Optimization of filters with grounded OpAmps using "VIV"-graphs

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Abstract: *Novel signal flow graphs are introduced. They facilitate optimization of active filters consisting of OpAmps with grounded inputs. The Tow-Thomas and the Åckerberg-Mossberg structures are typical representatives of such a filter class. In virtue of these graphs two propositions are framed, which enable optimization of the component ratio and dynamic range.*

Introduction

The Tow-Thomas and the Åckerberg-Mossberg second-order filters belong to the well-known filters that consist of the OpAmps with grounded inputs [1]. These circuits are excellent due to their insensitivity to the parasitic input capacitances of OpAmps and are suitable for cascade synthesis of active filters for higher frequencies. Their topology is also convenient for purposes of electronic control of parameters [2].
One of the Tow-Thomas variants of universal filter is in Fig. 1.

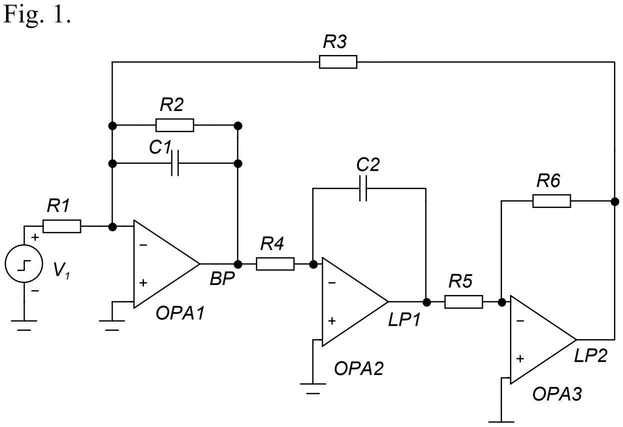

Fig. 1. Second-order three-OpAmp filter.

Amplifier OPA3 is connected as inverting amplifier, OPA1 as a lossy integrator, and OPA2 as an ideal integrator. For the outputs BP/LP1/LP2 the filter behaves as bandpass/lowpass/lowpass filters with parameters as given in Tab. 1.
Some facts can be implied from Tab. 1. The formulae for ω_0, Q, and B provide a procedure how to design filter elements, or - in case of need – how to control electronically a certain filter parameter while fixing others. The designer has always several degrees of freedom at his disposal. He can utilize them for additional optimization, e.g. for the optimization of dynamic range, for the minimization of the influence of real properties, etc.

In this paper, we focus on the optimization of element ratios and on the maximization of the upper bound of the dynamic range. Simple signal flow graphs will be an important tool here. Their application is limited to blocks with grounded OpAmps.

out	$K(s)$	ω_0, Q, B
BP	$\dfrac{-\dfrac{1}{R_1C_1}s}{s^2+\dfrac{1}{R_2C_1}s+\dfrac{R_6}{R_3R_4R_5C_1C_2}}$ $K_{\max}=\dfrac{R_2}{R_1}$	$\omega_0=\sqrt{\dfrac{R_6}{R_3R_4R_5C_1C_2}}$
LP1	$\dfrac{\dfrac{1}{R_1R_4C_1C_2}}{s^2+\dfrac{1}{R_2C_1}s+\dfrac{R_6}{R_3R_4R_5C_1C_2}}$ $K_0=\dfrac{R_3R_5}{R_1R_6}$	$Q=\sqrt{\dfrac{R_2^2R_6C_1}{R_3R_4R_5C_2}}$ $B=\dfrac{1}{R_2C_1}$
LP2	$\dfrac{-\dfrac{R_6}{R_1R_4R_5C_1C_2}}{s^2+\dfrac{1}{R_2C_1}s+\dfrac{R_6}{R_3R_4R_5C_1C_2}}$ $K_0=\dfrac{R_3}{R_1}$	$R_1=R_2=R_3$ *) $R_5=R_6$ *)

Tab. 1. Survey of the properties of filter from Fig. 1. Both maximum transfer $K_{\max}$ of BP filter and DC gain K_0 of LP filters are 1 under conditions *).

Filter description using "VIV"-graphs

Consider the circuit in Fig. 2a). It can be understood as a basic building block of filters with grounded OpAmps. The following equation is true:

$$V_1Y_1+V_2Y_2+...+VY=0 \tag{1}$$

where the symbol „Y" specifies the admittances, which correspond to impedances „Z".
Mason-Coates' graph [3,4] in Fig. 2b) corresponds to this equation. However, equation (1) can be modified to the form

$$V=-ZI_i=-Z\left(V_1Y_1+V_2Y_2+...\right), \tag{2}$$

where I_i is the total current flowing from individual inputs to feedback impedance Z. The corresponding graph is in Fig. 2c). Let us call it „VIV"-graph: input voltages are first transformed into current I_i and this is again converted into voltage through feedback impedance Z. Two simple rules of thumb are valid for the compilation of the „VIV"-graph:

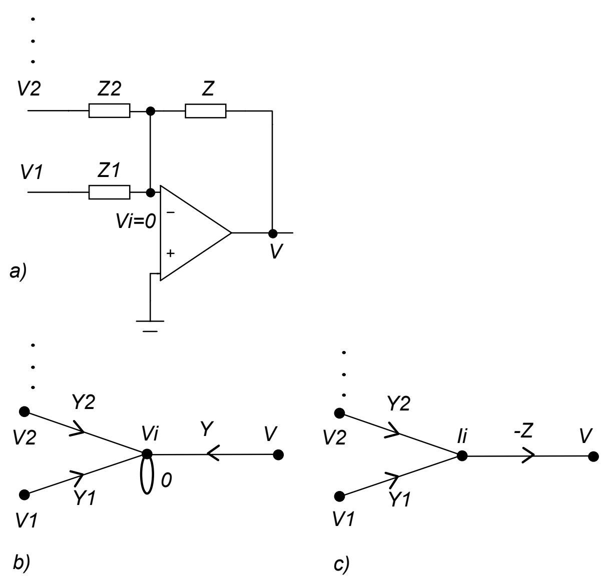

Fig. 2. a) Block with the grounded OpAmp, b) Mason-Coates' graph with the self-loop, c) modified Mason's graph with the self-loop reduction: "VIV"-graph.

1. Directed branches with gains Y_k flow from the nodes of voltage sources V_k to current node I_i. Here, Y_k are admittances of the elements that are connected between the OpAmp input and voltage source V_k.
2. The directed branch with the gain $-Z$ gets out of current node I_i and it leads to the node of the OpAmp output voltage. Here, Z is the impedance of the feedback element that is connected between the OpAmp input and output.

In case of more feedback impedances in parallel (e.g. the block with OPA1 in Fig. 1, where C1 and R2 are in parallel), one can use the following procedures for graph compilation. Either all the impedances in parallel are joined to the resulting impedance Z and graph 2c) is then used, or one of the impedances is chosen as Z and we model the others by the feedback admittance branches that lead from the OpAmp output to current node I_i. The second variant is used for the graph construction of the entire filter from Fig. 1 (see Fig. 3).

Evaluating the graph, we can easily determine all the transfer functions from Tab. 1. Furthermore, the "VIV" graph enables direct observation of the influence of element changes on the properties of transmission to all outputs. The main conclusions will be summarized in two propositions. Similar propositions were conceived earlier [5,6] for certain structures of switched capacitor filters.

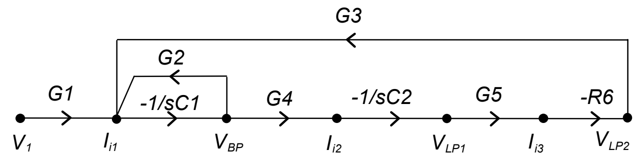

Fig. 3. Signal flow "VIV" graph of filter from Fig. 1.

Propositions resulting from the graph description

Let us consider such a variation of filter elements that the transfer functions to all nodes remain unchanged. The well known possibility is impedance scaling: impedances of all filter elements are multiplied by the same constant a>0. However, further and more specific possibilities result from the properties of "VIV" subgraphs of individual blocks.

The "VIV" graph of the given block in Fig. 2a) consists of current node I_i and of the voltage nodes (one of them is the node of OpAmp output voltage). Varying the elements leads to a change in input current I_i. As is obvious from the "VIV" graph, this change can be neutralized by the modification of impedance Z to leave the output voltage unchanged. To have voltages/transfer functions to all the nodes unchanged, the variation of filter elements must be performed only in such a way that both the forward-path gains from the input to individual outputs and all the loop gains must remain unchanged.

There are analogous ways of changing the transfer to a concrete OpAmp output and preserving voltages at the outputs of the other OpAmps.

Proposition 1. *We multiply by a > 0 impedances of all elements that are connected to the OpAmp input. Then neither the OpAmp output voltage nor the other nodal voltages are changed. In other words, the transfer functions from the input to all the nodes remain unchanged.*

Proof of this proposition is easy: All forward-path gains from the input to a given output that go through the block considered comprise the product of the admittance, connected to the input, and the feedback impedance. This product is independent of the multiplication described in proposition 1. If the given block is part of feedback loops, there can be generally two types of loop: **1**. Loops of the local feedback inside the block (see the loop with the gain –G2/sC1 in Fig. 3).

They are due to more feedback impedances in parallel. Then the loop gain is given by the sum of products of impedance Z and of the admittances of the other feedback elements. These products are also unchanged. **2.** Loops of the global feedback through more blocks. The gains of these loops comprise products of feedback impedance Z and the admittances connected between the OpAmp input and the output of the other amplifier in the loop. These products are also unchanged. We can conclude that neither the denominator of all the transfer functions nor the numerators are changed by the above operation.

This proposition can be utilized for the minimization of the ratios of filter elements.

Proposition 2. *We multiply by a > 0 impedances of all elements that are connected to the OpAmp output. Then the OpAmp output voltage will increase a-times, and the other nodal voltages remain unchanged. In other words, the transfer function from the input to the OpAmp output will be multiplied by a, and the transfer functions to the other nodes remain unchanged.*

It should be noted that only the feedback impedance of the given block and the input impedance of the cascading block are connected to the OpAmp output. In the "VIV" graph, these elements represent a forward path leading to the current node of the immediately following block. The gain of this path remains constant after multiplying both impedances by the same number. That is why the gains of global feedback loops that comprise the given path, are preserved. The gain preservation of the prospective local feedback loop is ensured by the same mechanism. The only thing that is changed is the gain of the forward path between the current node and the output node of the given block (it is changed a-times). Thus proposition 2 is proved.

This proposition can be utilized for the optimization of the dynamic range of the whole filter.

Optimization example

Let us consider the filter in Fig. 1, which is designed as a bandpass filter with the maximum gain 0 dB at the output BP. The preliminary design leads to the component values

R1=R2=R3=24kΩ, R4= 955Ω, R5=R6=1kΩ,
C1=C2=330pF, (3)

which correspond to the following filter parameters:

f_0 =100.7kHz …	central frequency
Q =5.01 …	quality factor
B =20.1kHz…	3-dB bandwidth.

The 50MHz OpAmp AD826 has been selected for realization. Simulation results (MicroCap VI, Spice models) are in Fig. 4a). The gain peaks measured around the frequency 100kHz are as follows: 0.3 dB for the BP output, 14.3 dB for outputs LP1 and LP2.

It is obvious that the upper bound of the dynamic range is not optimized: OPA2 and OPA3 will saturate for relatively low input signal because their gain peaks are 14 dB above the peak of BP output. The required lowering by 14 dB corresponds to the number $10^{14/20} \doteq 5$.

In the first step, we lower five times the transfer to the LP1 output. According to proposition 2, we must increase C2 five times and decrease R5 five times: C2=1.65nF, R5=200Ω. The corresponding responses are in Fig. 4b). Note the modification of the bandpass response in the low-frequency region due to the real properties of OpAmps.

Now we lower five times the transfer to output LP2, i.e. we reduce five times R6 and R3: R6=200Ω, R3=4.8 kΩ. The responses in question are in Fig. 4c). The upper bound of the dynamic range is now optimized.

Let us use proposition 1 for final filter optimization. Applying this proposition to the filter leads to the following:

we split the passive components into three independent sets:

1. R1, R2, R3, C1
2. R4, C2
3. R5, R6

The elements of set No. i represent the resistors and capacitors that are connected to the input of OpAmp No. i. Then if we increase resistances in an arbitrary set a-times and if simultaneously we decrease capacitances in the same set a-times, where a>0, then the transmission properties of the filter will not be changed.

We decide to change capacitance C2 back from 1.65nF to 330pF. C2 belongs to set No. 2. That is why we increase R4 from 955Ω to 4775Ω. Then we modify R5 and R6 from set No. 3 to original values of 1kΩ. The final frequency responses are in Fig. 4d).

Conclusion

The "VIV" graphs described are suitable for a fast analysis of circuits with OpAmps with grounded inputs. On their basis two propositions are stated, which enable us to subsequently optimize the upper bound of the dynamic range and to optimize of the element values and ratios according to the designer's requirements.

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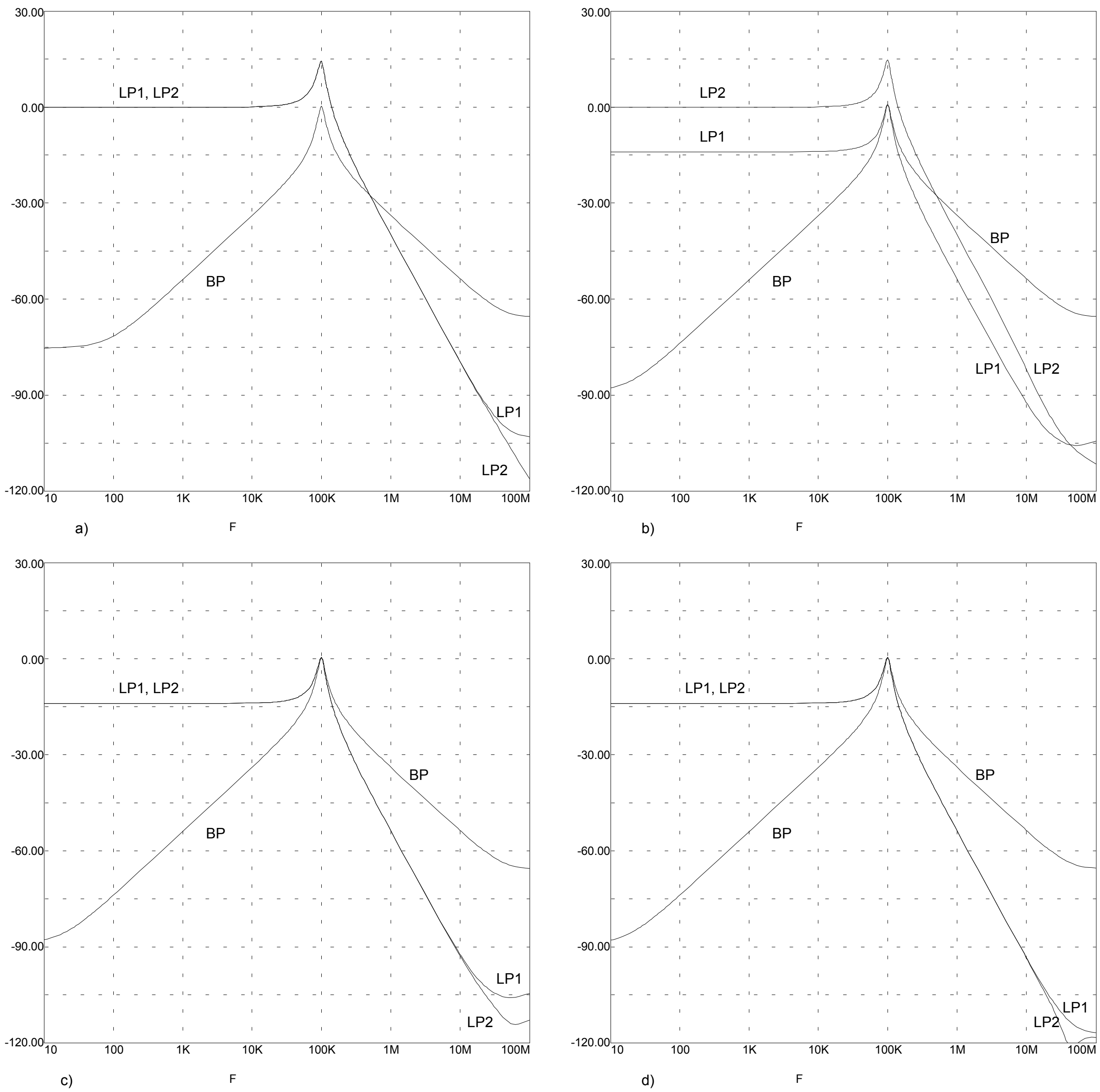

Fig. 4. Frequency responses of filter from Fig. 1, a) element values according to (3), b) lowering the gain peak in LP1 output to the level of BP peak, c) lowering the gain peak in LP2 output to the level of BP peak, d) final responses after the overall optimization of filter elements.