

Fully Balanced Voltage Differencing Buffered Amplifier and its Applications

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Abstract—An active circuit element, namely Fully Balanced Voltage Differencing Buffered Amplifier (FB-VDBA), is introduced. Its input stage is composed of a fully-differential operational transconductance amplifier (OTA). Voltage buffer is connected to each OTA output. Several applications are proposed which demonstrate the element's versatility. The results of SPICE simulation and measurements on experimental specimen are included.

I. INTRODUCTION

A number of active elements for analog signal processing, based on various principles, have been proposed. Their detailed review is given in [1]. Some of them were designed such that the original topology was generalized to a topology with differential inputs or outputs, or to fully balanced structures. Two motivation factors exist for such a generalization: 1) Increasing the universality of the element and extending the area of its potential applications. 2) Resistance to external noise sources, particularly increased immunity of analog subcircuits to digital noise and interference. The Differential Voltage Current Conveyor (DVCC) [2], a generalization of conventional second-generation current conveyor CCII [3], is a typical representative of Item 1. Similarly, Item 2 can be represented by the Fully Differential Current Conveyor (FDCCII) [4], sometimes also called the Fully Balanced CCII (FBCCII) [5]. The well-known commercial integrated instrumentation operational amplifiers with differential structures [6] are based on the so-called three-OpAmp structure [7]. Other examples of the generalization of classical structures of active elements to their differential versions are summarized in [1].

In [1], the circuit principle called VDBA (Voltage Differencing Buffered Amplifier) is proposed as an alternative to the existing CDBA (Current Differencing Buffered Amplifier) [8]. The input stage of VDBA is composed of the differential-input OTA. The voltage buffer is connected to the OTA current output. Note that this structure is semi-differential. A method of augmenting the voltage buffer by an inverting output is also mentioned in

[2], with the corresponding abbreviation DOBA (Differential Output Buffered Amplifier). Replacing the voltage buffer in the VDBA by the DOBA yields a fully differential circuit element. According to the methodology in [1], such an element should be specified as VDDOBA (Voltage Differencing Differential Output Buffered Amplifier).

A specific drawback of the VDDOBA consists in the necessity to implement both the voltage buffer and the inverter. Among other shortcomings, it implies a more complicated circuit structure. Therefore, another solution is proposed in this paper, which is based only on voltage buffers, concurrently providing more versatility than VDDOBA. The latter was the main motivation factor for designing this new circuit element. To differentiate it from VDDOBA, it was termed FB-VDBA (Fully Balanced VDBA).

II. FULLY BALANCED VDBA

The proposed schematic symbol and behavioral model of the FB-VDBA are in Figs 1 (a) and (b). The model can be described by the following set of circuit equations:

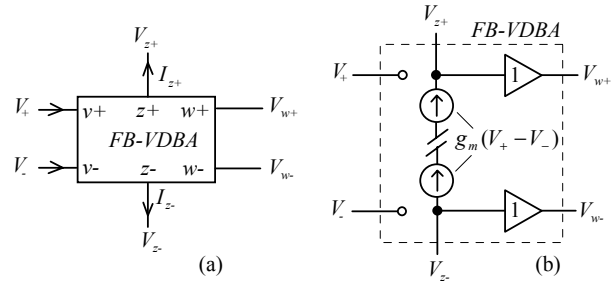


Figure 1. (a) Schematic symbol, (b) behavioral model of FBVDBA.

$$\begin{pmatrix} I_{z+} \\ I_{z-} \\ V_{w+} \\ V_{w-} \end{pmatrix} = \begin{pmatrix} g_m & -g_m & 0 & 0 \\ -g_m & g_m & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} V_+ \\ V_- \\ V_{z+} \\ V_{z-} \end{pmatrix}. \quad (1)$$

It should be noted from the above that FB-VDBA has a pair of high-impedance voltage inputs $v+$ and $v-$, a pair of high-impedance current outputs $z+$ and $z-$, and two low-impedance voltage outputs $w+$ and $w-$. The input stage can be simply implemented by a differential-input differential-output OTA. When connecting two identical grounded resistors to the $z+$ and $z-$ terminals, the voltage drops on them will be of equal value but different directions. The output voltages of $w+$ and $w-$ terminals thus will be $V_{w-} = -V_{w+}$. In this way, the voltage inversion is achieved without the utilization of voltage inverter.

An example of FB-VDBA implementation by two integrated circuits OPA860 [9] is shown in Fig. 2. OPA860 contains the so-called diamond transistor and fast voltage buffer. The diamond transistor with its terminals E (emitter), B (base) and C (collector) acts as a current-controlled current conveyor CC-CCII+ [10] with X, Y, and Z terminals, with resistance $R_x = 1/g_{mT}$ of the x terminal, where g_{mT} is the diamond transistor transconductance, electronically controllable via the bias current. The diamond transistor can be also considered as an OTA, because the current flowing from the collector and also from the emitter is proportional to the transconductance and to the base-emitter voltage. In order to increase the linearity of collector current versus input voltage, a degenerating resistor $R_g \gg R_x$ is added in series to the emitter [9]. Then the total transconductance decreases to an approximate value of $1/R_g$. The pair of transistors $T+$ and $T-$ in Fig. 2 is connected such that it forms a differential-input differential-output OTA. The properly designed value of R_g ensures a high input resistance of the amplifier and also minimizes the influence of the voltage offset of transistors on the offsets of currents I_z . In the extreme case, R_g can be replaced by a short circuit. Then the OTA transconductance will be determined only by the internal transconductances of diamond transistors, thus enabling its electronic control. Then, however, we lose all the benefits resulting from the effects of negative feedback caused by the degenerating resistor.

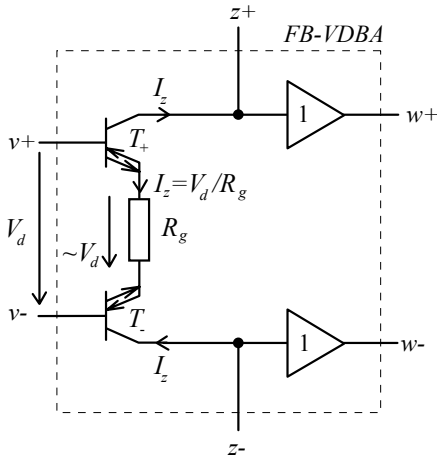


Figure 2. FB-VDBA implementation by two OPA860.

III. EXAMPLES OF FD-VDBA APPLICATIONS

Fig. 3 shows the basic circuit employing FD-VDBA and two grounded impedances Z_+ and Z_- . For the equality $Z_+ = Z_- = Z = R$, the circuit represents a conventional fully-differential amplifier of differential input voltage V_d with zero output common-mode voltage and with differential output voltage $V_{dout} = 2g_m R V_d$.

When implementing the above impedances by a pair of identical capacitors, the circuit in Fig. 3 will represent a fully-differential integrator. However, a nonsymmetrical version can also be useful when the impedances Z_+ and Z_- are of different characters. Then two different transfer functions can be implemented by a single active element. This fact can be utilized, for example, to increase the number of degrees of freedom when designing active filters.

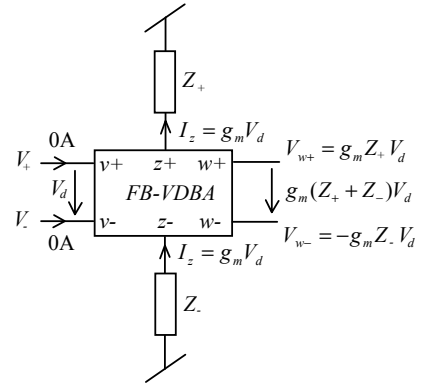


Figure 3. FD-VDBA in the basic configuration.

A fully-differential voltage inverter is shown in Fig. 4. In addition, this circuit simulates a floating resistor with the resistance $R_{in} = 1/g_m$ between the $v+$ and $v-$ terminals.

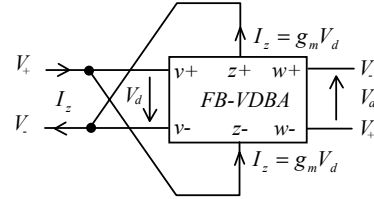


Figure 4. FD-VDBA as a floating resistor and fully-differential voltage inverter.

It is well known that the lossless floating inductor can be simulated by means of two OTAs [11]. That is why it can be also done with two FB-VDBAs. Utilizing the FB-VDTA universality, a lossy inductor can be synthesized via only one active element, see Fig. 5 (a). A simple analysis leads to the following formula for the impedance between terminals A and B:

$$Z_{A-B} = \frac{1}{g_m} + s \frac{RC}{g_m}. \quad (2)$$

This implies that the circuit simulates a series connection of the inductor with the inductance RC/g_m and the lossy resistor with the resistance $1/g_m$. Such a circuit can then be used, for example, for an economical synthesis of lossy ladder filters.

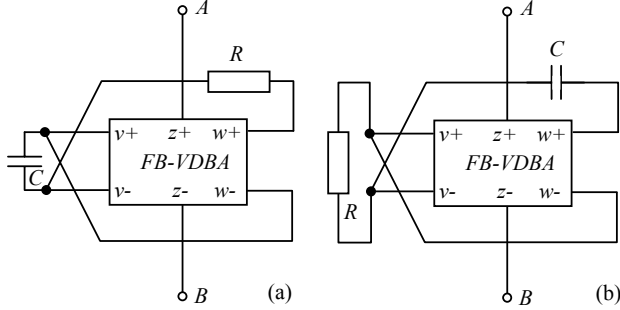


Figure 5. Simulation of a lossy (a) floating inductor, (b) capacitance multiplier.

The impedance between terminals A and B of the circuit in Fig. 5 (b) is

$$Z_{A-B} = \frac{1}{g_m} + \frac{1}{sRCg_m}, \quad (3)$$

and thus it represents a series connection of a capacitor with the capacitance RCg_m and the lossy resistor with the resistance $1/g_m$.

An example of the universal voltage-mode biquad with two FB-VDBAs is given in Fig. 6. This filter provides one high-impedance voltage input (V_{in}), four low-impedance voltage outputs (V_{HP} , V_{BP} , $-V_{BP}$, V_{LP}), and also two high-impedance current outputs, when currents I_{HP} and I_{BP} flow into the grounded loads R_{HP} and R_{BP} .

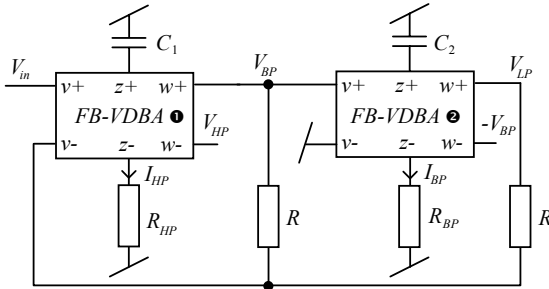


Figure 6. Universal voltage-mode biquad.

An analysis of circuit in Fig. 6 yields the following transfer functions:

$$\begin{aligned} \frac{V_{HP}}{V_{in}} &= \frac{-g_{m1}R_{HP}s^2}{D}, \quad \frac{V_{BP}}{V_{in}} = \frac{s g_{m1}/C_1}{D}, \quad \frac{V_{LP}}{V_{in}} = \frac{\frac{g_{m1}g_{m2}}{C_1C_2}}{D}, \\ \frac{I_{HP}}{V_{in}} &= \frac{-g_{m1}s^2}{D}, \quad \frac{I_{BP}}{V_{in}} = \frac{-s \frac{g_{m1}g_{m2}}{C_1}}{D}, \end{aligned} \quad (4)$$

where

$$D = s^2 + s \frac{g_{m1}}{2C_1} + \frac{g_{m1}g_{m2}}{2C_1C_2}. \quad (5)$$

Equations (4) and (5) confirm that the circuit from Fig. 6 is a universal 2nd-order filter, providing the transfer functions of LP-, BP-, and HP-types. The natural frequency ω_0 and the quality factor Q can be derived from (5) as follows:

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{2C_1C_2}}, \quad Q = \sqrt{2 \frac{C_1}{C_2} \frac{g_{m2}}{g_{m1}}}. \quad (6)$$

The symbols g_{m1} and g_{m2} represent the transconductances of FB-VDBAs No. 1 and No. 2. The values of equal resistances R of both feedback resistors in Fig. 6 do not affect the above parameters. Resistors R make for summing up the voltages V_{BP} and V_{LP} . For equal resistances, the summing voltage is divided by two and led to the v- input of active element No. 1. The factor „2“ then appears also in formulae (6) for ω_0 and Q . Note from (5) and (6) that the value of the low-frequency transfer V_{LP}/V_{in} of lowpass filter and that of the maximum transfer V_{BP}/V_{in} of bandpass filter are 2. This can be useful when it is necessary to compensate the voltage drop on the matching circuit between the coaxial cable and the filter input. The voltage gains of the V_{HP} and $-V_{BP}$ sections can be set by means of resistors R_{HP} and R_{BP} independently of the parameters ω_0 and Q .

IV. EXPERIMENTAL VERIFICATION

For the purposes of experimental verification of applications employing FB-VDBA, this circuit element was implemented on the basis of the topology in Fig. 2, and its corresponding SPICE model was compiled with the utilization of the original SPICE models of OPA860 by Texas Instruments (Rev. B - Revised 4/25/06) [9]. A complete printout of SPICE subcircuit of FD-VDBA is shown in Table I.

TABLE I. SPICE MODEL OF FB-VDBA BASED ON DIAMOND TRANSISTORS.

```
.subckt FBVDBA v+ v- z+ z- w+ w- params: Rg=470
Vcc Vcc 0 5V
Vee Vee 0 -5V
Radj1 adj1 Vee 330
Radj2 adj2 Vee 330
Rb1 v+ b1 100
Rb2 v- b2 100
XQ1 b1 z+ e1 adj1 Vcc Vee OPA860_OTA
XQ2 b2 z- e2 adj2 Vcc Vee OPA860_OTA
Xbuf1 z+ w+ Vcc Vee OPA860_BUF
Xbuf2 z- w- Vcc Vee OPA860_BUF
Rg e1 e2 {Rg}
.ends FBVDBA
```

As shown in Tab. I, OPA860 was supplied with symmetrical voltages of $\pm 5V$. According to the datasheet [9], internal transconductances g_{mT} of both diamond transistors were set to ca 100mS via auxiliary resistors R_{adj1} and R_{adj2} , and the corresponding emitter resistances are ca 10 Ω . These values should be taken into account when designing the resistances R_g , which operate in series with the emitter resistances. Based on the recommendation in [9], auxiliary 100 Ω resistors were included in series with transistor bases.

The universal filter in Fig. 6 was selected for the exploratory verification. It was designed and manufactured for the parameters $f_0 = \omega_0/(2\pi) = 1$ MHz, $Q = 1$. The parameters of passive components were designed by means of Eqs (6) as follows: $C_1 = C_2 = 330$ pF, $R_{m1} = 1/g_{m1} = 235$ Ω , $R_{m2} = 1/g_{m2} = 470$ Ω . The „ R_m “ resistance includes the R_g resistance from Fig. 2 and two 10- Ω emitter resistances of each transistor. That is why $R_{g1} = 225$ Ω , $R_{g2} = 450$ Ω . The design value of remaining resistances in the circuit from Fig. 6 was 470 Ω .

The measured frequency responses of the biquad are compared with results of SPICE AC analysis in Fig. 7. The curves also include a gain drop on the input block of the impedance matching. These results correspond well with the design intentions. The roll-off effect of the high-pass section near 100 MHz is caused by the frequency limitations of the diamond transistors.

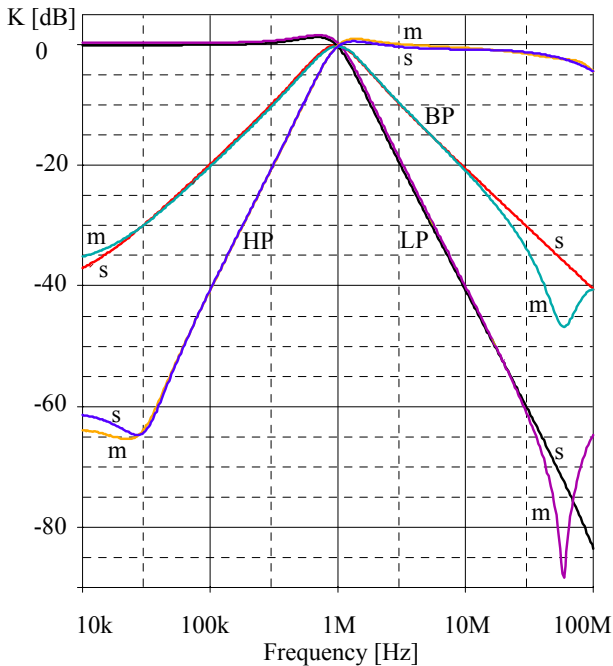


Figure 7. Frequency responses of the biquad in Fig. 6: simulated in PSPICE (s), measured (m).

V. CONCLUSIONS

The circuit element FB-VDBA, described in this paper, is designed primarily for voltage-mode analog signal processing. It starts from the well-known circuit principle of the CDBA (Current Differencing Buffered Amplifier), where its input unit is replaced by a fully-differential OTA, and its output section is extended by an additional voltage buffer. The FB-VDBA is of the fully-differential structure. It is shown in the paper that there are two different methods of utilizing the FD-VDBA. If the application circuit is also symmetrical, then one can profit from the well-known advantages of fully-balanced structures. An intentional violation of the symmetry yields additional degrees of freedom for designing concrete applications. It is also shown that FB-VDBA can be easily made up from commercial integrated circuits. Measurements and SPICE simulations confirm the correct operation of FB-VDBA in the universal 2nd-order filter in the frequency region up to ca 100 MHz.

ACKNOWLEDGMENT

Research described in the paper was supported by the Czech Grant Agency under grants 102/08/0851 and 102/09/1628, by the research programmes of BUT No. MSM0021630503 and UD Brno No. MO FVT0000403, by the European Community's Seventh Framework Programme under agreement No. 230126, and by the ENIAC European programme E3CAR.

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