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PUSH-PULL CURRENT-TO-CURRENT AND VOLTAGE-TO-CURRENT CONVERTERS WITH OUTPUT SIGNAL SWITCHING

The paper considers push-pull current-to-current and voltage-to-current converters with output signal switching. Relevance and expediency of designing such converters in order to expand functional capabilities due to providing additional ability to perform high-precision fast switching of the signals are substantiated. The circuits of push-pull current-to-current and voltage-to-current converters with output signal switching are proposed and analyzed. In order to analyze dynamic errors, occurring in the process of the diode commutation, its mathematical model is developed and calculated. The modeling results confirm adequacy of the model. Engineering recommendations on circuit implementation of the above push-pull current-to-current and voltage-to-current converters with output signal switching are presented.

Keywords: *current switches, high linearity, push-pull current-to-current converters.*

Introduction

In primary converters of multichannel analog-to-digital systems for measuring, registering and processing of the signals voltage-to-current converters (VCC) are most common and sometimes current-to-current converters (CCC) are used. Before output signals of such converters are supplied to measuring ADC, they must be commutated using the analog switch.

Relevance

It is known [1, 2] that to ensure fast high-precision conversion and switching of the analog signal, it is the current that should be chosen as the most informative parameter since most parasitic parameters of the integrated circuits are capacitances. Here we should remember the First switching law. It states that voltage across the capacitance cannot change stepwise while the current stepwise changes, when it flows through the capacitance, are possible. There are many circuits of diode current switches [1, 2], which provide fast and high-precision current switching. It should be noted that reverse currents of diode switches could, in most cases (with the exception of high temperature conditions), be neglected. Besides, if VCC or CCC have two bidirectional paraphase outputs, for output signal switching quite simple diode switches can be used as in the case of digital-to-analog converters [3]. Unfortunately, there are not many circuits of push-pull converters with the required configuration of outputs. In publications [4 – 6] the variants of VCC configuration with high-resistance outputs are presented. However, such converters are not universal and cannot be used for current-to-current conversion.

The authors propose a somewhat different approach to building said converters, namely, the use of push-pull balanced direct current amplifiers with paraphase low input resistance as well as of specialized current deflectors with bidirectional paraphrase high-resistance outputs. This enables building structures that are, to a certain extent, universal and can be used both as CCC and VCC with output signal switching. Here it should be noted that the proposed approach is new and it has not been sufficiently covered in scientific-technical literature. Therefore, subject of the paper, namely, consideration of push-pull current-to-current and voltage-to-current converters with output signal switching, is relevant.

Research aim

Research aims at expanding functional capabilities of current-to-current and voltage-to-current converters by means of performing high-precision fast switching of the output signal in addition to conversion itself.

Research tasks

To analyze the proposed method of structural and functional organization of high-linearity CCC (VCC) with the application of specialized current deflectors with bidirectional outputs, which are switched using fast-acting diode switch elements;

To develop mathematical models of static and dynamic characteristics, which simulate the process of switching CCC (VCC) output currents, as well as to evaluate the limit resolution of such converters, taking into account the influence of errors that occur depending on the load resistances;

To propose engineering recommendations on the circuit implementation of the above high-linearity CCC (VCC) with output current switching and to evaluate linearity of the static transfer characteristic of the circuits under consideration.

Solving of the tasks set

For creating high-linearity push-pull CCC (VCC), availability of a number of functional units, integrated in a single structure, is required: a specialized push-pull direct current amplifier (PDCA) with two or four bidirectional paraphase outputs, a set of specialized current deflectors (SpCD) with high-resistance outputs as well as a pair of diode switches K_1 and K_2 for switching output currents. Depending on the system requirements, CCC (VCC) converters may have different structural organization.

Fig. 1a presents a circuit of the push-pull CCC (PVC) with a pair of bidirectional paraphase current outputs, which is an improved variant of the circuits proposed in [7, 8]. The circuit comprises a specialized balanced (SpB) PDCA with low input resistance, two specialized current deflectors SpCD1 and SpCD2, two diode switch elements K_1 and K_2 as well as a current divider at the resistors R_{SC} and $R_{L.S.}$. This PDCA should have a sufficient internal current transfer coefficient K_I for maintaining a deep feedback mode as well as low input resistance. This provides certain universality for the device, namely, if the input signal (current) is formed by a sensor with high input resistance, it operates as CCC. At the same time, if generator of voltage ($\pm U_{input}$) is the source of input current, it operates as VCC. It should be noted that in this case the level of input current I_{input} is set by the resistor R_G. In some applications (e. g., low-power generator of input voltage $\pm U_{input}$) a voltage buffer should be additionally installed at the input.

Deflectors SpCD1 and SpCD2 must have two current outputs each, where sensor currents I'_S and I''_S are generated, as well as main outputs where currents I'_{OUTPUT} and I''_{OUTPUT} flow. To ensure small linearity error of transfer characteristic $I_{OUTPUT} = f(I_{INPUT}$, equalities $I'_S = I'_{INPUT}$ and $I''_S = I''_{OUTPUT}$ should be satisfied (in a certain approximation). Principles of building such SpCD are stated in [9]. Differential current $I_S = I'_S - I''_S$ of the sensor is supplied to the feedback circuit at resistors R_{SC} and $R_{L.S}$, which form a divider, and further to the circuit output. Coefficient of current transfer to the sensor output is given by

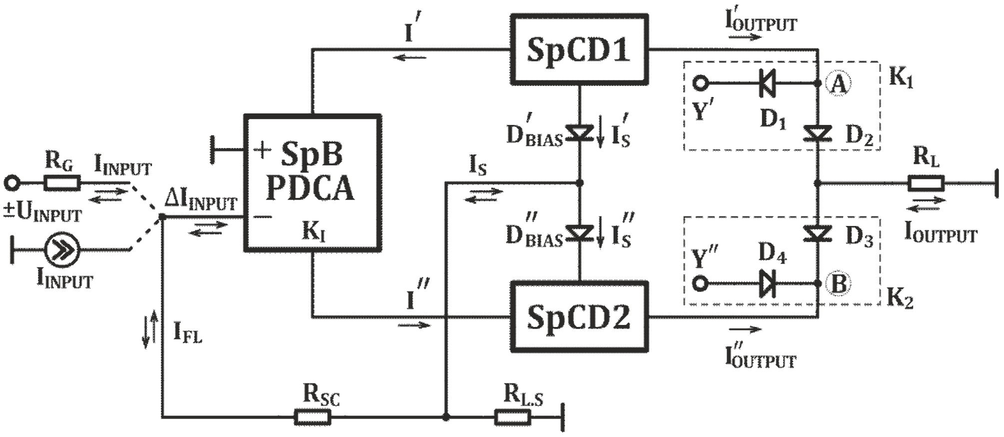
$$K_{TI.S} = \frac{I_S}{I_{INPUT}} = \frac{R_{SC} + R_{L.S}}{R_{L.S}}.$$

Output current of CCC (VCC) is generated in the form of the difference $I_{OUTPUT} = I'_{OUTPUT} - I''_{OUTPUT}$ and supplied to the load (R_L). In order to create equal conditions of the circuit operation for the main output and for the sensor output, it is expedient to install bias diodes D'_{BIAS} i D''_{BIAS}. Besides, if possible, fulfillment of the following equality is desirable:

$$R_L = \left(R_{L.S} \mid R_{SC}\right) = \frac{R_{L.S} \cdot R_{SC}}{R_{L.S} + R_{SC}}.$$

Diode switches K_1 and K_2 are controlled by digital signals Y' and Y'' in the form of voltages U' and U''. If $U' \geq U_A$ U'', diodes D_2 i and D_4 are opened while diodes D_1, D_3 are closed and current $I_{OUTPUT} = I'_{OUTPUT} - I''_{OUTPUT}$ is supplied to resistor $R_{L.}$ If control signals Y' and Y'' open diodes Y'

and Y″, diodes D_2 and D_4 are closed, and only differential leakage current of diodes gets to resistor R_L. It is known that leakage current of silicon diodes, based on low-power n-p-n transistors, has the value of 10 pA at room temperature [4].



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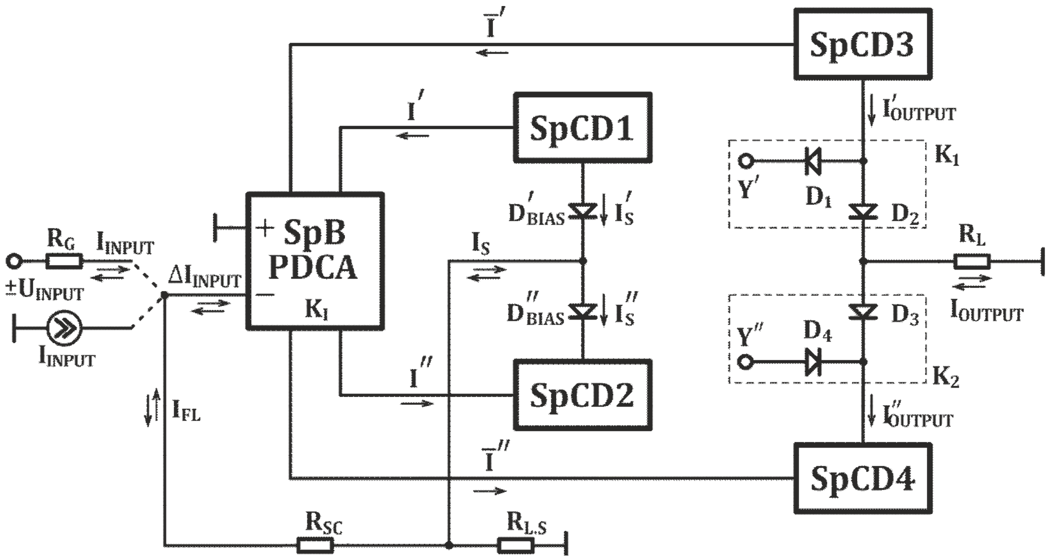

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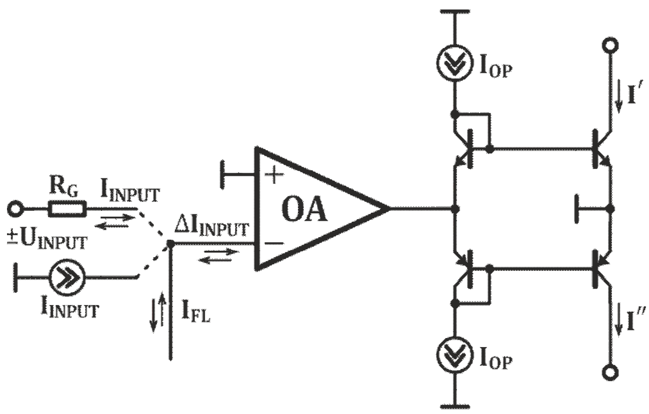


c)

Fig. 1. Push-pull CCC (CVC) based on specialized PDCA: a) with a pair of bidirectional outputs; b) with two pairs of bidirectional outputs; c) with Sp PDCA based on OA

If the values of output current I_{OUTPUT} are in the range of milliamp units, resolution of diode switches reaches $10^{-7} \div 10^{-8}$ A, which cannot be achieved for other types of switch elements with the exception of mechanical ones. At the same time, availability of non-zero resistance R_L could bring certain error of ΔI_R conversion, the value of which can be estimated as relation $\Delta I_R = R_L / r_{OUTPUT}$, where r_{OUTPUT} is output resistance of CCC (VCC). In the case of R_L being constant, this will cause a change of the scaling factor of transfer characteristic $I_{OUTPUT} = f(I_{INPUT})$ and will, practically, have no influence on linearity error of ΔI_l . And if R_L varies, $\Delta I_l = \Delta R_L / r_{OUTPUT}$, where ΔR_L is load resistance gain. The components of R_L could be dependences of differential resistances r_d of diodes D_2 i D_4 on currents I'_{OUTPUT} and I''_{OUTPUT}. It is known that [10] $r_d = \varphi_T / I_D$, where $\varphi_T \approx 26$ mV – thermopotential and I_D – current across the diode. For $I_D = 1$mA $r_d \approx 26$ Ohm.

From the above it is obvious that it is necessary to increase output resistance of SpCD. It should be noted that if $I'_{OUTPUT} = I''_{OUTPUT} = 1$mA, for this type of SpCD $r_{OUTPUT} \sim 1$MOhm. In this case ΔR_L is of the order of tens of ohms and relative error δI_L will be of the order $\leq 0{,}01\%$. Linearity of the transfer characteristic of CCC (VCC) depends also on linearity error of the specialized PDCA and, therefore, gain coefficient K_I should be sufficient for this error to be minimal in the deep feedback mode for the set value of $K_{TI.S}$ It should be noted that linearity of Sp PDCA significantly depends on the values of its output currents I' and I''. Therefore, it is expedient to increase SpCD transfer coefficient (SpCDTC) to the value exceeding 1.0 – to about 2.0 and 3.0. In this case, the linearity of CCC (VCC) can be improved. It is expedient to choose optimal values of $K_{TI.CD}$ by modeling in the range of $I_{OUTPUT.}$ It should be noted that high final I_{OUTPUT} is required and, correspondingly, also $K_{TI} = I_{OUTPUT} / I_{INPUT} \geq 10^3$. So, to increase internal $K_I \geq 10^6$, commercial operational amplifier (OA) could be additionally used (see Fig. 1c). It should be noted that the circuit shown in Fig. 1 has a special feature, namely: reductions of output resistance of the sensor $r_{OUTPUT.S}$ and of the main r_{OUTPUT} for SpCD with two pairs of bidirectional outputs could be somewhat different. E.g., if SpCD is built as it is recommended in [9], for $I_{OP} = 1$mA we have $r_{OUTPUT.S} \approx 60$MOhm, $r_{OUTPUT} \approx 90$MOhm. With the increase of R_L linearity of CCC (VCC) could become worse.

An improved circuit is presented in Fig. 1b. It includes a specialized balanced PDCA with internal gain coefficient K_I with two pairs of bidirectional paraphrase outputs where currents I', $\overline{I}'$ and I'', $\overline{I}''$ are formed, four specialized deflectors SpCD1 – SpCD4, two diode switch elements K_1 and $K_{2,}$ which are installed at the diodes D_1, D_2 and D_3, D_4 respectively. Current transfer coefficient $K_{TI} \approx K_{TI.S}$ is set by the ratio of resistors R_{SC} and $R_{L.S}$ of the feedback loop. The circuit operates in the following way. I_{INPUT} is supplied to the input of SpPDCA, amplified and branched into components, which, in their turn, are supplied to the inputs of SpCD1 – SpCD4. At the outputs of SpCD1 and SpCD2 sensor currents are formed, I'_S and I''_S correspondingly, which in the form of the summarized component I_S, flow to the feedback loop via bias diodes D'_{BIAS} i D''_{BIAS}. Output current I_{FL} of the feedback loop is supplied to the circuit input and creates a balanced mode with pre-set $K_{TI.S.}$ Components I' and I'' are supplied to the inputs of the deflectors SpCD3 and SpCRD4 respectively, at the outputs of which currents I'_{OUTPUT} and I''_{OUTPUT} are formed. Digital control signals Y' and Y'' switch the elements K_1 and K_2 to the corresponding state, depending on which output currents I'_{OUTPUT} and I''_{OUTPUT} are either switched off from the circuit output or, in the form of the summarized component $I_{OUTPUT} = I'_{OUTPUT} - I''_{OUTPUT}$, are connected and supplied to the load R_L.

A principle feature of the above CCC (VCC) operation should be noted, namely: there could be a slight difference (not exceeding $0.1 \div 0.2\%$) between current transfer ratios of the sensor $K_{TI.S}$, and of the main K_{TI}. A number of factors determines this. First, outputs of the circuits are not covered by the general negative feedback loop, which causes a certain mismatch between I_S and I_{OUTPUT}. Second, SpCD transistors have technological scattering of the gain coefficients of currents I_S and I_{OUTPUT}. Also, in spite of deep local negative feedbacks acting inside these elements, which significantly neutralizes the influence of the above scatterings (dozens of times and more), an inconsiderable difference between K_{CDTI} values for different SpCD still remains. Thus, transfer characteristic $I_{UTPUT} = f(I_{INPUT})$ has a scale error that can be corrected, provided that the circuit is a part of analog-digital systems with self-correction [11, 12]. At the same time, such component as linearity error of $I_{OUTPUT} = f(I_{INPUT})$ can be reduced mostly by means of using circuit technology and, therefore, this is the approach that requires separate investigations [9].

Let us analyze dynamic errors of CCC occurring during switching of components I'_{OUTPUT} and I''_{OUTPUT} to the load resistor R_L and when bypassing it. The commutating circuit, based on diode switches, is presented in Fig. 2a. It includes diodes D_1 and D_2, which switch current I'_{OUTPUT}, as well as diodes_D_3 and D_4, which switch I''_{OUTPUT} component. The difference between these currents I_{OUTPUT} is supplied to the load resistor R_L. The switches are controlled by voltages $\pm U'$ and $\pm U''$.

It is expedient to build an equivalent circuit of this commutating unit, based on the integral Hummel-Poon model, described, in particular, in [13]. The view of this equivalent circuit is presented in Fig. 2b, where conditional directions of the currents and voltage at its elements are shown. Applying Kirchhoff's laws, a system of differential equations can be composed:

$$\begin{cases} E_1 = U_1(t) + U_2(t) + U_3(t) + U_7(t), \\ -E_2 = -U_4(t) - U_5(t) - U_6(t) + U_7(t), \\ I_{R1}(U_1) + I_{D1}(U_2) - C_{D1}(U_2) \cdot \dfrac{dU_2(t)}{dt} = 0, \\ -I_{D1}(U_2) + C_{D1}(U_2) \cdot \dfrac{dU_2(t)}{dt} + I_{01} - I_{D2}(U_3) - C_{D2}(U_3) \cdot \dfrac{dU_3(t)}{dt} = 0, \\ -I_{R2}(U_4) - I_{D4}(U_5) + C_{D4}(U_5) \cdot \dfrac{dU_5(t)}{dt} = 0, \\ I_{D4}(U_5) - C_{D4}(U_5) \cdot \dfrac{dU_5(t)}{dt} - I_{02} + I_{D3}(U_6) + C_{D3}(U_6) \cdot \dfrac{dU_6(t)}{dt} = 0, \\ I_{D2}(U_3) + C_{D2}(U_3) \cdot \dfrac{dU_3(t)}{dt} - I_{D3}(U_6) - C_{D3}(U_6) \cdot \dfrac{dU_6(t)}{dt} - I_{R3}(U_7) - C3 \cdot \dfrac{dU_7(t)}{dt} = 0. \end{cases}$$

where E_1, E_2 – control voltages $\pm U'$ and $\pm U''$; R1, R2 – output resistances of the control elements; I_{01}, I_{02} – components of I'_{OUTPUT} and I''_{OUTPUT}, which are switched; C3, R3 – capacitance and load resistance; I_{D1}, I_{D2}, I_{D3}, I_{D4} – sources of currents that simulate dependence $I_D = f(U_D)$ for diodes D1, D2, D3, D4 and C_{D1}, C_{D2}, C_{D3}, C_{D4} – capacitances of p-n junctions of the corresponding diodes.

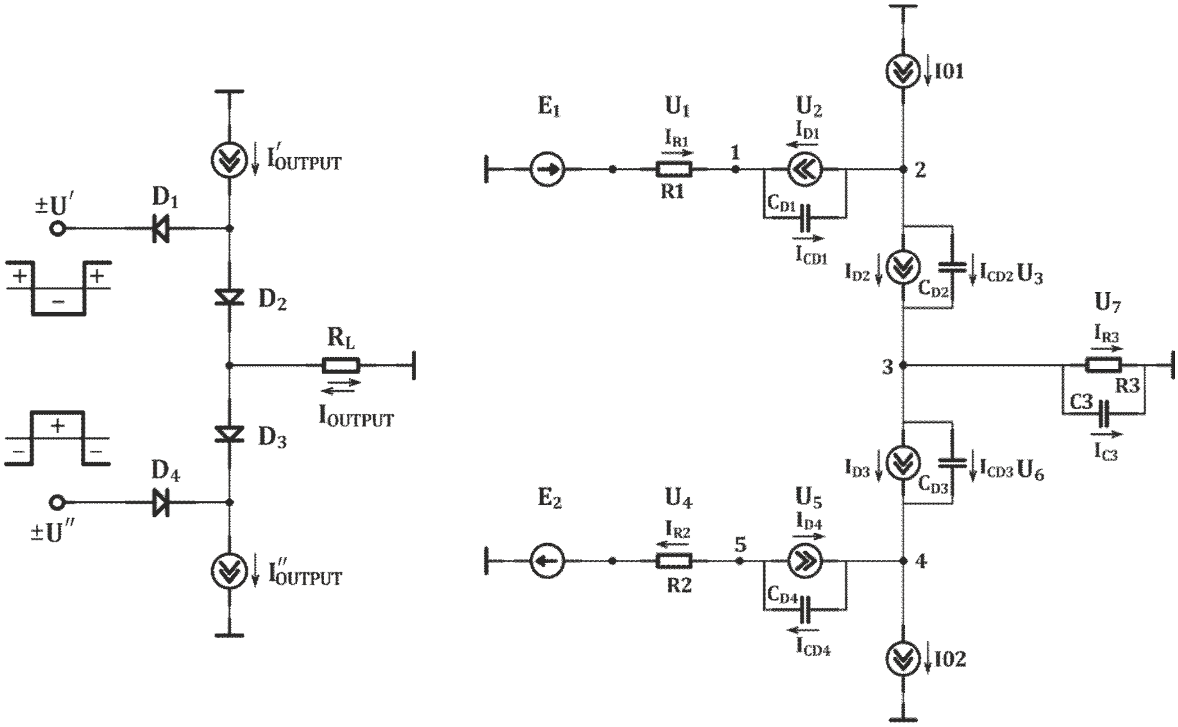


Fig. 2. The circuit of commutation unit at the diode switches: a) general view; b) equivalent circuit

Taking into account, that [13]

$$I_D = I_0 \cdot \left(e^{\frac{U_D}{\phi_T}} - 1 \right),$$

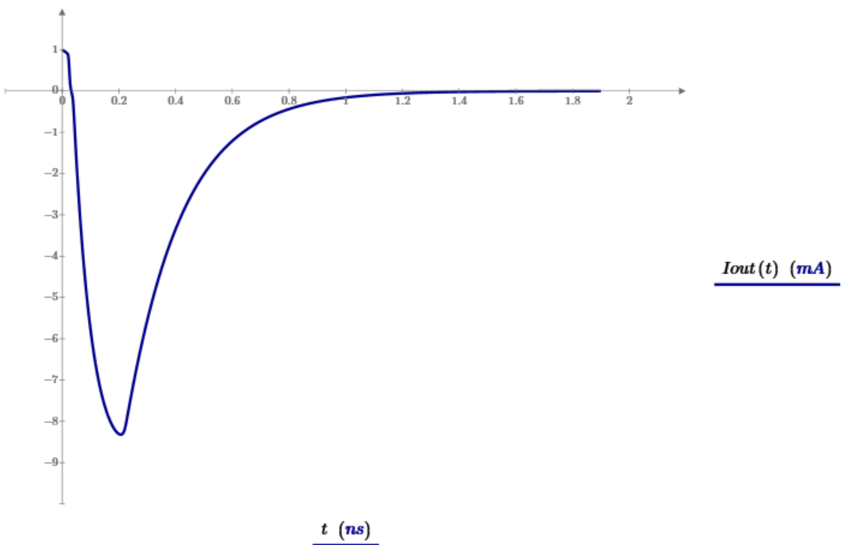
$$C_D = C_{BAR} + C_{DIF} = \frac{C_0}{\left(1 - \dfrac{U_D}{\phi_J}\right)^m} + \tau \cdot \frac{I_0}{\phi_T} \cdot \left(e^{\frac{U_D}{\phi_T}} - 1 \right).$$

where I_0 – thermal saturation current, φ_T – thermal potential, U_D – voltage across the diode, φ_J – contact difference of potentials of p-n junction, τ – time of charge transfer through p-n junction, C_0 – barrier capacitance of p-n junction for zero bias, m – smoothness factor of p-n junction, we obtain a system of differential equations, which is convenient for use in the integral software package of computer algebra Mathcad (Copyright 1987-2016 © PTC Inc.):

$$\begin{cases}
E_1 = U_1(t)+U_2(t)+U_3(t)+U_7(t), \quad E_2 = U_4(t)+U_5(t)+U_6(t)-U_7(t), \\
\dfrac{dU_2(t)}{dt} = \dfrac{\dfrac{U_1(t)}{R1} + I_0 \cdot \left(e^{-\frac{U_2(t)}{\phi_T}} - 1 \right)}{\left(\dfrac{C_0}{\left(1+\dfrac{U_2(t)}{\phi_J}\right)^m} + \tau \cdot \dfrac{I_0}{\phi_T} \cdot \left(e^{-\frac{U_2(t)}{\phi_T}} - 1 \right) \right)}, \quad \dfrac{dU_3(t)}{dt} = \dfrac{\dfrac{U_1(t)}{R1} - I_0 \cdot \left(e^{\frac{U_3(t)}{\phi_T}} - 1 \right) + I_{01}}{\left(\dfrac{C_0}{\left(1-\dfrac{U_3(t)}{\phi_J}\right)^m} + \tau \cdot \dfrac{I_0}{\phi_T} \cdot \left(e^{\frac{U_3(t)}{\phi_T}} - 1 \right) \right)}, \\
\dfrac{dU_5(t)}{dt} = \dfrac{\dfrac{U_4(t)}{R1} + I_0 \cdot \left(e^{-\frac{U_5(t)}{\phi_T}} - 1 \right)}{\left(\dfrac{C_0}{\left(1+\dfrac{U_5(t)}{\phi_J}\right)^m} + \tau \cdot \dfrac{I_0}{\phi_T} \cdot \left(e^{-\frac{U_5(t)}{\phi_T}} - 1 \right) \right)}, \quad \dfrac{dU_6(t)}{dt} = \dfrac{\dfrac{U_4(t)}{R1} - I_0 \cdot \left(e^{\frac{U_6(t)}{\phi_T}} - 1 \right) + I_{02}}{\left(\dfrac{C_0}{\left(1-\dfrac{U_6(t)}{\phi_J}\right)^m} + \tau \cdot \dfrac{I_0}{\phi_T} \cdot \left(e^{\frac{U_6(t)}{\phi_T}} - 1 \right) \right)}, \\
\dfrac{dU_7(t)}{dt} = \dfrac{1}{C3} \cdot \left(\dfrac{U_1(t)}{R1} + I_{01} - \dfrac{U_4(t)}{R1} - I_{02} - \dfrac{U_7(t)}{R3} \right).
\end{cases}$$

If high-frequency diode 1S2092 and its parameters are used, we will have transient processes of the form presented in Fig. 3. The graph of the switch closure process, obtained using Mathcad software package, is shown in Fig. 3a and that of the opening process – in Fig. 3b.

It is expedient to validate adequacy of the composed model of the commutation unit by simulation of transient processes in the integrated package Microcap 11 (Copyright© 1982-2017 Spectrum Software). Simulation results are displayed on the time diagram shown in Fig 3c (graph 1). Somewhat better results can be obtained if the diodes are realized based on transistors *NUHFARRY* [14] in diode connection (graph II). Analysis of these graphs reveals that the second option has better dynamic characteristics. In this case the output current setting time (at the level of 5τ) with the error ≤0.7% at the resistor R_L = 100 Ohm does not exceed 2 ns and with the error of 0.001% – 5ns.



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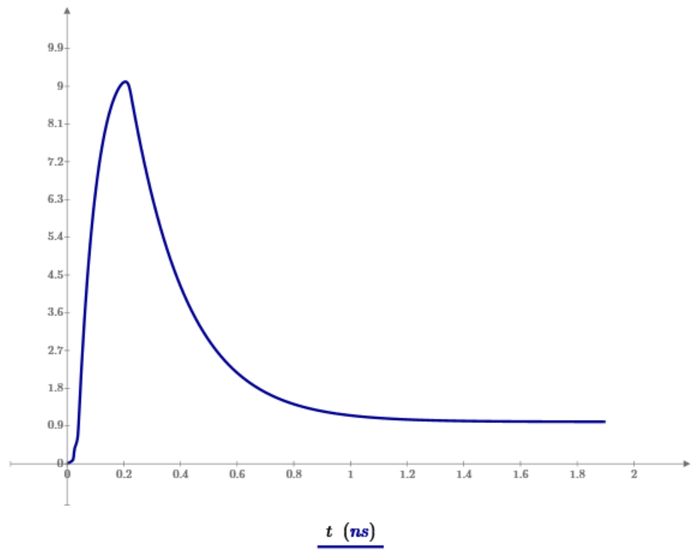

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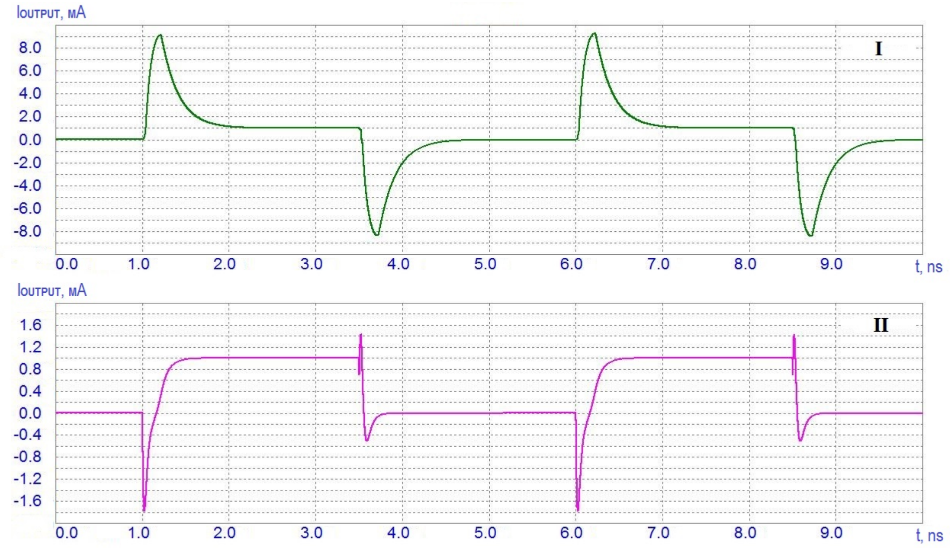

c)

Fig. 3. Transient processes during the diode switch commutation, graphs: a) the switch closure process; b) the switch opening process; c) on the results of simulation in Microcap software (I – for high-frequency diode; II – for the transistor in the diode connection)

Conclusions

It has been determined that that the proposed method of structural and functional organization of high-linearity CCC (VCC) with switching of the output currents enables obtaining relative error values of current-to-current (voltage-to-current) conversion not exceeding 0.001%.

Mathematical models of the dynamic characteristics of the diode current commutation unit have been developed and the performed computer simulation has proved that the output signal setting time does not exceed nanoseconds (5 ns) with dynamic error of 0.001 %.

Recommendations on engineering realization of high-linearity (static error δI_L<0.001%) current-to-current and voltage-to-current converters, based on push-pull balanced direct current amplifiers, as well as on fast output signal switching are presented.

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Editorial office received the paper 06.03.2018.
The paper was reviewed 16.03.2018.

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