Low-Voltage Low-Power Fully-Integratable Automatic Gain Controls

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ABSTRACT

This paper discusses the design of low-voltage low-power fully-integratable automatic gain controls. Four different AGCs are presented, all consisting of three elementary building blocks: a controlled amplifier, a comparator and a voltage follower. Their design is treated separately. As an example, the final section describes an automatic gain control for hearing instruments.

INTRODUCTION

Low-voltage low-power circuit techniques are applied in the area of battery-operated systems.

Automatic gain controls (AGCs) are widely used in communication systems to modify the dynamic range of a signal. They can be found in e.g. radio receivers and transmitters, audio amplifiers and hearing instruments.

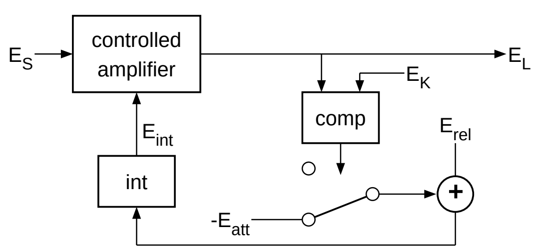

Figure 1: Block diagram of an AGC (C.R. = ∞)

In Figure 1 a typical AGC circuit is drawn. The output signal E_L is compared with a reference level E_K (the knee level) by a comparator that determines whether the integrating circuit – in practice often nothing more than a RC network – is discharged (by $E_{\rm att} - E_{\rm rel}$) or charged (by $E_{\rm rel}$). The output signal of the integrator, $E_{\rm int}$, forms the control signal of the controlled amplifier. The operation is as follows: When $E_{\rm att}$ is larger than $E_{\rm rel}$ the output signal E_L is controlled towards the knee level E_K. Variations of the input signal therefore always result in smaller or equal variations of the output signal.

An important parameter is the *compression ratio* (C.R.), defined as the ratio of the variation of the input signal and the variation of the output signal (both in dBs), or

$$C.R. = \frac{\Delta E_{S,\rm dB}}{\Delta E_{L,\rm dB}} \quad (1)$$

The circuit of Figure 1 realizes an infinite compression ratio. In the next section realizations with different compression ratios will be discussed.

AGCS WITH FINITE COMPRESSION RATIOS

Controlled amplifiers in cascade

One way of obtaining a finite compression ratio is to pass the output signal of the AGC, E_L, through another controlled amplifier, which is controlled by the same control signal $E_{\rm int}$. The output of this second amplifier then can be compared with E_K and thus kept constant. This situation is depicted in Figure 2.

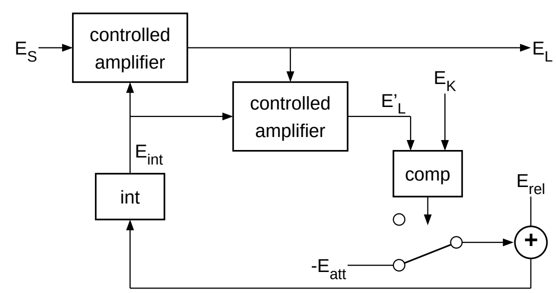

Figure 2: AGC with C.R. = 2 using two controlled amplifiers in cascade

If the controlled amplifier consists of a simple multiplier three equations can be extracted: $E'_L = E_K$, $E_L = E_S E_{\rm int}$, and $E'_L = E_L E_{\rm int}$, with E_L the output signal of the AGC, and E'_L the output signal of the second controlled amplifier, which is kept equal to E_K. For the compression ratio of the AGC we thus can write

$$C.R. = \frac{\Delta E_{S,\rm dB}}{\Delta E_{L,\rm dB}} = \frac{20 \log E_S}{20 \log \sqrt{E_K E_S}} = 2 \quad (2)$$

because E_K is a constant DC level.

Realizing compression ratios other than two is done using more controlled amplifiers in cascade. However, because of the larger complexity this is believed to be of little practical value.

Differently controlled amplifiers

Another possibility is making use of two controlled amplifiers that both have the same input signal E_S, but are controlled by different control signals. This is depicted in Figure 3. The output signal of the integrator, $E_{\rm int}$, is passed to the controlled amplifier that generates the output signal and to a multiplier that multiplies $E_{\rm int}$ by a constant factor m. This multiplied version of $E_{\rm int}$ is then passed to the second controlled amplifier that generates the signal that is to be compared with E_K.

In order to operate properly the input-output relation of the controlled amplifiers cannot be that of a multiplier for this would result in an infinite compression ratio. We therefore

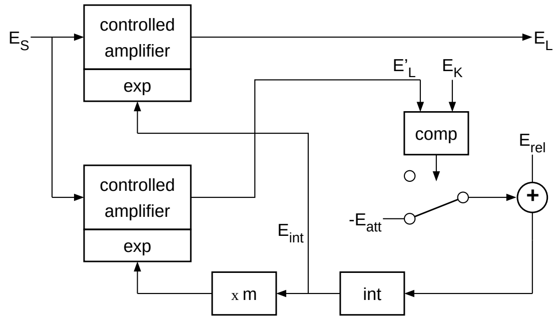

Figure 3: AGC with C.R. = $\frac{m}{m-1}$ using differently controlled amplifiers

assume that both amplifiers realize an exponentially controlled transfer function, or

$$E_{\text{out}} = E_{\text{in}} \exp E_{\text{control}} \tag{3}$$

This transfer function can easily be realized, as will be shown in Section . For the circuit of Figure 3 again three expressions can be found: $E'_L = E_K$, $E_L = E_S \exp E_{\text{int}}$, and $E'_L = E_S \exp mE_{\text{int}}$. For the compression ratio we then find

$$C.R. = \frac{\Delta E_{S,\text{dB}}}{\Delta E_{L,\text{dB}}} = \frac{1}{1 - 1/m} = \frac{m}{m-1} \tag{4}$$

Using this technique all compression factors between zero and infinity can be realized. A compression ratio of two, for example, is thus obtained by choosing $m = 2$.

Controlled knee level

Finally there is also the possibility of passing the reference level E_K through another controlled amplifier and comparing its output signal to the output signal of the AGC. This is depicted in Figure 4. As E_K contains no signal information (i.e. is a constant DC level) the demands that are made upon the second controlled amplifier can be much less, thereby reducing the circuit complexity.

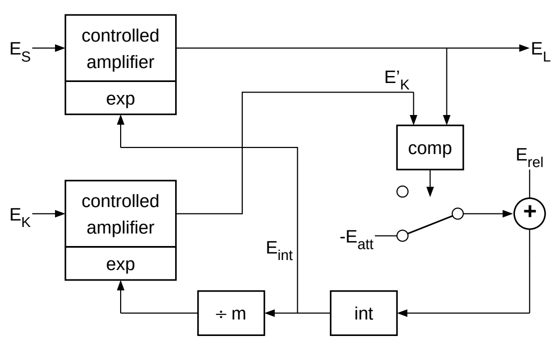

Figure 4: AGC with C.R. = $1 - m$ using a controlled knee level

Again both amplifiers are controlled exponentially. The output signal of the integrator, E_{int}, is passed to the controlled amplifier that generates the output signal of the AGC and to a divider that divides E_{int} by a constant factor m. This divided version of E_{int} is then passed to the second controlled amplifier that generates the signal that is to be compared with the output signal E_L from the reference level E_K. Again three expressions can be found: $E'_K = E_L$, $E_L = E_S \exp E_{\text{int}}$, and $E'_K = E_K \exp E_{\text{int}}/m$. For the compression ratio this results in

$$C.R. = \frac{\Delta E_{S,\text{dB}}}{\Delta E_{L,\text{dB}}} = \frac{1}{1/(1-m)} = 1 - m \tag{5}$$

A compression ratio of two, for example, is obtained by choosing $m = -1$. Hence, in this situation the divider is an inverter.

AGCS IN THE CURRENT DOMAIN

Low-voltage low-power integrated circuits for preference operate in the current domain [1]. For this reason all signals will be represented by currents as much as possible. However, we will see in the next section that the exponentially controlled amplifiers proposed here are controlled by means of a voltage. As the only integratable integrating element is a capacitor, and its input signal is a current, whereas its output signal is a voltage, the integrator will thus consist of a capacitor followed by a voltage follower. This voltage follower generates a low-impedance version of the voltage across the capacitor to avoid interaction between the capacitor and the controlled amplifier.

CONTROLLED CURRENT AMPLIFIERS

Controlled amplifiers can be divided into two different types. First there is the class of controlled amplifiers of which the output signal shows no significant variation, but of which the input signal varies over a large range (type 1). As an example we mention an AGC with infinite compression; its input signal varies significantly but the output signal is almost unchanged. On the other hand there are controlled amplifiers of which the input signal shows no significant variation, but of which the output signal varies over a large range (type 2). For example in an ordinary audio amplifier: the output signal is controlled so that the resulting sound pressure level corresponds to the need of the listener.

Four fundamental ways of controlling the gain

A suitable implementation is a current amplifier of which the gain equals the ratio of two transconductances: the scaling current amplifier (Figure 5) [1]. As the transconductance of a bipolar transistor is proportional to its (DC) collector current we can vary the gain by varying the collector current of either Q_1 or Q_2.

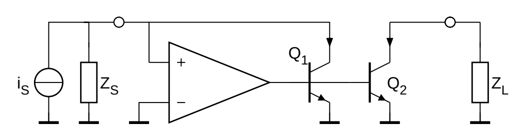

Figure 5: Controlling the gain of a scaling current amplifier by controlling the ratio of the collector currents of Q_1 and Q_2

Another way of controlling the ratio of the transconductances and thus the gain of the amplifier is by means of a controlling voltage V_C connected between the emitters of Q_1 and Q_2. We now obtain a gain A_i that is proportional to the anti-log of V_C, or

$$A_i = -g_{m,Q_2}/g_{m,Q_1} = -e^{V_C/V_T} \approx 335\ V_C \text{ dB} \tag{6}$$

in which V_T equals the thermal voltage kT/q, approximately 26 mV at 300 K.

As the controlled current amplifiers are either current- or voltage-controlled and either belong to the first or second type we can distinguish four different kinds:

- a current-controlled type 1 scaling current amplifier
- a current-controlled type 2 scaling current amplifier
- a voltage-controlled type 1 scaling current amplifier
- a voltage-controlled type 2 scaling current amplifier

These four are the subject of the next four subsections. Unless there is the possibility of on-chip filtering, the biasing of a circuit is done for preference by setting the common-mode quantities [1]. In order to do so the signal path has to be symmetrical. As current- or voltage-controlled and type 1 or type 2 has nothing to do with the signal behavior of the amplifier, we will assume that the design of the symmetrical signal path is completed in an earlier stage and start our considerations from here.

The current-controlled type 1 symmetrical scaling current amplifier

The general biasing solution for a current-controlled type 1 symmetrical scaling current amplifier is depicted in Figure 6. The transfer function is controlled by means of two current sources I_C. In order to make the DC collector currents of the output transistors equal to I, a common-mode output is generated by two extra output transistors. The sum of their collector currents is compared with $2I$ resulting in an error signal. This error signal is amplified by the op amp and fed back to both emitters of the input transistors, thereby setting the correct emitter current.

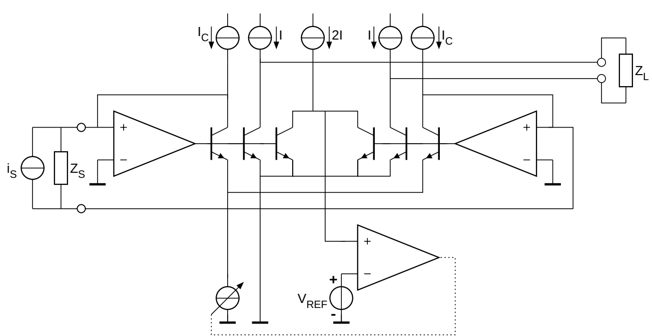

Figure 6: Current-controlled type 1 symmetrical scaling current amplifier

The current-controlled type 2 symmetrical scaling current amplifier

This situation does not differ much from the preceding one. Only now the transfer function is controlled by varying the current through the *output transistors*. Because the current-controlled type 2 symmetrical scaling current amplifier is less suited for implementation in automatic gain controls [1], we do not discuss it here.

The voltage-controlled type 1 symmetrical scaling current amplifier

The general solution for a voltage-controlled type 1 symmetrical scaling current amplifier is depicted in Figure 7. Voltage source V_C controls the gain. Again a common-mode replica of the common-mode collector currents through the output transistors is compared with $2I$, resulting in an error signal. This error signal is amplified by the op amp and controls the collector current of the input stages.

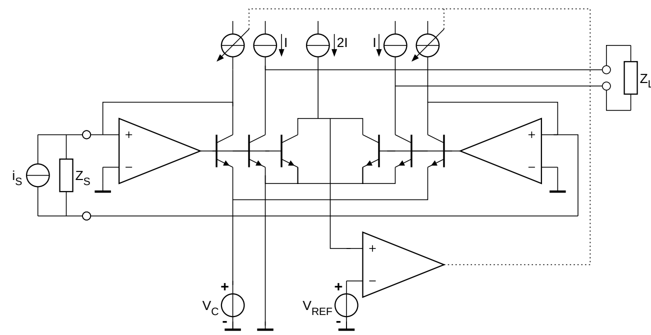

Figure 7: Voltage-controlled type 1 symmetrical scaling current amplifier

The voltage-controlled type 2 symmetrical scaling current amplifier

Because the voltage-controlled type 2 symmetrical scaling current amplifier is less suited for implementation in automatic gain controls [1], we do not discuss it here.

COMPARATORS

The comparator is the circuit that compares the output current of the controlled amplifier with the reference level I_K by means of a highly non-linear input-output relation.

For a comparator which has a current-current input-output relation we can choose either a cascade connection of a non-linear one-port and a linear two-port or an amplifier with a saturating input-output relation.

Cascade of a non-linear one-port and a linear two-port

Examples of (bipolar) non-linear one-ports are diodes and pinch resistors. An example of a (current) comparator consisting of a cascade of a non-linear one-port and a linear two-port is shown in Figure 8. Although relatively simple, this comparator is supposed to be of less practical importance in low-voltage low-power integrated circuits.

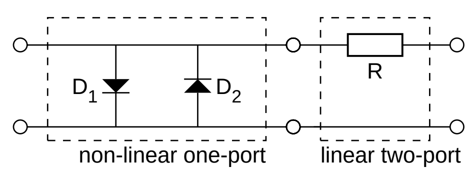

Figure 8: Example of a comparator consisting of a cascade connection of a non-linear one-port and a linear two-port

Amplifiers with a saturated input-output relation

It is not difficult to design an amplifier with a saturated input-output relation; every practical amplifier will come into saturation if its input signal exceeds a certain level. Three examples are depicted in Figure 9.

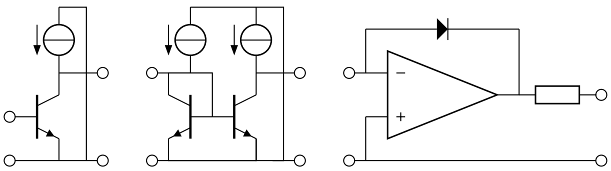

Figure 9: Three possible implementations of amplifiers with a saturated input-output relation

VOLTAGE FOLLOWERS

The last stage in the design of low-voltage low-power AGCs is the design of the voltage follower. The voltage follower forms a buffer between the capacitance C and the controlled amplifier. Since the input current of a field effect transistor (JFET or MOST) is far below the other currents that charge and discharge the integrating capacitor these devices are very well suited for this task. When using bipolar transistors this can only be achieved using negative-feedback techniques. The basic voltage-follower configuration and three possible implementations, with either one, two or three transistors, are shown in Figure 10.

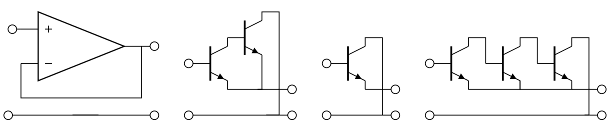

Figure 10: Basic voltage-follower configuration and three possible implementations

AN EXAMPLE: AN AGC FOR HEARING INSTRUMENTS

The circuit that is described here is an AGC for hearing instruments with an infinite compression ratio [2], of which the block diagram was shown in Figure 1. Its *current-domain* realization is shown in Figure 11. Apart from the integrator signal E_{int} all signals are represented by currents. The nominal signal level at both input and output amounts to 25 nA (peak value).

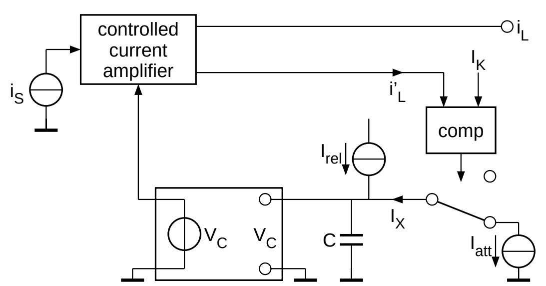

Figure 11: Block diagram of an AGC-O operating in the current domain

The controlled amplifier

From the considerations in Section it may be clear that the best choice will be a type 1 symmetrical scaling current amplifier. From the two variants we choose the voltage-controlled one as this results in a control action in dBs, which is perceptibly the most comfortable. A possible implementation of a voltage-controlled symmetrical scaling current amplifier is shown in Figure 12 (at the left side). As the absolute value of the (differential) loop gain is always larger than $B_F/4$ there is no need for additional loop gain; the op amps thus are replaced by short circuits. We can call this a voltage-controlled type 1 symmetrical current mirror.

The comparator

The comparator is the subcircuit that decides whether the output current i'_L of the controlled amplifier is larger or smaller than the reference level I_K. For this purpose we can use again a symmetrical current mirror now acting as an amplifier with a saturated input-output relation. Its implementation is shown in Figure 12 (right under).

The voltage follower

The chosen (two-stage) voltage follower is depicted in Figure 12 (above).

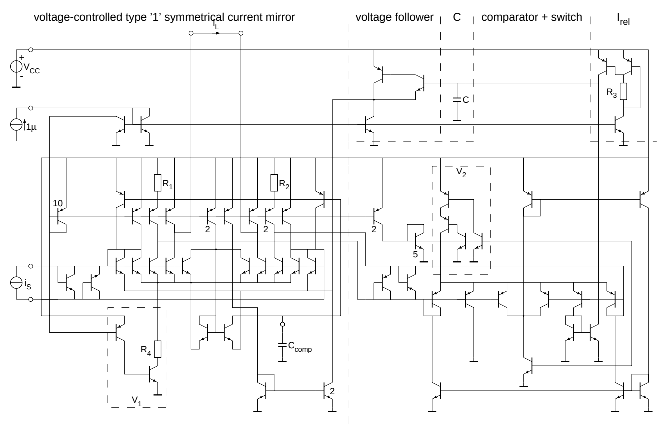

Figure 12: The total AGC

Experimental results

The active circuitry of the circuit shown in Figure 12 was integrated in the DIMES01 process fabricated at the Delft Institute of Microelectronics and Submicron Technology.

Table 1: Measurement results of the AGC

Parameter	Value	Unit
Compression range	38	dB
Attack time, i_s=1 μA$_p$, 1 kHz	4.2	ms
Release time, i_s=10 nA$_p$, 1 kHz	58	ms
Dynamic Range, G=1, B=10 kHz	62	dB
Bandwidth	$>$100	kHz
Min. supply voltage	1	V
Supply current, G=1	4	μA

REFERENCES

[1] W.A. Serdijn: *The design of low-voltage low-power analog integrated circuits and their applications in hearing instruments*, Ph.D. Thesis, Delft University of Technology, Delft, the Netherlands, 1994.

[2] W.A. Serdijn et al.: *A low-voltage low-power fully-integratable automatic gain control for hearing instruments*, Proc. ESSCIRC, pp. 258-261, 1993.