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THE MODEL OF GAIN CHARACTERISTIC OF PUSH-PULL CURRENT AMPLIFIER WITH SELECTIVE FEEDBACK

The paper considers mathematical model of input-output characteristic of push-pull direct current amplifier and analytical relations for the gain in the range of input signal. It is shown that the usage of push-pull intermediate amplifying stages enables to increase considerably the linearity of gain characteristic of the amplifier.

Key words: *push-pull current amplifier, gain linearity error, intermediate stage, current mirror, controlled current generator.*

Introduction

Last two decades are characterized by increasing interest of the developers of analog devices to push-pull direct current amplifiers (PPDCA). Their advantage, as compared with single-ended structures, is high linearity of the gain and also the symmetry of fronts of transient characteristic during the response to rectangular pulse. Characteristic feature of push-pull circuits is wide frequency range of maximum non-distorted power of sinusoidal signal.

Topical character of the problem

The first version of PPDCA construction can be considered the circuit (1), suggested by the American researcher G.J.FRYE as far back as in 1976. In contains input push-pull stage in the form of self-completing circuit with common base on bipolar transistors of different conduction and two single- ended paths of intermediate antiphase amplification. The drawback of this circuit is that it is rather complicated to set transistor operating points of intermediate stages, and also high level of zero bias current. Further development of PPDCA is the introduction of current mirrors in the structure and push-pull path of intermediate amplification, that can contain also output stage [2, 3].

Separate direction of the development is so-called "current conveyers", on the base of which a number of operational current and voltage converters can be built. General drawback of the above-mentioned circuits is excessive increase of the number of stages in order to achieve great gain factor on the level of 100 – 120 dB and, correspondingly, considerable phase shift between input and output signals, that leads to decrease of operation rate. Besides, in case of loads resistance increase circuit amplification in such devices decreases.

It should be noted, that for the first time the solution of the problem dealing with selfbalancing of operational points of intermediate amplification stages was suggested in Vinnytsia National Technical University (VNTU) [4]. Self- balancing is realized by means of application of selective feedback (SFB). Besides, in this case gain factors of intermediate stages, built on transistors of different types of conduction are balanced. At the same time, in spite of certain theoretical developments, nowadays there are no generalized mathematical models of PPDCA gain factors, that enables to evaluate their linearity in the process of design. In this connection, the subject of the paper "Model of gain factor of push-pull current amplifiers with selective feedback" is urgent.

Goal of research

Derivation of mathematical model of PPDCA static gain factor built by means of introduction of selective feedback into intermediate amplifying stages.

Tasks to be solved by the research

1. Obtain analytical relations of input-output characteristic of PPDCA with selective feedback, structural- functional model of which is built, applying controlled and functional current generators;
2. Evaluate the adequacy of PPDCA gain factors by means of comparison of the results, obtained by means of analytical relations and also obtained by means of computer analysis of the

suggested circuit solutions.

3. Suggest recommendations regarding structural-functional organization of PPDCA with selective feedback for single and multiple intermediate stages, as well as recommendations regarding the increase of gain factor linearity.

Problems solution

Let us consider generalized structural functional diagram of push-pull symmetric DCA (Fig. 1a), that realizes the method of balanced set of operating points currents of intermediate amplifying stages. The essence of the method is: two integrated contours of selective feedback are introduced into the intermediate amplifying stages, realized on the transistors of different types of conduction, operating points of intermediate amplification paths are set.

The given circuit of the amplifier consists of push-pull input stage, built on VT1 and VT2 transistors, two paths of intermediate, antiphase amplification with gain factors $K_i^{'}$ i $K_i^{''}$, and output stage, realized on current mirrors CMI and CMII. These integrated contours (denoted by dashed line) consist of bi-directional current mirror (BCM) and current compensators CC1 and CC2. Balancing of operating points is realized by means of current compensators I'_{CC} i I''_{CC}.

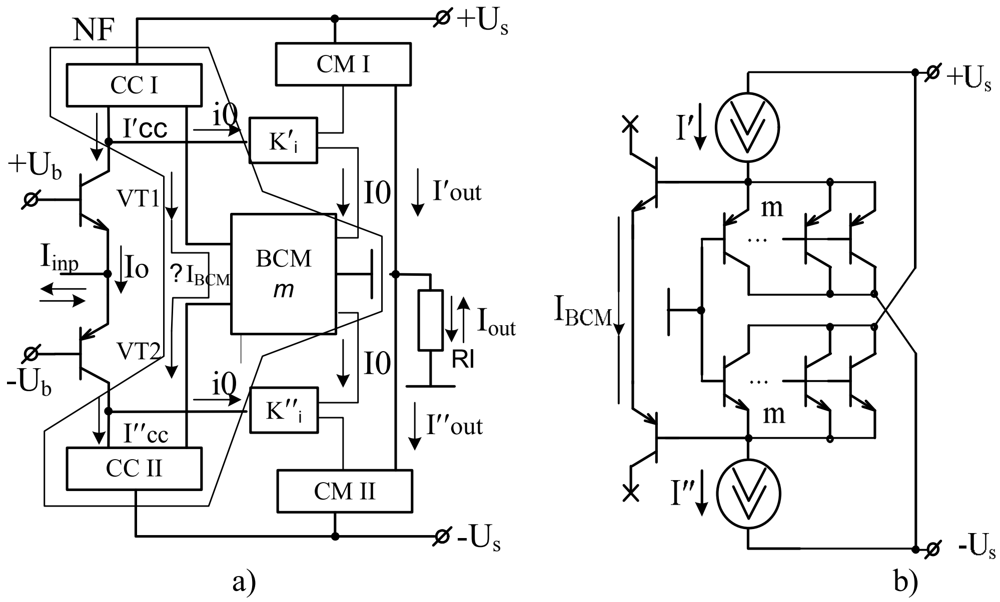


Fig. 1. PPDCA with selective feedback:
a) structural-functional diagram; b) bidirectional current mirror

Selectivity of feedback contour means its ability to react only to non-proportional current increments of intermediate stages of antiphase amplification and form corresponding compensating currents I'_{CC} and I''_{CC} by means of compensators CCI and CCII. Introduction of BCM in amplifier structure enables to form continuous signals of I' and I'' relation and correspondingly regulate compensation currents till reaching circuit balancing by the contours of the feedback. One of the possible variants of BCM realization is the circuit, shown in Fig. 1b, which is built on complementary transistors with common base [5].

Action of feedbacks leads to maintaining in the circuit the balance relation:

$$\frac{I'}{I_o} = \frac{I_o}{I''}. \tag{1}$$

If this balance is available $I'_{CC} \approx I''_{CC} \approx I_o$, where I_o – is the current of operating point.

Parameter *m* defines the depth of BCM feedback. Current I_{BCM}, formed at the outputs of BCM equals:

$$I_{BCM} = I_o = \frac{\sqrt{I' \cdot I''}}{m}. \tag{2}$$

Potential characteristics of PPDCA can be evaluated by means of replacement of real elements of the circuit by ideal (transistors are replaced by controlled current generators). For this purpose equivalent circuit of the amplifier, built on controlled current generators (linear and functional) was suggested. The circuit is shown in Fig. 2 [6].

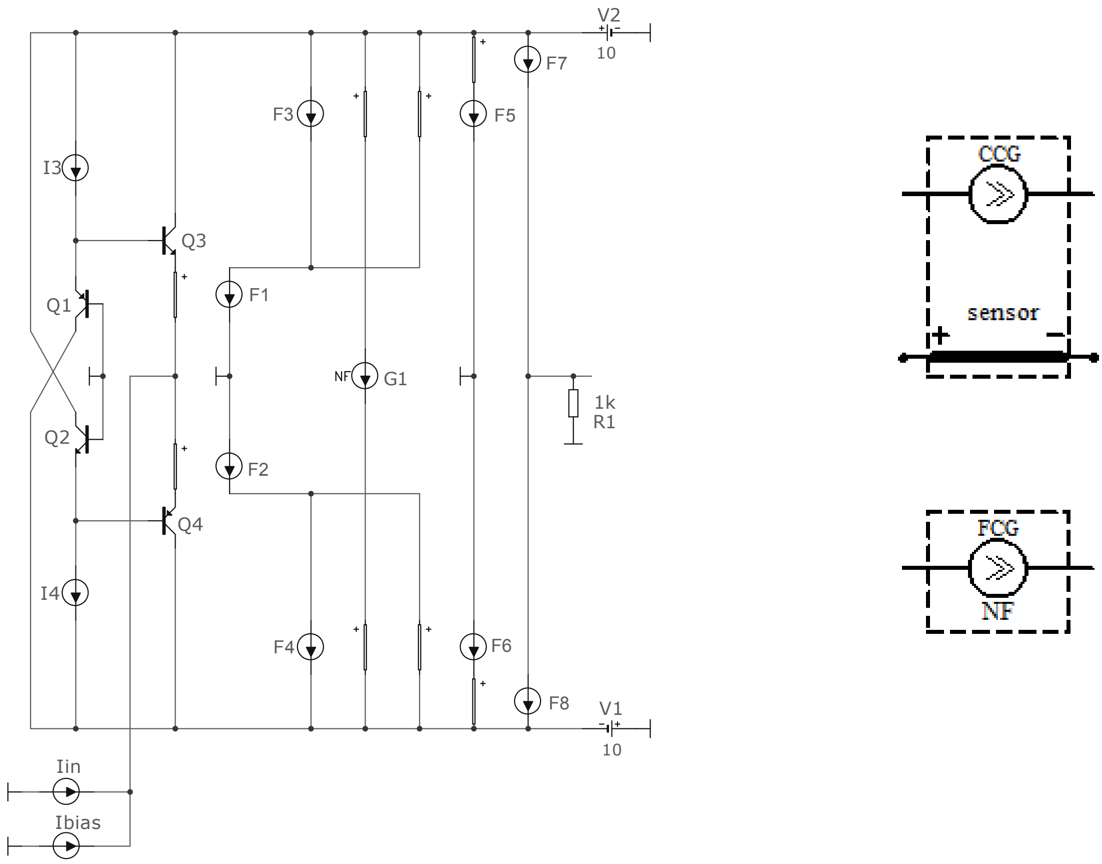


Fig. 2. PPDCA on controlled and functional current generators

We will analyse currents, flowing in this circuit. Input current I_{inp} and zero bias current I_{bc} are divided in the input stage and together with current ΔI_{BCM} forms increments of input current in upper and lower channels i'_{inp} and i''_{inp}. The system of equations can be composed:

$$\begin{cases} i'_{inp} = -\frac{1}{2}(I_{inp} + I_{bc}) + \Delta I_{BCM}, \\ i''_{inp} = \frac{1}{2}(I_{inp} + I_{bc}) + \Delta I_{BCM}. \end{cases} \tag{3}$$

Further increments i'_{inp} and i''_{inp} are amplified at the intermediate stage with corresponding gain factors $K_i^{'}$ and $K_i^{''}$. Taking into account that the increment of current at the output of BCM $\Delta I_{BCM} = \sqrt{I' \cdot I''} - I_o$, we obtain the following system of equations:

$$\begin{cases} I' = (-\dfrac{1}{2}(I_{inp} + I_{bc}) + \sqrt{I' \cdot I''} - I_o)K', \\ I'' = (\dfrac{1}{2}(I_{inp} + I_{bc}) + \sqrt{I' \cdot I''} - I_o)K'', \end{cases} \tag{4}$$

where I' and I'' – are output currents of upper and lower amplification channels.

To obtain equation of transfer characteristic of PPDCA, it is necessary to solve the system of equations (4), relatively currents I' and I''. First, we divide the first equation by K_i' and the second – by K_i'' and we get:

$$\begin{cases} \dfrac{I'}{K'} = -\dfrac{1}{2}(I_{inp} + I_{bc}) + \sqrt{I' \cdot I''} - I_o, \\ \dfrac{I''}{K''} = \dfrac{1}{2}(I_{inp} + I_{bc}) + \sqrt{I' \cdot I''} - I_o. \end{cases} \tag{5}$$

We subtract the first equation from the second equation and obtain:

$$I_{inp} + I_{bc} = \frac{I''}{K''} - \frac{I'}{K'} \tag{6}$$

From equation (2) we obtain the values of currents I' and I'' :

$$I' = \frac{I_o^2 m^2}{I''}, \tag{7}$$

$$I'' = \frac{I_o^2 m^2}{I'}. \tag{8}$$

Further we substitute the expression (8) into (6) and obtain:

$$I_{inp} + I_{bc} = \frac{I_o^2 m^2 K' - I'^2 K''}{I'K'K''}. \tag{9}$$

Solving the equation (9) relatively I', we obtain such real roots:

$$I_1' = \frac{-(I_{inp} + I_{bc})K'K'' - \sqrt{((I_{inp} + I_{bc})K'K'')^2 + 4I_o^2 m^2 K'K''}}{2K''},$$

$$I_2' = \frac{-(I_{inp} + I_{bc})K'K'' + \sqrt{((I_{inp} + I_{bc})K'K'')^2 + 4I_o^2 m^2 K'K''}}{2K''}.$$

In the same way, substituting (7) into (6), we obtain the roots of the equation for I'' :

$$I_1'' = \frac{(I_{inp} + I_{bc})K'K'' - \sqrt{((I_{inp} + I_{bc})K'K'')^2 + 4I_o^2 m^2 K'K''}}{2K'},$$

$$I_2'' = \frac{(I_{inp} + I_{bc})K'K'' + \sqrt{((I_{inp} + I_{bc})K'K'')^2 + 4I_o^2 m^2 K'K''}}{2K'}.$$

Taking into account physical principle of amplifier operation, namely – the phenomenon , if the currents flows into circuit, then it flows out into its output from the load, for currents I' and I'' we can compose common equation of transfer characteristic in the range of input in the form:

$$
\begin{aligned}
& I_{out}(I_{inp}) = I_2' - I_1'' = \\
& = \frac{-(I_{inp}+I_{bc})K'K'' + \sqrt{((I_{inp}+I_{bc})K'K'')^2 + 4I_o^2 m^2 K'K''}}{2K''} - \\
& - \frac{(I_{inp}+I_{bc})K'K'' - \sqrt{((I_{inp}+I_{bc})K'K'')^2 + 4I_o^2 m^2 K'K''}}{2K'} .
\end{aligned} \tag{10}
$$

Such important quality of the circuit as the availability of certain non-linearity in the dependence $I_{out} = f(I_{inp})$. should be paid attention to. In this case, absolute and relative errors of PPDCA linearity are determined by means of currents I' and I'' by the formula:

$$\Delta I_{nl} = |I'| - |I''|, \tag{11}$$

$$\delta I_{nl} = \frac{\Delta I_{nl}}{max(I', I'')} \cdot 100\%. \tag{12}$$

The error of amplifier linearity can be illustrated by means of transfer characteristic graph, shown in Fig. 3.

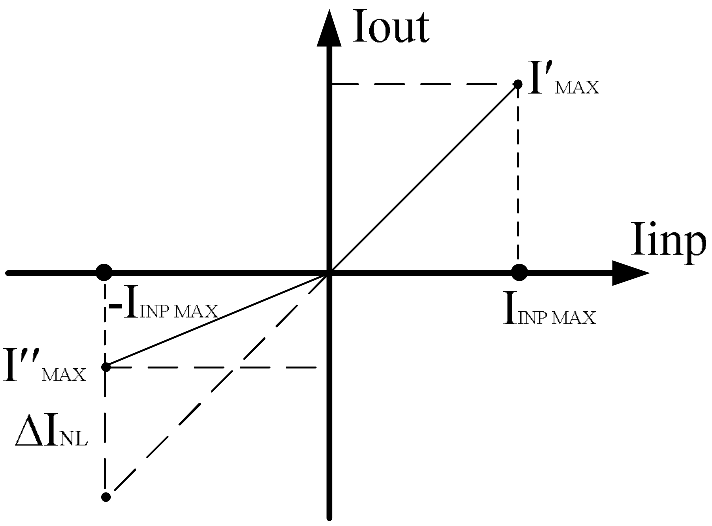


Fig. 3. Graph of linearity error of DCA transfer characteristic

Gain factor $K_{i\,\mathrm{out}}$ can be found by means of equation derivative (10) of transfer characteristic in the form:

$$K_{i\,\mathrm{out}} = \frac{dI_{\mathrm{out}}(I_{inp})}{dI_{inp}} =$$

$$
= -\frac{K'K'' + \dfrac{2K'^2K''^2(I_{inp}+I_{bc})}{2\sqrt{K'K''(4I_o^2m^2 + K'K''I_{inp}^2 + 2K'K''I_{inp}I_{bc} + K'K''I_{bc}^2)}}}{2K'} -
$$

$$
- \frac{\dfrac{K'K''}{2} - \dfrac{2K'^2K''^2(I_{\hat{a}\tilde{o}}+I_{\c{c}\grave{\imath}})}{4\sqrt{K'K''(4I_o^2m^2 + K'K''I_{inp}^2 + 2K'K''I_{inp}I_{bc} + K'K''I_{bc}^2)}}}{K''} .
$$

Graph of $K_{i\,\mathrm{out}}$ dependence on input current is shown in Fig. 4. As it is seen from this Fig., $K_{i\,\mathrm{out}}$ changes in the range of input signal, that proves the presence of linearity error.

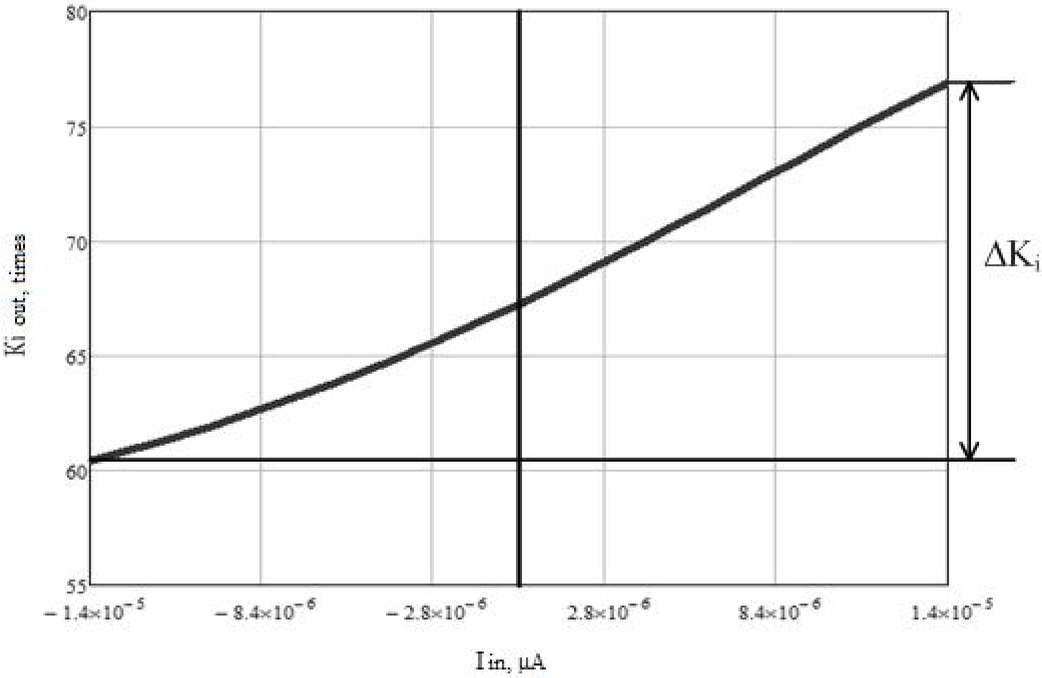
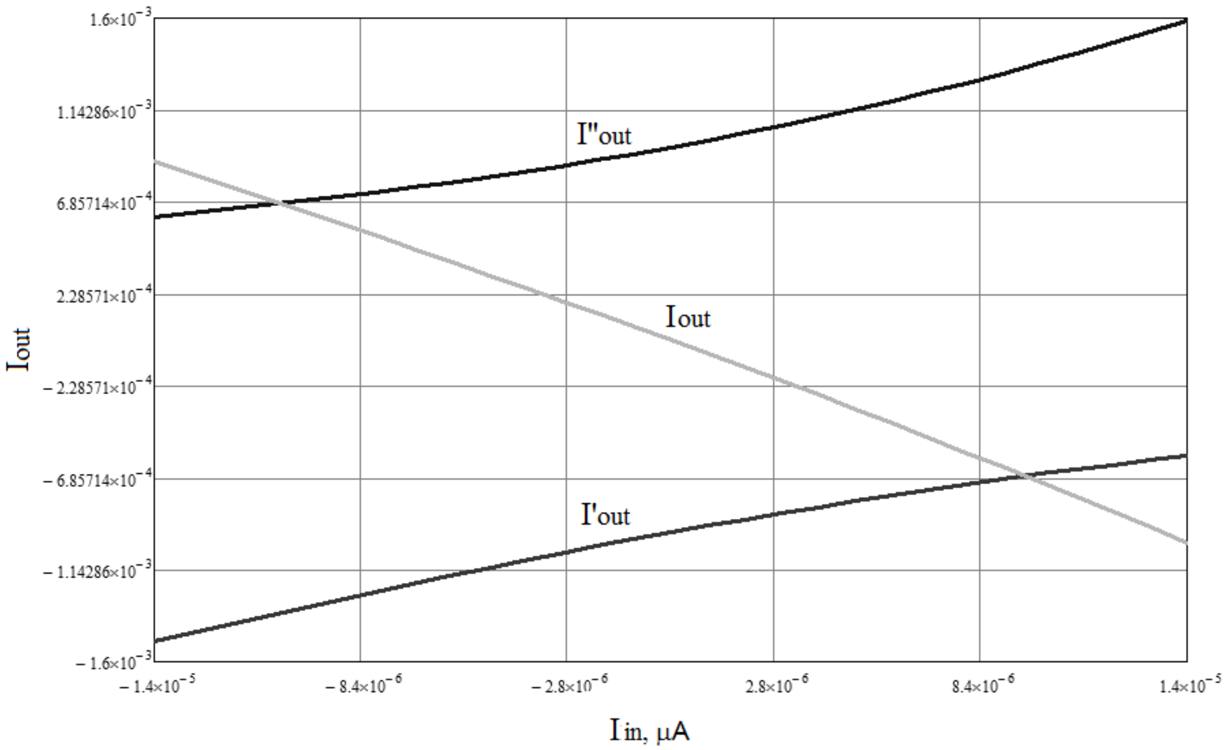
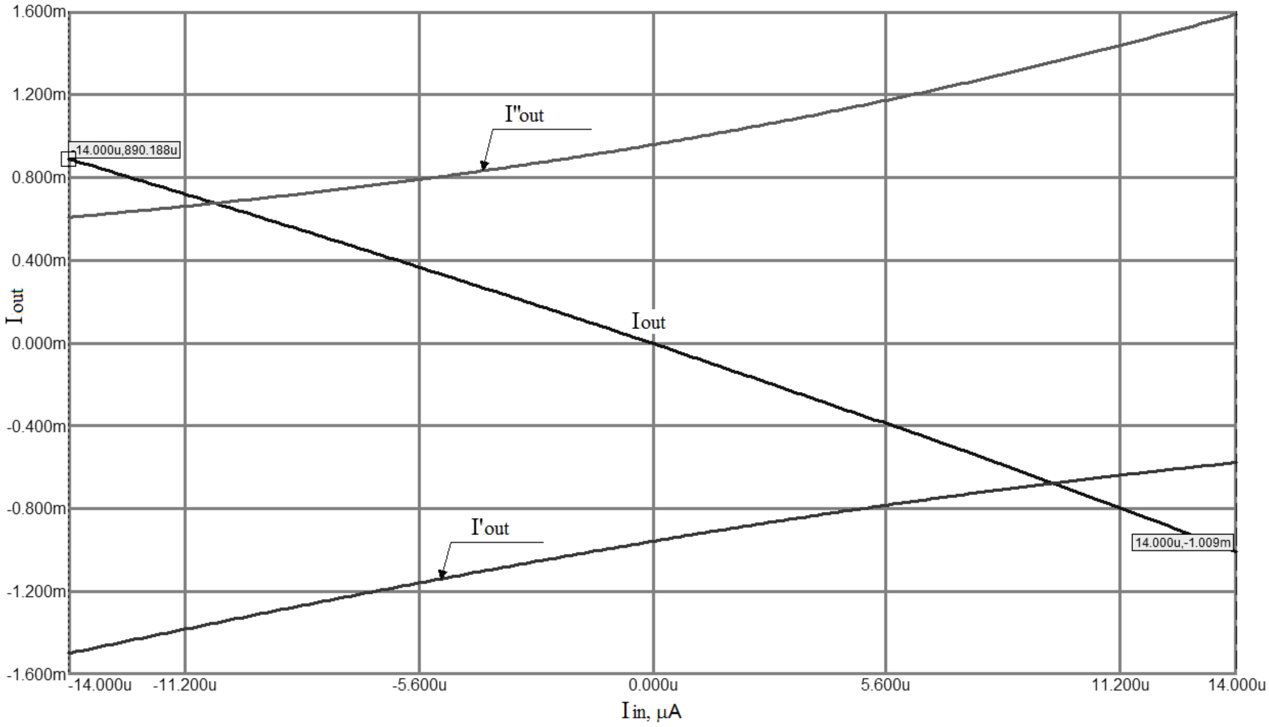


Fig. 4. Dependence of $K_{i\,\text{out}} = f(I_{inp})$ on input current

One of the factors, influencing the error of amplifier linearity is non-identity of intermediate stages amplification factors $K_i^{'}$ and $K_i^{''}$. For instance, for the circuit, shown in Fig. 2. linearity error is ≈ 90 μA at $K_i^{'}$=52 and $K_i^{''}$=93 (if models of bipolar transistors Intersil HFA 3178 are used) [7]. Graphs of transfer characteristic for the given ideal circuit, where corresponding units, such as: current mirrors and current compensators, BCM, intermediate amplifying stages are replaced by controlled and functional current generators, shown in Fig. 5.



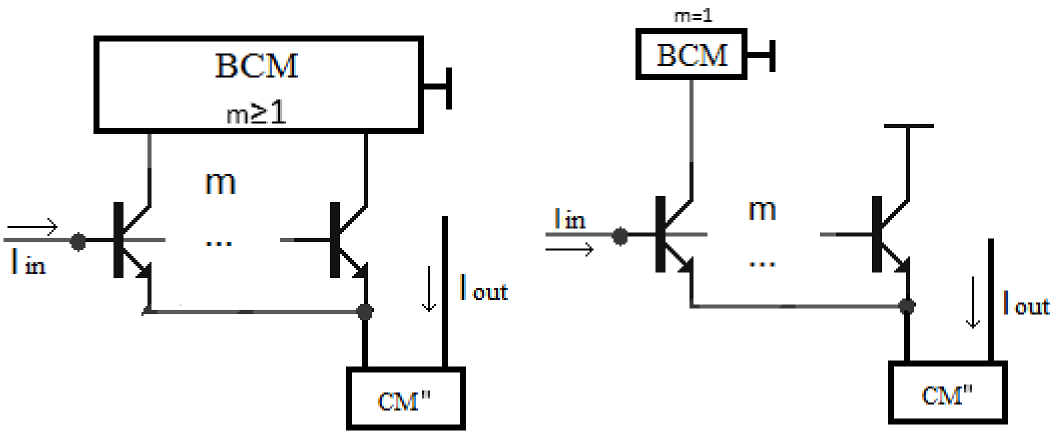
a)



b)
Fig. 5. Transfer characteristics of ideal DCA obtained:
a) in Mathcad environmnet;
b) by the results of computer modeling in Microcap

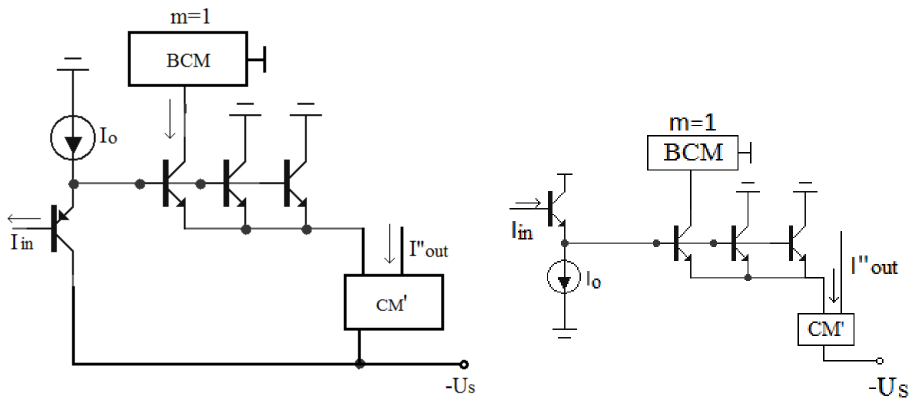
It should be noted the convergence of the results of mathematical and computer modeling, that certifies the adequacy of the obtained model of PPDCA transfer characteristic.

The task of decreasing linearity error is very important. One of the ways of its solution is equalizing of amplification factors $K_i^{'}$ and $K_i^{''}$ of intermediate channels of antiphase amplification [8]. For this purpose it is expedient to use the construction of intermediate stages with m-fold parallelization of amplifying transistors and parallelization of BCM transistors, as it is shown in Fig. 6.



a) b)
Fig. 6. Variants of connections of single-ended intermediate stages to BCM:
a) with concentrated transistors;
б) with branching of transistors

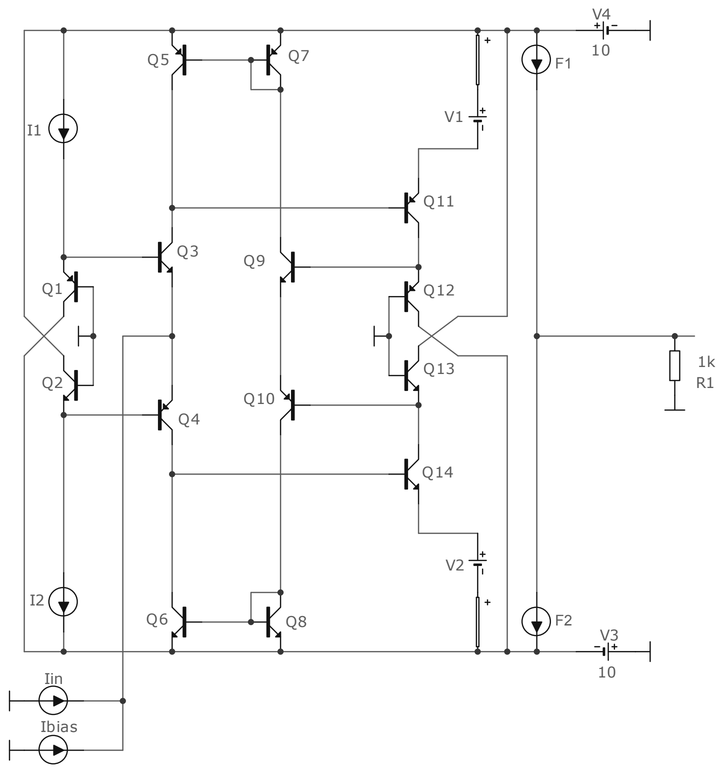
Using m parameter, i.e. m pairs of parallely connected transistors in BCM (see Fig. 6a) enables to decrease the depth of internal feedback of amplifier and prevent generation of the circuit, however (as compared with another variant (Fig. 6b)) this requires more hardware resources. The second way is the usage in each channel of intermediate amplification, push-pull circuits using the combination of *n-p-n-* and *p-n-p-*transistors.



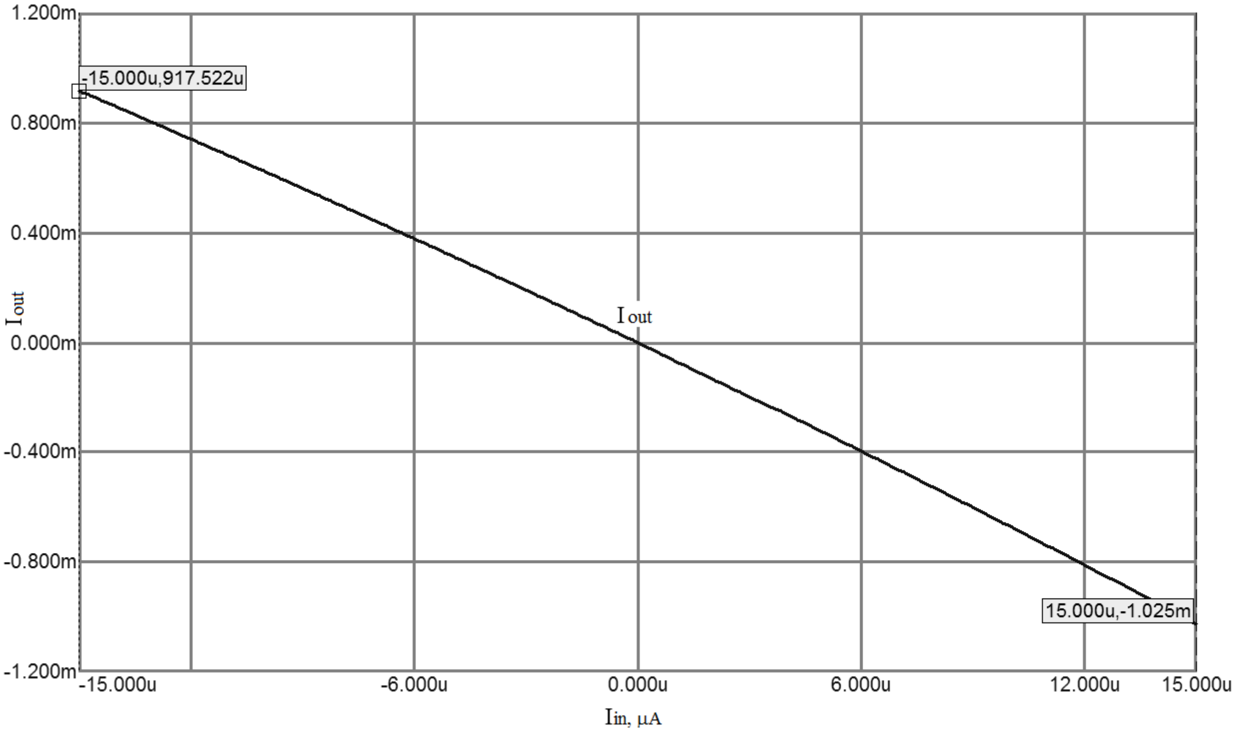
a) b)

Fig. 7. Connection of push-pull intermediate stages to BCM
a) with combination of p-n-p and n-p-n transistors;
b) with combination of the transistors of the same conduction (on the example of n-p-n)

It should be noted, that usage of BCM with $m>1$ parameter, besides linearity error decrease and transfer factor increase, also allows to decrease bias current m times. Let us consider several basic circuits of PPDCA and compare their characteristics. Fig. 8 shows simplified diagram and transfer characteristic of DCA with single-ended intermediate stage, where output transistor current mirrors are replaced by controlled current generators.



a)

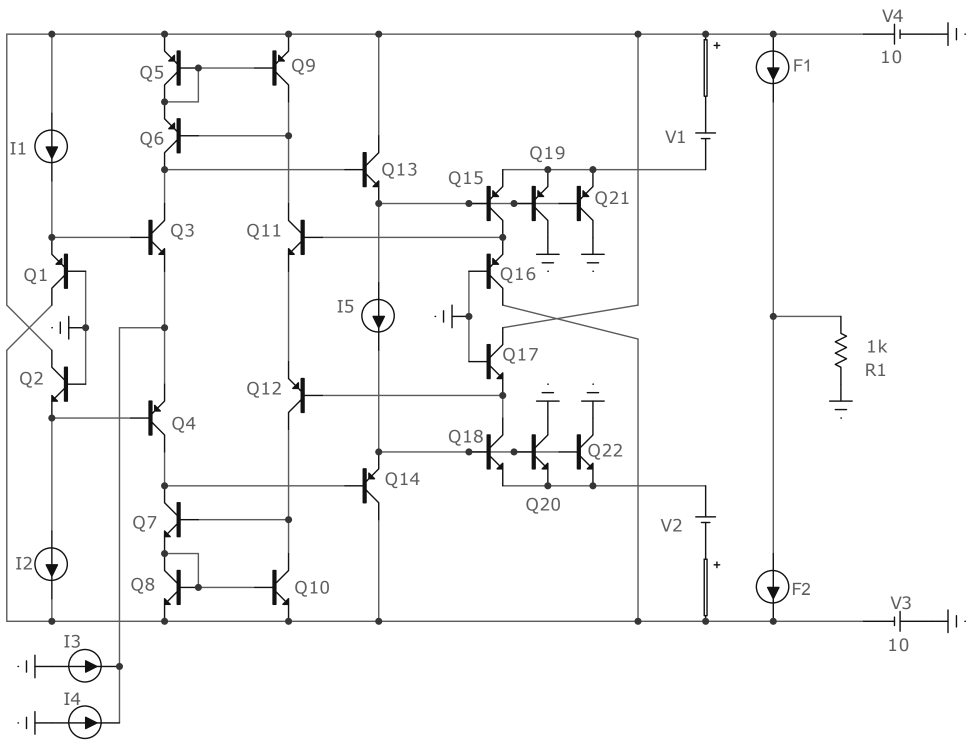


b)

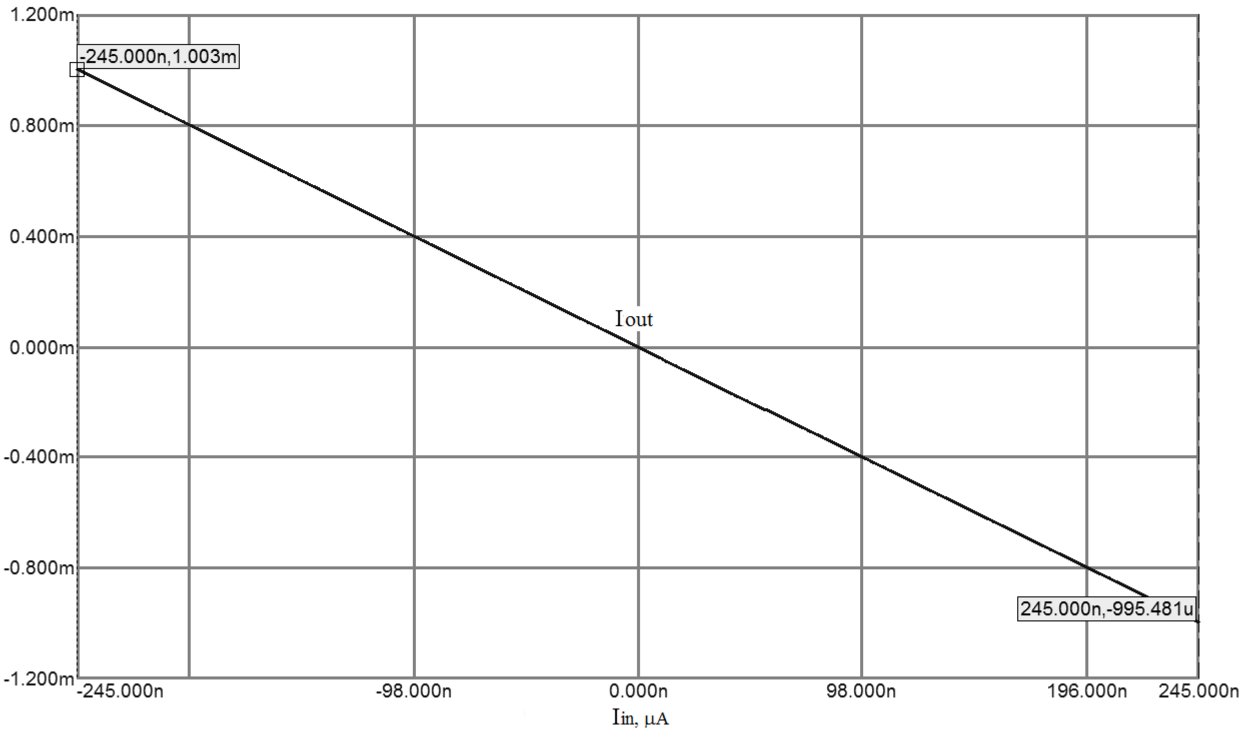
Fig. 8.Push-pull DCA:
a)simplified basic circuit;
b) transfer characteristic $I_{out} = f(I_{inp})$

As it can be calculated from the graph, linearity error of the considered circuit is $\Delta I_{nl} = 104$ μA, or 10.4 % on condition that K_i'=52, K_i''=93 and $\Delta I_o = 104$ mA.

We will consider DCA circuit with push-pull distributed intermediate amplifying stages (Fig. 9). Gain factors K_i' and K_i'' of such circuit are much higher as compared with the previous circuit and equal 63.8 dB and 62.6 dB, parameter *m*=3.



a)



b)

Fig. 9 DCA with push-pull intermediate stages:
a) basic circuit;
b) transfer characteristic

The results obtained certify the efficiency of using pull-push intermediate stages. This allows to increase circuit amplification, extend the bandwidth, that results in accuracy increase. Linearity error of the given circuit is 8 μA, that is 0.8% at operating current being 1 mA. Hence, the given approach has all the advantages over DCA circuits with single-ended intermediate stages.

Conclusions

1. Mathematical model of PPDCA static transfer characteristic has been obtained, that enables to define the value of I_{out} at preset I_{inp}, and evaluate its linearity.

2. The comparison of the results of transfer characteristic investigation applying analytical expression and computer modeling proves their convergence, that certifies the adequacy of the obtained relations.

3. Recommendations, regarding structural-functional organization of amplifiers circuits are suggested. It has been proved that usage of *m* parameter and composition of n-p-n- and p-n-p-transistors allows to increase the linearity of transfer characteristic.

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