_{inVT''}}{1+k''_i} \approx 2.9 \Omega,$$

where  $r_{inVT'}$  and  $r_{inVT''}$  are small-signal resistance of transistors VT1 and VT2, respectively, that are used in the scheme of common-emitter;  $k'_i$  and  $k''_i$  – current transmission rate by the upper and lower channels of amplification with torn feedback loop:  $k'_i = \beta' k_{BCM} k'_{CM}$ ,  $k''_i = \beta'' k_{BCM} k''_{CM}$ , where  $\beta'$  and  $\beta''$  – current gain of VT1 and VT2 transistors,  $k'_{CM}$  and  $k''_{CM}$  – the current transmission rates of CMI and CMII. The output impedance of the scheme was evaluated by computer simulation, its value is at  $\approx 1.6 \text{ M}\Omega$  (Tietze *et al.*, 2008).

## 5. Conclusions

1. Analysis of circuit variations and functional organization of the push-pull DC amps with selective feedback, which can potentially provide high

linearity of transfer characteristics, was made.

2. The analytical expressions to describe the hypothetical and actual static transfer characteristic of the PPDCA with selective feedback in separate single-cycle intermediate cascade were proposed.

3. The estimation of linearity error of the static transfer characteristic for proposed schemes of amplifiers was made and optimal transmission coefficient of SpCM was analysed, in which this error is minimum.

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### ERORI DE LINIARITATE ALE AMPLIFICATOARELOR PUSH-PULL CU CASCADA INTERMEDIARĂ SEPARATĂ

(Rezumat)

Se analizează schemele funcționale ale amplificatoarelor CC tip push-pull. Se demonstrează că un feedback selectiv permite echilibrarea punctelor de operare din stadiile intermediare și, de asemenea, micșorarea semnificativă a erorilor de liniaritate ale caracteristicii de transfer. Sunt propuse expresii analitice ce descriu caracteristica ipotetică și pe cea de transfer static și sunt prezentate estimări ale erorilor de liniaritate și a curbării măsurate.

