Advanced Voltage Controlled Amplifier for Volume Expanders

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Abstract: - In this paper a design of an advanced voltage controlled amplifier is discussed. This amplifier is supposed to be employed in audio signal processing systems, for instance volume expanders and. The design has been processed with the help of the Maple software and the results have been verified by numbers of simulations, some of which were also included in this paper.

Key-Words: operational amplifier, voltage-controlled amplifier, audio processing, VCA design

1 Introduction

Voltage-controlled amplifiers (VCAs) are widely used in audio systems for several purposes. In this case a voltage-controlled amplifier was designed in order to be used in audio volume expander with the range of 10 dB. Audio recordings are usually processed by dynamic range compression which should ensure a better signal-to-noise ratio and lower demands on the output power of the reproducing device. On the other hand, this compression leads to dynamic range distortion that can, in some cases, end in disruptive effects. Because it is usually not known how the parameters of the dynamic compression were set at the moment of audio signal processing, it is impossible to process the reverse expansion. Nevertheless there is still a possibility to make an estimation of these parameters.

Let us expect we have the proper driving unit and need the executing circuit – a low-distortion amplifier the gain of which can be set by the external control voltage. The gain is adjustable within the range of 0 to + 10 dB and the amplification factor is linearly dependent on the driving voltage (1 to 3.25 V). There are several possibilities how to achieve this. One could for example employ a CC-CFA application (modified for larger voltages) as shown in [1], or operational transconductance amplifiers [2], but all these concepts seem too complex to this application. Another possibility, utilizing a discrete BJT differential amplifier driven by the bias current, suffered from insufficient input voltage swing. For these reasons we decided to build a circuit that employs one quad low noise amplifier and a unipolar transistor connected as a driven resistor. The linearity of the unipolar transistor for large audio signals is ensured by the local feedback according to [5] and the linearity of amplification factor dependence on the control voltage is ensured by using a complementary reference amplifier. The accuracy of this kind of linearization is highly dependent on how the device parameters in both amplifiers are matched together. For this reason, several simulations were made to verify the proper function of the circuit.

2 Circuit description

This chapter provides a description of the appropriate circuit.

2.1 General description

Generally, the circuit can be particularized into several blocks, as can be seen in Fig. 1. The basic requirements are as follows: the input gain is variable in the range of - 10 to + 10 dB. At the nominal input voltage of 0.775 V (0 dBu) the overexcitation of the whole circuit must be at least 10 dB. Considering the maximum amplification factor of 10 dB, minimal voltage swing of 20 V must be ensured at the output of the circuit. To achieve this, the optimal power supply voltage is around ± 15 V.

The input gain setting is assured by a linear potentiometer being connected in the net of resistors so it acts as the logarithmical one. This is because stereo linear potentiometers usually embody better parameters matching of their both channels.

Afterwards, the signal, whose level is now set by the input amplifier to the correct level, proceeds to the voltage controlled amplifier VCA 1 where it is amplified by the proper amplification factor. This amplification factor is set by the DC voltage level at the output of the DC control voltage amplifier. The linear dependence of the amplification factor on the input control voltage is achieved by utilizing the negative feedback from the voltage controlled amplifier VCA2 back to the DC control voltage amplifier.

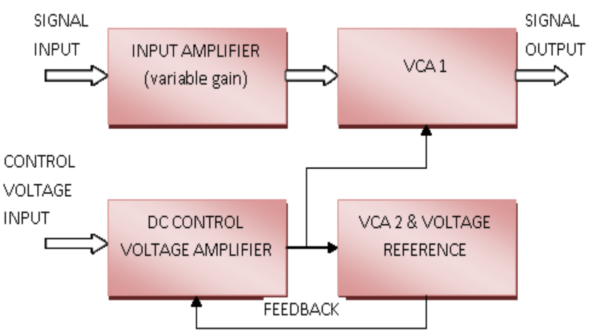

Fig.1, Circuit block diagram

2.2 Detailed description

The schematic layout of left channel of the circuit (for simplicity, the right channel, which is identical, is not shown here) can be seen in Fig. 2. The circuit employs one connector, SV1, by the help of which it is connected to the main board of the expander. This connector is common to both channels and is connected in a symmetrical way. How the pins are connected can be seen in table 1. The pins in brackets are used by the right channel that is not shown in the Fig. 2.

Table 1, SV1 Connector Pinout

Pin	Description
1, (19)	Signal input
2, (20)	Signal output
3, 4, 5, (17, 18, 15)	Gain potentiometer
6, (16)	Control voltage
7, (13)	Output for VU meters (dry signal)
8, (14)	Output for VU meters (wet signal)
9	+ 15 V supply
10	- 15 V supply
11	GND

The input amplifier with variable gain employs the operational amplifier IC1B. This amplifier is connected as a differential amplifier both inputs of which are driven by the input signal. If the appropriate resistor net was ideally balanced, the amplification factor of this amplifier would be 1/∞. By connecting a potentiometer to pins 3, 4, 5 we can make this structure disbalanced according to the potentiometer setting. The principle of superposition allows us to form an expression describing how the amplification factor depends on setting the potentiometer:

$$A_{IC1B} = 20 \cdot log\left(-\left(\frac{R2}{R1+R2} \cdot \left(1 + \frac{xP+R5}{(1-x)P+R4}\right) - \frac{xP+R5}{(1-x)P+R4}\right)\right) \qquad (1)$$

where R1 to R5 are values of the appropriate resistors, P is the value of the potentiometer and x is a potentiometer setting factor that belongs to the interval from 0 to 1. Optimal resistor values were found by several mathematical calculations applied to (1) in Maple. For the values indicated in Fig. 2 the dependency of amplification factor on setting the potentiometer with a resistance of 100 kΩ can be seen in Fig. 2.

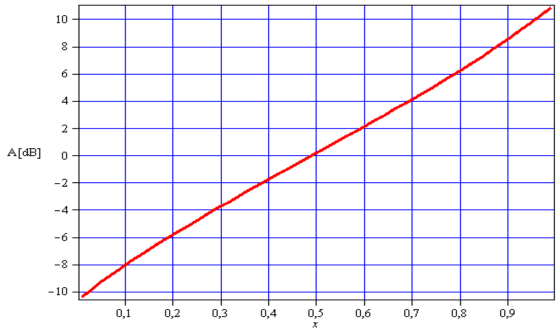

Fig.2, Quasi-logarithmical preamplifier gain adjusting (optimised by Maple)

The signal voltage-controlled amplifier is built with the operational amplifier IC1A. It is also connected as a differential amplifier but the feedback is invariable now. The amplification factor depends on the resistance of T1 transistor. As stated in [2], the amplification factor of such differential amplifier can be expressed like:

$$A_{diff} = \frac{R_a}{R_b} \qquad (2)$$

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Where Ra = R11 = R12 and Rb = R8 = R10. The lower the internal impedance of T1 is, the lower is the voltage at its drain (the voltage drop on R9 ises). In this configuration, theoretically, the amplification factor can vary from 0 to 3.9. Considering we need to restrain the amplification factor to the interval from 1 to approximately 3.25, we can deduce the values of several devices. The transistor BF245B achieves a minimal drain-to-source resistance of approximately 200 Ω. Considering possible non-linearity and dispersion of parameters it is reasonable to add 220 Ω R13 resistor to it. Neglecting the influence of resistors R15 and R25, for the output voltage there is the following expression available:

$$A(U_{GS}) = \left(\frac{R12}{R10}\right) \cdot \left(1 - \frac{\dfrac{R14 \cdot \left(\dfrac{r_{DS_0}}{1 - \sqrt{\dfrac{|U_{GS}|}{U_P}}} + R13 \right)}{R14 + R13 + 1 - \sqrt{\dfrac{|U_{GS}|}{U_P}}}}{R9 + \dfrac{R14 \cdot \left(\dfrac{r_{DS_0}}{1 - \sqrt{\dfrac{|U_{GS}|}{U_P}}} + R13 \right)}{R14 + R13 + 1 - \sqrt{\dfrac{|U_{GS}|}{U_P}}}} \right) \qquad (3)$$

where U_{gs} is the gate-to-source voltage at T1 transistor, U_p is the threshold voltage of T1 transistor and r_{DS0} is the minimal internal resistance of the T1 transistor. Moreover, the resistors R11 and R12 must be of the equal value as well as the resistors R8 and R10. The amplification factor is dependent on the value of U_{gs}. As can be seen, this dependency is not linear. With Maple, the function $A(U_{gs})$ for transistors with U_P from -3 to -2.5 V can be figured as follows:

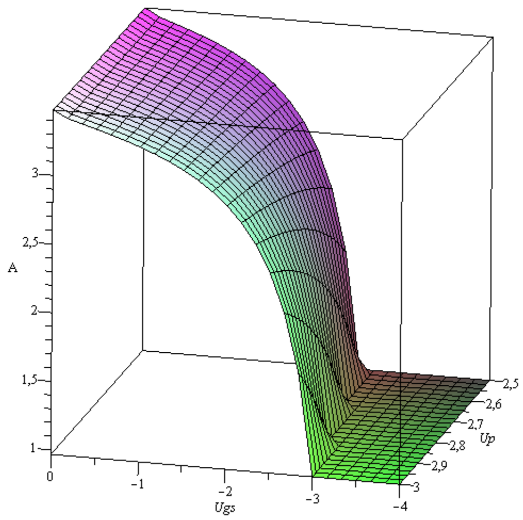

Fig. 3, Amplification factor A [dB] dependency on U_{gs} [V] and U_p according to equation (3)

Another complication is based on the fact that there exists and influence of the U_{gs} by signal voltage which will produce a perceptible distortion for large signals. This effect and its cancellation is described in [5]. According to [5], the distortion is cancelled by resistors R15 and R25. Moreover, the transistor T1 is driven near its minimal drain-to-source resistance the nonlinearity of which is in addition

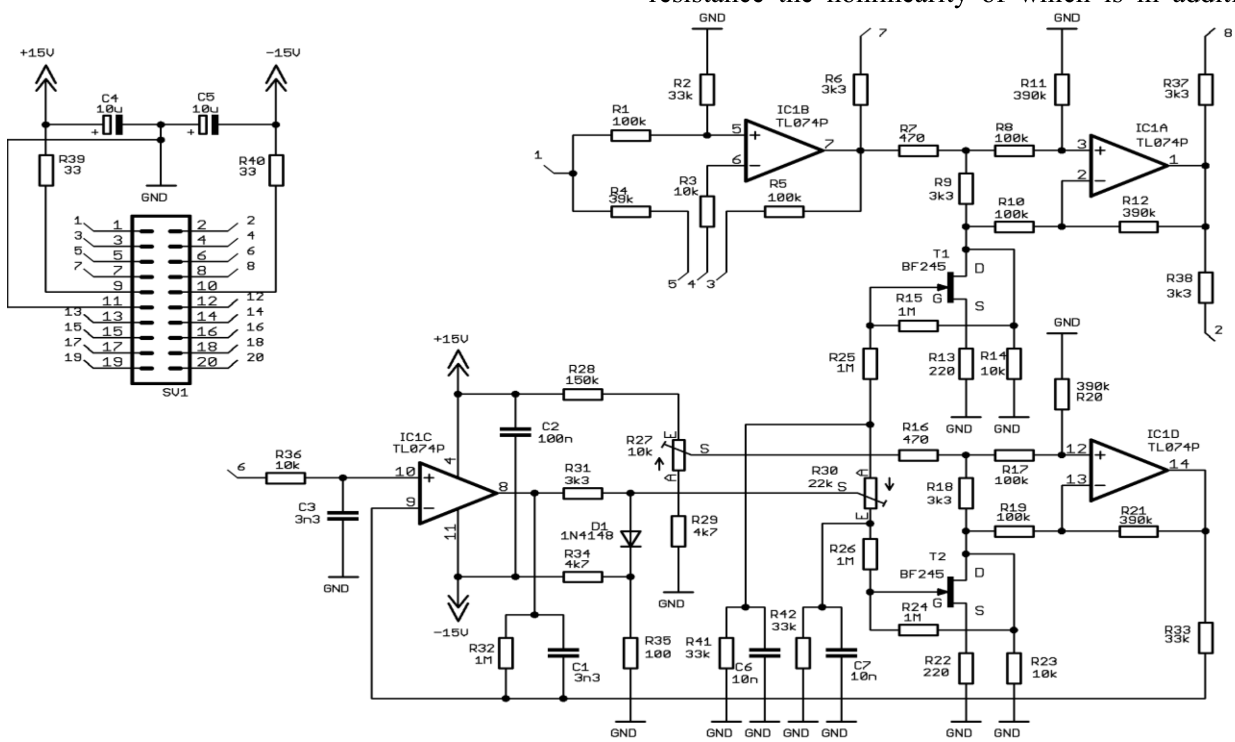

Fig. 4. Voltage controlled amplifier schematics (one of two channels)

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eliminated by adding R13 resistor. When the transistor T1 is nearly closed, its nonlinearity increases but this effect is cancelled by R14 resistor that also determines the minimal amplification factor of the voltage-controlled amplifier. For the proper function of the circuit, only transistors with Up ≥ 2.6 V can be used so their function was not affected by large signals up to + 10 dBu.

An auxiliary amplifier of the same construction is made with the operational amplifier IC1D. This amplifier serves to define a dependence of the amplification factor on the control voltage. This amplifier is fed with the DC voltage of 1 V. This level is set by the rotary trimming resistor R27. Let us assume that the amplifiers made with the operational amplifiers IC1A and IC1D are identical, which means that all used components are of zero value tolerances. Then the output voltage of the auxiliary amplifier refers to the amplification factor set by the U_{gs} voltage of the T2 transistor and this amplification factor indirectly corresponds to the amplification factor of the signal VCA. The output of the auxiliary amplifier serves as a feedback for the DC input amplifier made with the operational amplifier IC1C. This DC amplifier sets the control voltage U_{gs} of the transistors T1 and T2 to such level in which the output voltage of the auxiliary amplifier is equal to the input control voltage. In other words, if both, the signal and the auxiliary amplifier are of equal characteristics, their amplification factor is equal to the control voltage connected to the PIN6 of the SV1 connector. Obviously, this dependence is only valid for the amplification factors achievable with the appropriate circuit construction. In our case 1 V control voltage refers to the amplification factor of 1 (0 dB) and 3.25 V refers to the amplification factor of 3.25 (+ 10 dB). To prevent driving the PN junctions of T1 and T2 transistor to their on-state in case the control voltage exceeded the upper boundary there is the diode D1 connected at the output of the IC1D operational amplifier. Its cathode is connected to a potential roughly equal to its junction potential so the transistors cannot be driven by voltages higher than zero. The rotary trimming resistor R30 serves to balance the small differences of the threshold voltages of the T1 and T2 transistors. However, for the proper function of the circuit these transistors should be paired and mounted close each to other in order their temperature was equal. The capacitors C6 and C7 are to cancel the influence of not-symmetrically-set rotary trimming resistor R30 to the feedbacks made with resistors R15, R25 and R24, R26. The capacitor C1 was added after the simulation experiences that proved that the feedback loop tends to oscillate.

3 Simulation results

Several simulations were made in order to proof the design of the circuit. Firstly only the preamplifier made with the IC1B operational amplifier was checked. Secondly, other simulations were run on the whole circuit as it is shown in Fig. 4.

3.1 Preamplifier

Several simulations of the preamplifier circuit were made in order to check its gain adjustment, frequency response, distortion, input impedance and output voltage swing. First of all there were 5 AC analyses made in order to verify the frequency response and gain adjustment. These analyses were run for 5 different gain potentiometer settings (0 %, 25 %, 50 %, 75 % and 100 %) at the range of frequencies from 10 Hz to 100 kHz. The result of these analyses can be seen in Fig. 5.

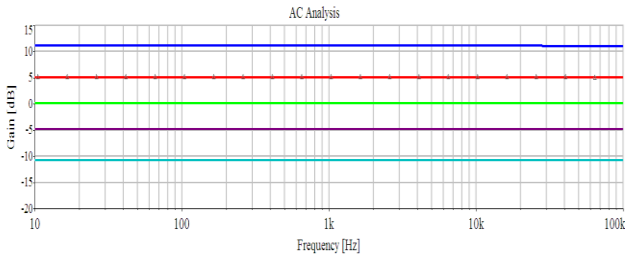

Fig. 5, Preamplifier frequency response at 5 different gain settings

The results of the simulation proved that the gain is adjustable from approximately -10.5 dB to approximately + 11 dB and that the control progression is logarithmical. At the worst there is a 0.2 dB attenuation at 100 kHz compared to 1 kHz when the gain is set to + 10 dB.

The distortion was simulated by Fourier analysis at the frequencies of 1 kHz and 15 kHz, in both cases also for 5 gain settings. In all cases the input was fed with 0 dBu sinusoidal signal. The results can be seen in Fig. 6.

Defining the input impedance is quite more complicated. To do this an indirect method was used. The complex element of the impedance has been neglected.

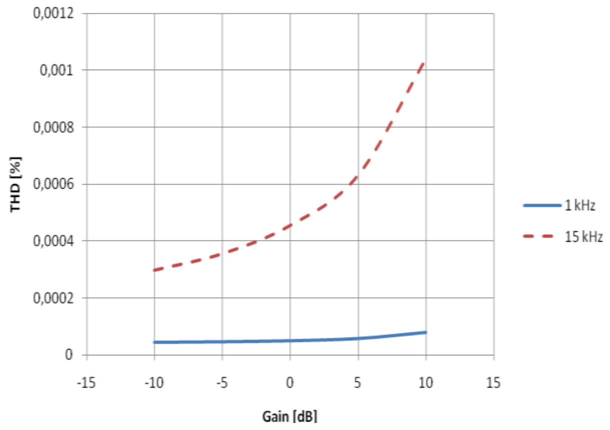

Fig. 6, Preamplifier distortion versus its gain setting

The input of the circuit was fed with 1 kHz sinusoidal signal the amplitude of which was 1 V and the current through the signal source was measured. Then the input resistance was calculated. It was found that the input impedance varies from 35 to 75 kΩ, depending on the gain setting.

The voltage swing was proved by feeding the circuit with + 20 dBu 1kHz sinusoidal signal when the gain was set to + 10 dB. Smooth limitation at the levels of ± 13.5 V was indicated. This refers to the overexcitation of 21.8 dB.

3.2 Voltage controlled amplifier

Simulations of the VCA were carried on the whole circuit shown in the Fig. 4, together with the preamplifier. Throughout the simulations, frequency response of the circuit was checked as well as the dependency of the amplification factor on the input control voltage and its time response to the input control voltage shift. Secondly, noise analyses and distortion analyses were processed.

The frequency response was checked at the preamplifier gain set to 0 dB and the VCA amplification factor set to 0 dB and + 10 dB. The simulation results can be seen in Fig. 7. It is obvious the frequency response is flat it the range of audible frequencies.

The amplification factor dependency on the input control voltage is shown in Fig. 8 and 9. The input of the circuit was fed with 1 kHz 0 dBu sinusoidal signal while the control voltage was changed within the range from 0.75 to 3.5 V. Smooth and steep control voltage changes were applied. The rise and fall periods were considered to be at least 5 and 10 ms because there is no need to change the control voltage faster.

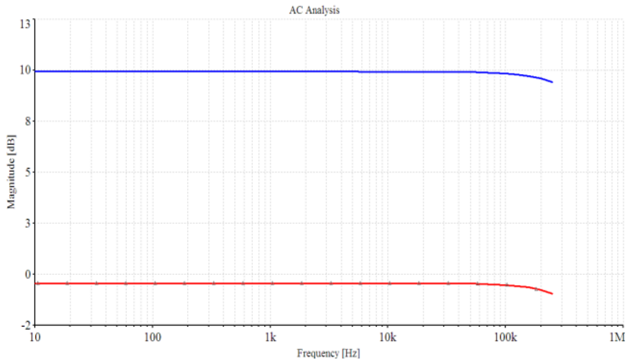

Fig. 7, The whole VCA frequency response at the preamplifier gain set to 0 dB and the VCA amplification factor set to 0 dB and + 10 dB

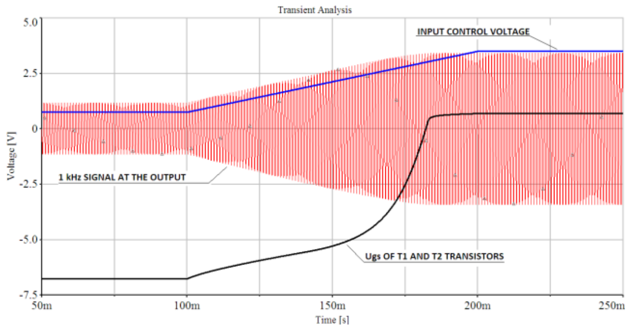

Fig. 8, VCA response to the input control voltage (slow sweep)

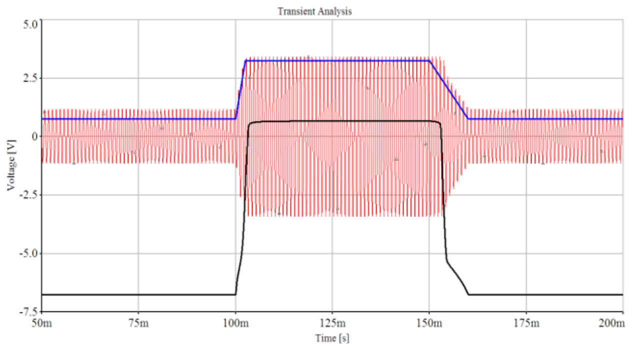

Fig. 9, VCA response to the input control voltage (fast sweep)

The noise analysis was made for the 0 dBu input signal, 0 dB preamplifier gain and two VCA amplification factors – 0 dB and + 10 dB. The frequency range was restricted from 200 Hz to 10 kHz and no weighting filter was applied. Compared to the 0 dBu signal level this method helped us to estimate the signal-to-noise ratio to 90 dB at minimal and 86 dB at maximal amplification factor.

To discover how the total harmonic distortion depends on the amplification factor setting, Fourier analyses were processed for amplification factors of 0, + 3, + 6 and + 9 dB with the input sinusoidal

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signal of 0 dBu level and 1 kHz frequency. The results were plotted into a diagram in Fig. 10.

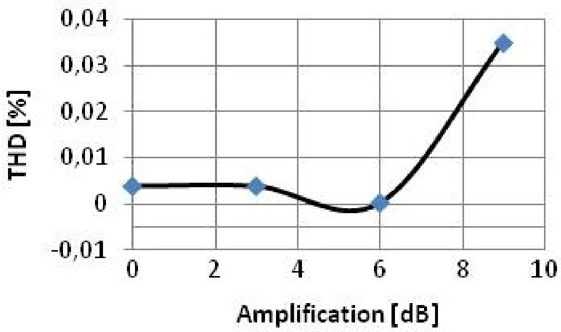

Fig. 10, Total harmonic distortion versus VCA amplification factor

4 Conclusion

With the aid of software design tools like Multisim and Maple the construction of the voltage-controlled amplifier was projected and its proper function was proved by a set of simulations.

Very low distortion (THD < 0,05 %) and the linear amplification factor dependence on the input control voltage was achieved. This circuit is suitable to be utilized in audio volume expanders.

Acknowledgements

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