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NOVEL HIGH–ORDER ALLPASS FILTERS EMPLOYING VOLTAGE CONVEYORS

Kamil Vrba — Josef Čajka *

The design procedure for a high-order allpass filter using a new active element (voltage conveyor) is described. Three types of voltage conveyors are given: generalized voltage conveyors, concrete voltage conveyors and universal voltage conveyors. The proposed network has a minimum number of active elements. It works in the voltage mode, can be loaded by an arbitrary one-port element and can be also easily transformed into its adjoint counterpart.

K e y w o r d s: voltage conveyors, allpass filters

1 INTRODUCTION

We try to introduce into the circuit theory an n-port ($n \geq 3$) *voltage conveyor* as a counterpart to the current conveyor. The driving quantity is in this case the nodal voltage V^* applied only to one *voltage port*, the live terminal of which is denoted by symbol x. An independent voltage $V_x = V^*$ is *conveyed* with the positive or the negative sign *always* to the *output ports* z_j ($j = 1, 2, \ldots, Z$), but only *sometimes* to the *current ports* y_i ($i = 1, 2, \ldots, Y$). Independent nodal currents I_{yi} are always conveyed to the voltage port x with the plus or the minus sign, whereas the remaining independent nodal currents I_{zj} are never conveyed to the voltage port x. The sum of all independent currents is $Y + Z = n - 1$.

The number of current ports Y characterizes the *conveyor kind*, the number of current ports with conveyed voltages V^* specifies the *conveyor class*.

A useful tool for the design procedure is a *generalized voltage conveyor* (GVC), which represents a family of concrete voltage conveyors. For the design of the allpass filter a generalized *four-port second-kind voltage conveyor*, the schematic symbol of which is shown in Fig. 1, is suitable. This hypothetical device is defined by the following matrix equation:

$$\begin{bmatrix} I_x \\ V_{y1} \\ V_{y2} \\ V_{z1} \end{bmatrix} = \begin{bmatrix} 0 & a_1 & a_2 & 0 \\ b_1 & 0 & 0 & 0 \\ b_2 & 0 & 0 & 0 \\ c & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} V_x \\ I_{y1} \\ I_{y2} \\ I_{z1} \end{bmatrix} \tag{1}$$

The letters a_1, a_2, b_1, b_2, c are the so-called *conveyance coefficients*. The choice of coefficients then determines a concrete voltage conveyor. A special case of the above GVC was published in [1] and denoted as CDBA (Current Differencing Buffered Amplifier). Its conveyance coefficients are: $a_1 = +1$, $a_2 = -1$, $b_1 = b_2 = 0$, $c = +1$.

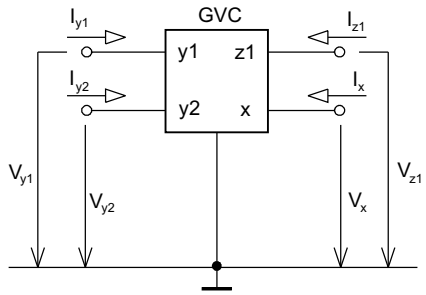

Fig. 1. Schematic symbol of a generalized four-port second-kind voltage conveyor.

The properties of voltage conveyors are similar to those of current conveyors (*eg*, frequency passband).

In this paper, we use the following notation of the live VC terminals when drawing concrete conveyor of class zero ($b_1 = b_2 = 0$) in the circuit diagram: The voltage port is denoted by the letter $x+$, the output port denoted $z+$ corresponds to $c = +1$, the notation $z-$ signifies that $c = -1$. Since $b_i = 0$ ($i = 1, 2$), all terminals y_i remain without any notation. The signs of the current conveyance-coefficients a_1 and a_2 are denoted on the connection lines to the y_i terminals by small black triangles oriented into the VC element if $a_i = +1$ or out of the element if $a_i = -1$.

2 DESIGN PROCEDURE

Let us return to the high-order allpass filter (AF) design published recently in this journal [2]. It is possible to reduce the number of active elements if we use a new building block, *ie*, the above VC. We have to realize a two-port network with the voltage transfer function as follows:

$$H(s) = \frac{V_{out}}{V_{in}} = \frac{M(s)}{A(s)} = \frac{P(-s)}{P(s)} = \frac{\sum_{i=0}^{n} (-1)^i \alpha_i s^i}{\sum_{i=0}^{n} \alpha_i s^i}, \tag{2}$$

* Brno University of Technology, Faculty of Electrical Engineering and Communication, Department of Telecommunications, Purkyňova 118, 612 00 Brno, Czech Republic, e-mail: vrbak@feec.vutbr.cz

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where $P(s)$ is the polynomial of complex frequency variable s with coefficients α_i.

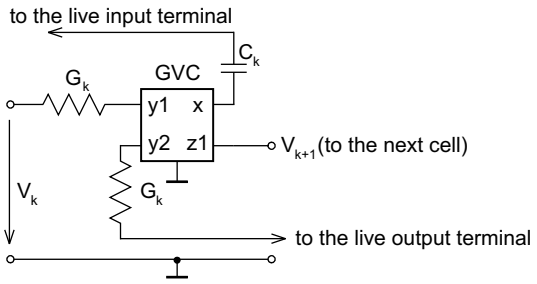

Fig. 2. A building cell containing a generalized voltage conveyor

We have proposed a building cell the circuit diagram of which is shown in Fig. 2. Let us suppose that the general voltage conveyor in the diagram is of class zero, *ie*, $b_1 = b_2 = 0$. The subscript k in Fig. 2 relates to the serial cell-number, beginning from the input port. We can connect n such basic building cells in cascade.

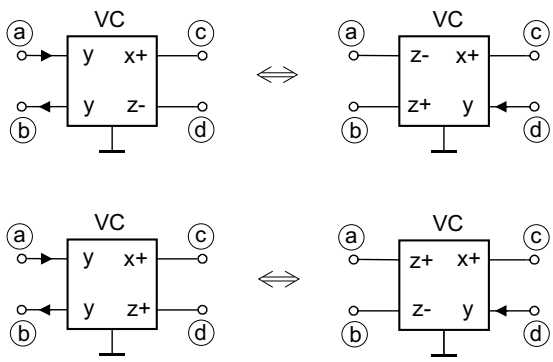

Fig. 3. Symbols of concrete voltage conveyors of class zero and their adjoint counterparts

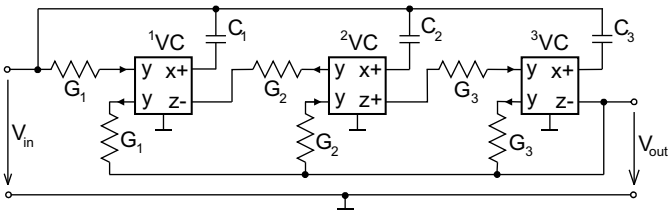

Fig. 4. A third-order allpass filter using VCs working in the voltage mode

We have computed the transfer functions $H(s)$ for different numbers of basic cells in cascade. The following relations are valid:
If $n = 1$, then

$$M(s) = -a_{11}c_1G_1 + sc_1C_1 \tag{3}$$

$$A(s) = a_{21}c_1G_1 + sC_1\,. \tag{4}$$

The last digit in the conveyance-coefficient subscript corresponds to the serial number of the GVC element in the cascade.

When comparing (3) and (4) with the numerator and denominator in (2), we obtain: $c_1 = -1$, $a_{11}c_1 = -1$ and $a_{21}c_1 = +1$. Therefore $a_{11} = +1$ and $a_{21} = -1$. A similar comparison can be made for $2, 3, \ldots$.

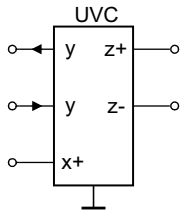

Fig. 5. Schematic symbol of a universal five-port voltage conveyor

Let us consider the case when $n = 3$. Then

$$M(s) = -a_{11}c_1a_{12}c_2a_{13}c_3G_1G_2G_3 + sc_1a_{12}c_2a_{13}c_3C_1G_2G_3 - s^2c_2a_{13}C_1C_2G_3 + s^3c_3C_1C_2C_3 \tag{5}$$

$$A(s) = a_{21}c_1a_{12}c_2a_{13}c_3G_1G_2G_3 - sa_{22}c_2a_{13}c_3C_1G_2G_3 + s^2a_{23}c_3C_1C_2G_3 + s^3C_1C_2C_3\,. \tag{6}$$

Comparing eqns (5) and (6) with the numerator and denominator of (2) we get:

$$c_3 = -1\,,\ a_{13} = +1\,,\ a_{23} = -1\,,\ c_2 = +1\,,\ a_{12} = -1\,,$$
$$a_{22} = +1\,,\ c_1 = -1\,,\ a_{11} = +1\,,\ a_{21} = -1\,.$$

Finally, when considering an nth-order AF we can formulate a simple rule for defining conveyance-coefficients of concrete voltage conveyors connected in cascade:

$$b_{1k} = b_{2k} = 0,\ a_{1k} = (-1)^{k-1} \text{ and } c_k = a_{2k} = (-1)^k, \tag{7}$$

where the letter $k = 1, 2, 3, \ldots, n$ denotes the position of each VC in the cascade.

The rule for creating the polynomial coefficients in (2) is also simple and may be generalized from eqns (5) and (6). We can write

$$\alpha_0 = \prod_{i=1}^{n} G_i\,,\quad a_k = \prod_{i=1}^{k} C_i \prod_{i=k+1}^{n} G_i\,,\quad \alpha_n = \prod_{i=1}^{n} C_i\,. \tag{8}$$

For example, if $n = 6$, it holds:

$$\alpha_0 = G_1G_2G_3G_4G_5G_6\,,\qquad \alpha_1 = C_1G_2G_3G_4G_5G_6\,,$$
$$\alpha_2 = C_1C_2G_3G_4G_5G_6\,,\qquad \alpha_3 = C_1C_2C_3G_4G_5G_6\,,$$
$$\alpha_4 = C_1C_2C_3C_4G_5G_6\,,\qquad \alpha_5 = C_1C_2C_3C_4C_5G_6\,,$$
$$\alpha_6 = C_1C_2C_3C_4C_5C_6\,.$$

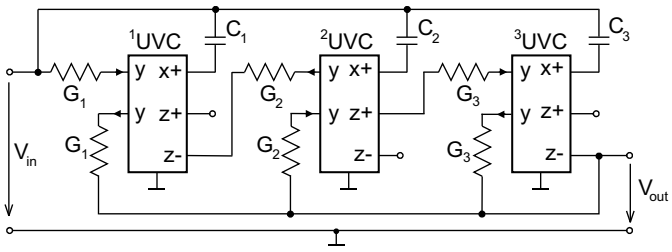

Fig. 6. Realization of the third-order allpass filter in Fig. 4 using UVC elements

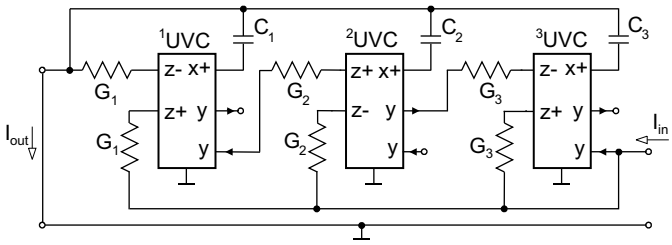

Fig. 7. An allpass filter adjoint to that in Fig. 6 operating in the current mode

Equation (7) shows that two different *concrete* second-kind voltage conveyors must be used to realize an nth-order allpass filter. A concrete conveyor lying in the odd places in the cascade is shown on the left side of Fig. 3a, the conveyor on the left side of Fig. 3b is connected in the even places in the cascade. A circuit diagram of a third-order allpass filter using the proposed concrete VCs is shown in Fig. 4.

All the designed allpass filters can be realized with the aid of a *universal five-port voltage conveyor* (UVC), the schematic symbol of which is drawn in Fig. 5. This element is described by the following equation set: $V_{z+} = V_{x+}$, $V_{z-} = -V_{x+}$, $I_{x+} = I_{y+} - I_{y-}$. The realization of the network in Fig. 4 using UVCs is shown in Fig. 6.

An arbitrary *zero-class voltage conveyor* (the independent voltage V_{x+} is not conveyed to the current ports) has always its adjoint counterpart. We obtain it in the following way: The voltage-port $x+$ remains the same. The output ports (denoted as z_i) must be changed to current ports (denoted as y_j), the current ports (denoted as y) must be changed to the output ports (denoted as z). Simultaneously, all the conveyance-coefficient signs must be changed. Two examples of adjoint elements are shown in Fig. 3, where the symbol $\Leftrightarrow$ denotes adjointness. Evidently, the second-kind and the first-kind four-port conveyors are mutually adjoint.

The circuit diagram of a two-port adjoint to that in Fig. 6 is shown in Fig. 7. This two-port network works therefore in the current mode.

3 CONCLUSION

The nth-order allpass filter just proposed has only n active elements (UVCs), $2n$ resistors and n capacitors, whereas the required number of active elements in [1] and [2] is $n+1$ (CDBAs and UCCs, respectively), in [3] as many as $n+2$ active elements (MO-OTAs). The transfer function of the proposed two-port network has a canonic form.

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Kamil Vrba(Prof, Ing, CSc) was born in Slavkovice, Czech Republic, in 1949. He received the Ing (MSc) degree in electrical engineering, in 1972, and the CSc (PhD) degree in 1977, both from the Technical University, Brno. He joined the Institute of Telecommunications at the Faculty of Electrical Engineering and Computer Science of the TU in Brno and since 1997 is in a Full Professor position. His research work is concentrated to problems aimed to accuracy of analog circuits.

Josef Čajka (Prof, Ing, DrSc) was born in Vracov, Czech Republic, in 1919. He received the Ing (MSc) degree in electrical engineering from VUT Brno, in 1946, and the CSc (PhD) degree from the Military Academy in Brno, in 1961, and the DrSc degree from the TU Brno, in 1981. He has been researcher at Baťa Corp. in Zlín (1947-1951), then joined the Military Academy in Brno and in 1972 the Technical University in Brno. Since 1984 he has been Professor Emeritus. His research and teaching interest was the circuit theory.