The Flow Graph Usage for the Attenuation Correction of the Low-pass Sallen-Key Biquad in the Current Mode

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***Abstract* – The second order Sallen-Key low-pass filter structures (so called biquads) in the voltage and the current mode have one common disadvantage. This is a decreasing of the attenuation at high frequencies, because active elements exhibit losses of the amplification. While some solutions for the voltage mode circuits have been already published, but this problem was not satisfactorily solved for circuits working in the current mode. Therefore, this article presents one of the possible solutions of this problem for circuits working in the current mode derived by graph method.**

Keywords-current mode; voltage mode; voltage graph; current graph; biquad; low pass filter in Sallen-Key structure.

I. INTRODUCTION

In [1] is described a biquad in the current mode (CM), that is shown in Fig. 1.

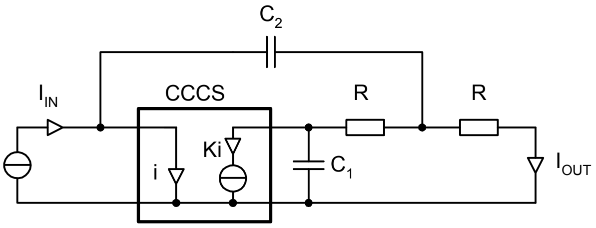

Figure 1. Biquad in the current mode.

We can see, that this is the Sallen-Key low pass filter [2], [3], [4] based on a polynomial structure. An active element is a current control current source (CCCS). The CCCS has current amplification factor marked as *K*.

The CCCS is composed of transistors. But this fact evokes the key problem of this way of CCCS realization, because transistor amplification factor is decreased with increasing frequency. Therefore, current amplification factor *K* decreases with frequency, too.

We consider the high frequency band, now. We know, that amplification factor *K* is reduced to zero at high frequencies. The output current of the biquad would be equal to zero in this case, too.

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II. FORMULATION OF THE PROBLEM

The real CCCS structure has nonzero input resistance *r* (thus $r \neq 0$). Reactance of capacitors nears to zero for frequencies closely to infinite. The amplification factor *K* nears to zero at high frequencies, too.

Thus schematic diagram of considered filter is adapted to form that is shown in Fig. 2.

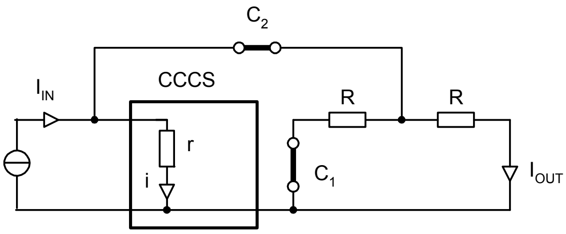

Figure 2. Biquad at the high frequencies.

An input signal goes to the output terminals through passive elements only, now. Thus the current ratio in this case has nonzero value (1)

$$\frac{I_{OUT}}{I_{IN}} = \frac{r}{R + 2 \cdot r}, \tag{1}$$

where I_{IN} is input current, I_{OUT} is output current, *r* is input resistance of CCCS and *R* is resistance of working resistor in the filter.

From (1) is clear evident that current ratio of filter does not decrease to zero at high frequencies. Thus the filter attenuation in the stopband don't increase to infinity, but it is determined by (2)

$$a = -20 \cdot \log\left(\frac{r}{R + 2 \cdot r}\right), \tag{2}$$

where *a* is the attenuation, *r* is input resistance of CCCS and *R* is resistance of working resistor in the filter.

The same problem occurs for Sallen-Key low pass biquad structure working in the voltage mode (VM). Punčochář [5], [6] proposes solution of this problem by following way: plugging another active element (that is an operational amplifier in VM) into the

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feedback loop. This proposed structure (for VM) is shown in Fig. 3.

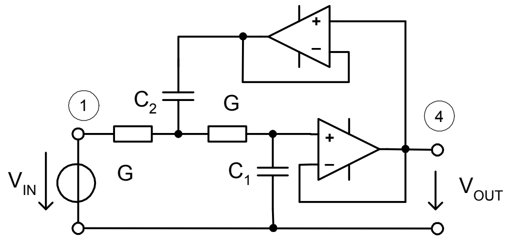

Figure 3. Proposed solution in the voltage mode [5].

III. Proposed Solution

A. Principle of the solution

For the solution of this problem is essential to find a transformation of circuits working in the voltage mode to the current mode [7], [8], [9], [10]. One way of this solution is the signal flow graphs [11], [12], [13]. Signal-flow graphs technique is very useful tool for the analysis and/or synthesis networks [14], [15] [16], many types of SFG´s and different methods of their derivation have been already proposed [17], [18], [19]. Another possibility of derivation is fully graph method which is described bellow.

Consider general circuit in voltage mode from Fig. 4, which is described by the Kirchhoff's Voltage Law (KVL).

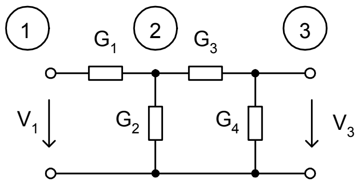

Figure 4. General circuit working in the voltage mode.

This circuit is represented by its MC-graph, which is shown in Figure 5.

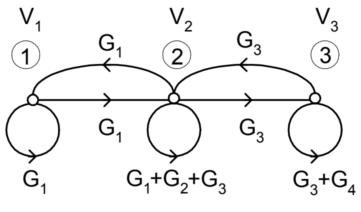

Figure 5. MC-graph of the circuit from Fig. 4.

The shortened graph [2] of this circuit is shown in Fig. 6. From this graph we evaluate the transfer function T as relationship (3).

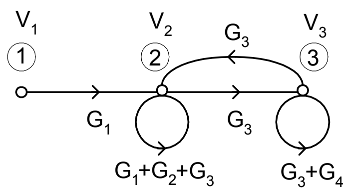

Figure 6. MC-shortened graph of the circuit from Fig. 4.

$$T = \frac{\sum p_{(i)}.\Delta_{(i)}}{V - \sum S^{(K)}.V^{(K)}} = \frac{G_1.G_3}{(G_1 + G_2 + G_3).(G_3 + G_4) - G_3^2} =$$

$$= \frac{G_1.G_3}{(G_1 + G_2).(G_3 + G_4) + G_3.G_4} \qquad (3)$$

We solve the same circuit, now. But this circuit working in the current mode (CM). Thus this circuit must be described by Kirchhoff's Current Law (KCL). Schematic diagram of corresponded circuit is shown in following Fig. 7.

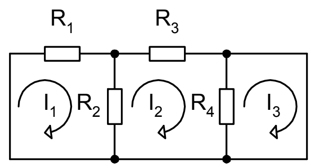

Figure 7. General circuit working in the current mode.

This circuit is represented by its MC-graph, which is shown in Figure 8.

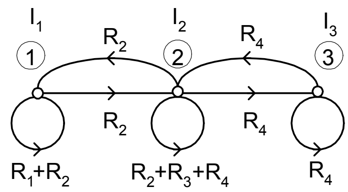

Figure 8. MC-graph of circuit from Fig. 7.

The shortened graph of CM circuit form Fig. 9 is evaluated to form of transfer function T (4).

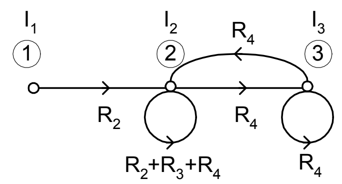

Figure 9. MC-shortened graph of the circuit for the transfer from node 1 to node 3 from Fig. 8.

$$T = \frac{\sum p_{(i)}.\Delta_{(i)}}{V - \sum S^{(K)}.V^{(K)}} = \frac{R_4.R_2}{(R_2 + R_3 + R_4).R_4 - R_4^2} =$$

$$= \frac{R_2}{R_2 + R_3} \qquad (4)$$

After recalculation we may see, that results from (3) and (4) are not equal (5).

$$\frac{R_2}{R_2 + R_3} = \frac{\frac{1}{G_2}}{\frac{1}{G_2} + \frac{1}{G_3}} = \frac{\frac{1}{G_2}}{\frac{G_2 + G_3}{G_2.G_3}} = \frac{G_3}{G_2 + G_3} \qquad (5)$$

Now we consider the transfer in the opposite direction (i.e. from node 3 to node 1), as is shown in Fig. 9. Evaluating of shortened graph of this circuit yields the transfer function T (6).

$$T=\frac{\sum p_{(i)}.\Delta_{(i)}}{V-\sum S^{(K)}.V^{(K)}}=\frac{R_4.R_2}{(R_1+R_2).(R_2+R_3+R_4)-R_2^2}=$$
$$=\frac{R_4.R_2}{(R_1+R_2).(R_3+R_4)+R_1.R_2} \qquad (6)$$

Now, after recalculation we may see, that the transfers (3) for VM and (6) for CM are the same, as shows (7).

$$\frac{R_4.R_2}{(R_1+R_2).(R_3+R_4)+R_1.R_2}=$$
$$=\frac{\frac{1}{G_4}.\frac{1}{G_2}}{(\frac{1}{G_1}+\frac{1}{G_2}).(\frac{1}{G_3}+\frac{1}{G_4})+\frac{1}{G_1}.\frac{1}{G_2}}=$$
$$=\frac{\frac{1}{G_4.G_2}}{\frac{G_1+G_2}{G_1.G_2}\frac{G_3+G_4}{G_3.G_4}+\frac{1}{G_1G_2}}=\frac{\frac{1}{G_4.G_2}}{\frac{(G_1+G_2)(G_3+G_4)+G_3G_4}{G_1.G_2.G_3.G_4}}=$$
$$=\frac{\frac{G_1.G_2.G_3.G_4}{G_4.G_2}}{(G_1+G_2).(G_3+G_4)+G_3.G_4}= \qquad (7)$$
$$=\frac{G_1.G_3}{(G_1+G_2).(G_3+G_4)+G_3.G_4}$$

For described solution was used a Mason-Coates graph, i.e. graph with own loop. The Mason graph, i.e. graph without own loops, can be used, too. But in this case graph solution is not so clearly.

This means that a voltage-mode circuit can be transferred to the circuit in the current mode using graphs. The both graphs have the same structure, only axially symmetrical, as is clear by comparing Fig. 5 and Fig. 8 and/or Fig. 6 and Fig. 10.

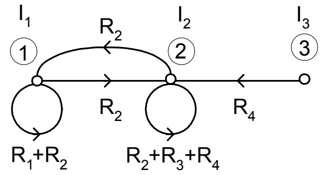

Figure10. MC-shortened graph for transfer from node 3 to node 1 of (i.e. in opposite direction) of circuit from Fig. 8.

B. *Application of the described principle for circuit solwing*

For conversion of circuit in Fig. 3 from the voltage to the current mode is necessary to draw the MC-graph firstly. This graph is shown in Fig. 11a and/or M-graph is shown in Fig. 11b. The coefficients in Fig. 11b are given in (8).

$$a_1=\frac{G}{2.G+sC_1},\ a_2=\frac{sC_2}{2.G+sC_1},\ a_3=\frac{G}{G+sC_1} \qquad (8)$$

This M-graph is in other words a flow-graph of circuit in the voltage mode. The role of this graph is only to show the structure of the circuit, therefore coefficients (8) are not necessary calculated for this purpose (i.e. for transfer between VM and CM).

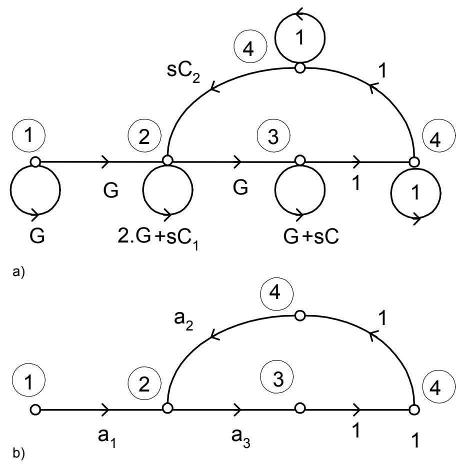

Figure 11. Corresponding voltage (a) and flow (c) graphs.

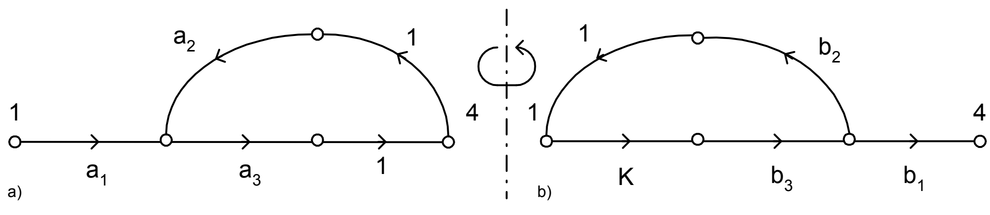

Figure 12. Corresponding voltage (a) and current (b) flow-graphs for convert from VM to CM.

In the second step we draw axis-symmetrical graph for the opposite direct (namely current) mode that is shown in Fig. 12b. Based on graphs from Fig. 12 we may then draw diagram of circuit working in reverse mode (in this case: the current mode), that is shown in Fig. 13.

We can see, that input signal does not cross via passive branch to the output terminals in this circuit, because this signal way is closed by new active element $CCCS_2$.

The element $CCCS_2$ in final Fig. 13 is connected as a current follower (i.e. its $I_{IN}=I_{OUT}$). This solution is similar to previous circuit that is shown in Fig. 3, because operational amplifier in feedback loop is connected as a voltage follower in circuit working in the voltage mode.

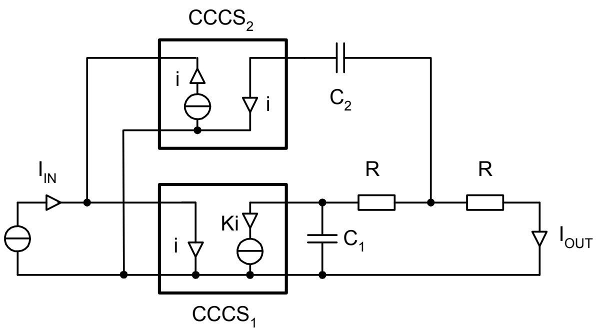

Figure 13. Proposed circuit from Fig. 3 in the current mode.

IV. Conclusion

It is described the usage of graph method to convert circuit between voltage and current mode. This conversion is derived using by the MC-graph.

This method restores the attenuation of the low pass Sallen-Key filter in current mode based on CCCSs as active elements at high frequencies.

The proposed solution is based on the circuit prototype in voltage mode. The Eq. (2) shows fact, that decreasing input resistance *r* evokes increasing of the attenuation *a*. This fact may be expressed for frequencies closely to infinite:

$$\lim_{r \to 0} a(r) = -20 \cdot \lim_{r \to 0} \left\{ \log\left(\frac{r}{R + 2 \cdot r} \right) \right\} = +\infty , \qquad (9)$$

where *a* is the attenuation, *r* is input resistance of CCCS and *R* is resistance of working resistor in the filter.

Thus the limit of *a* of *r* as *r* approaches zero equals infinity.

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